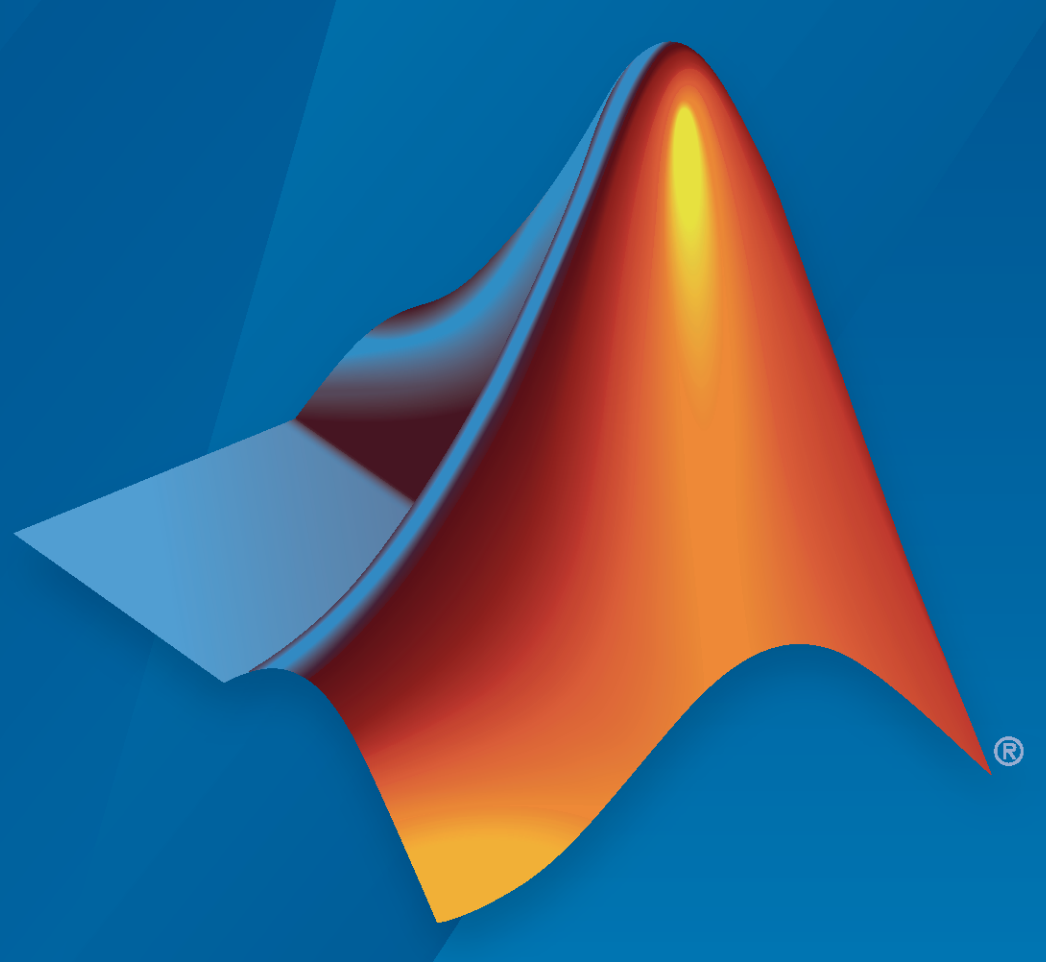
# Navigation Toolbox™

Reference



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**R**2023**a**

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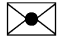

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*Navigation Toolbox™ Reference*


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**Revision History**

| | | |
|---|---|---|
| September 2019 | Online only | New for Version 1.0 (R2019b) |
| March 2020 | Online only | Rereleased for Version 1.1 (R2020a) |
| September 2020 | Online only | Revised for Version 1.2 (R2020b) |
| March 2021 | Online only | Revised for Version 2.0 (R2021a) |
| September 2021 | Online only | Revised for Version 2.1 (R2021b) |
| March 2022 | Online only | Revised for Version 2.2 (R2022a) |
| September 2022 | Online only | Revised for Version 2.3 (R2022b) |
| March 2023 | Online only | Revised for Version 2.4 (R2023a) |

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# Functions

# allanvar

Allan variance

## Syntax

```
[avar,tau] = allanvar(Omega)
[avar,tau] = allanvar(Omega,m)
[avar,tau] = allanvar(Omega,ptStr)
[avar,tau] = allanvar(___,fs)
```

## Description

Allan variance is used to measure the frequency stability of oscillation for a sequence of data in the time domain. It can also be used to determine the intrinsic noise in a system as a function of the averaging time. The averaging time series $\tau$ can be specified as $\tau = m/fs$. Here *fs* is the sampling frequency of data, and *m* is a list of ascending averaging factors (such as 1, 2, 4, 8, …).

`[avar,tau] = allanvar(Omega)` returns the Allan variance `avar` as a function of averaging time `tau`. The default averaging time `tau` is an octave sequence given as $(1, 2, ..., 2^{\text{floor}\{\log_2[(N-1)/2]\}})$, where *N* is the number of samples in `Omega`. If `Omega` is specified as a matrix, `allanvar` operates over the columns of `omega`.

`[avar,tau] = allanvar(Omega,m)` returns the Allan variance `avar` for specific values of `tau` defined by `m`. Since the default frequency `fs` is assumed to be 1, the output `tau` is exactly same with `m`.

`[avar,tau] = allanvar(Omega,ptStr)` sets averaging factor `m` to the specified point specification, `ptStr`. Since the default frequency `fs` is 1, the output `tau` is exactly equal to the specified `m`. `ptStr` can be specified as `'octave'` or `'decade'`.

`[avar,tau] = allanvar(___,fs)` also allows you to provide the sampling frequency `fs` of the input data `omega` in Hz. This input parameter can be used with any of the previous syntaxes.

## Examples

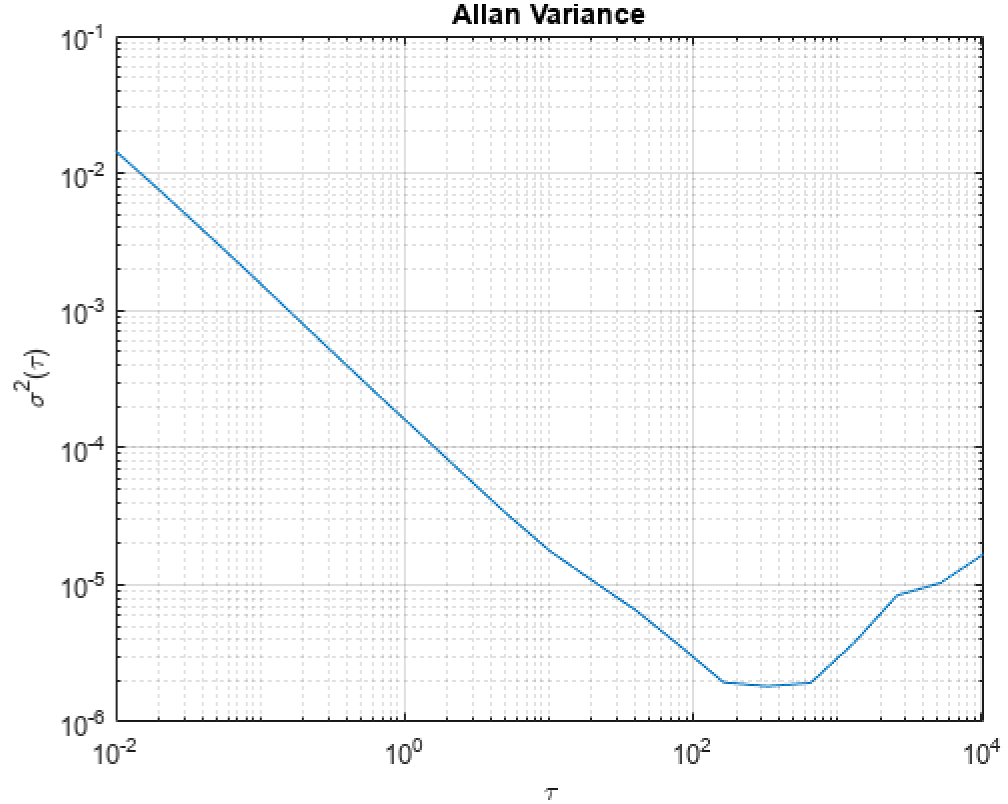
### Determine Allan Variance of Single Axis Gyroscope

Load gyroscope data from a MAT file, including the sample rate of the data in Hz. Calculate the Allan variance.

```
load('LoggedSingleAxisGyroscope','omega','Fs')
[avar,tau] = allanvar(omega,'octave',Fs);
```

Plot the Allan variance on a `loglog` plot.

```
loglog(tau,avar)
xlabel('\tau')
ylabel('\sigma^2(\tau)')
title('Allan Variance')
grid on
```




**Determine Allan Deviation at Specific Values of $\tau$**

Generate sample gyroscope noise, including angle random walk and rate random walk.

```
numSamples = 1e6;
Fs = 100;
nStd = 1e-3;
kStd = 1e-7;
nNoise = nStd.*randn(numSamples,1);
kNoise = kStd.*cumsum(randn(numSamples,1));
omega = nNoise+kNoise;
```

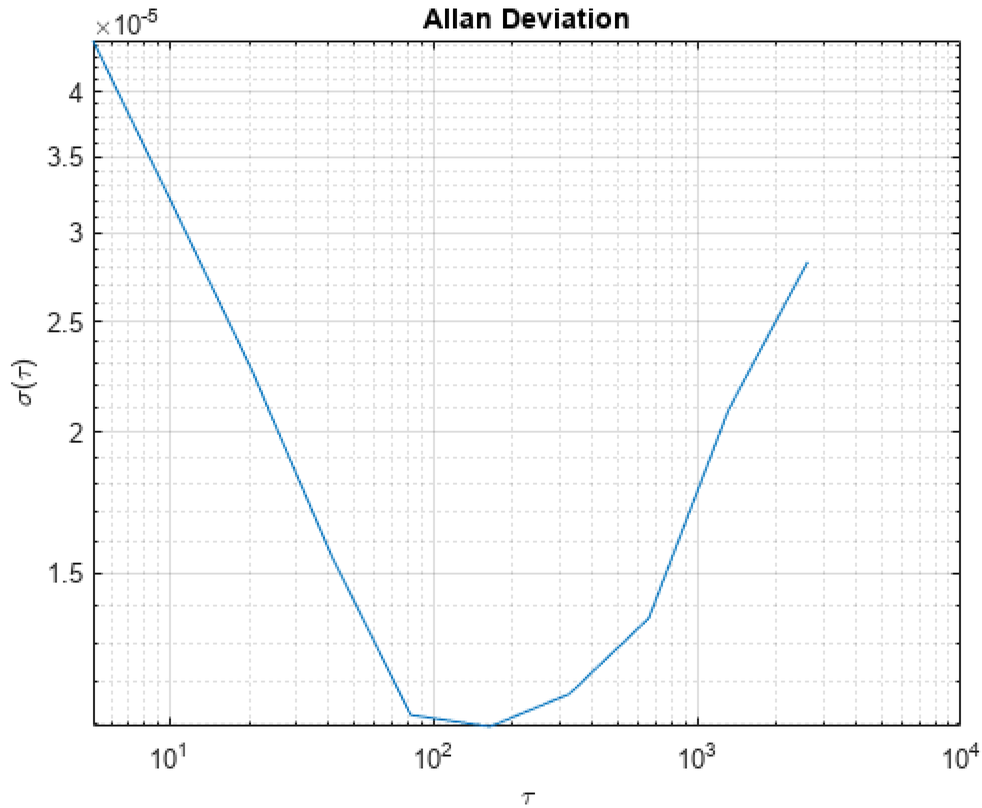
Calculate the Allan deviation at specific values of $m = \tau$. The Allan deviation is the square root of the Allan variance.

```
m = 2.^(9:18);
[avar,tau] = allanvar(omega,m,Fs);
adev = sqrt(avar);
```

Plot the Allan deviation on a `loglog` plot.

```
loglog(tau,adev)
xlabel('\tau')
ylabel('\sigma(\tau)')
```

```
title('Allan Deviation')
grid on
```




## Input Arguments

**Omega — Input data**
*N*-by-1 vector | *N*-by-*M* matrix

Input data specified as an *N*-by-1 vector or an *N*-by-*M* matrix. *N* is the number of samples, and *M* is the number of sample sets. If specified as a matrix, `allanvar` operates over the columns of `Omega`.

Data Types: `single` | `double`

**`m` — Averaging factor**
scalar | vector

Averaging factor, specified as a scalar or vector with ascending integer values less than (*N*-1)/2, where *N* is the number of samples in `Omega`.

Data Types: `single` | `double`

**`ptStr` — Point specification of `m`**
`'octave'` (default) | `'decade'`

Point specification of `m`, specified as `'octave'` or `'decade'`. Based on the value of `ptStr`, `m` is specified as following:

- If `ptStr` is specified as `'octave'`, `m` is:

$$\left[2^0, 2^1 \ldots 2^{\left\lfloor \log_2\left(\frac{N-1}{2}\right)\right\rfloor}\right]$$

- If `ptStr` is specified as `'decade'`, `m` is:

$$\left[10^0, 10^1 \ldots 10^{\left\lfloor \log_{10}\left(\frac{N-1}{2}\right)\right\rfloor}\right]$$

*N* is the number of samples in `Omega`.

**`fs` — Basic frequency of input data in Hz**
scalar

Basic frequency of the input data, `Omega`, in Hz, specified as a positive scalar.

Data Types: `single` | `double`

## Output Arguments

**`avar` — Allan variance of input data**
vector | matrix

Allan variance of input data at `tau`, returned as a vector or matrix.

**`tau` — Averaging time of Allan variance**
vector | matrix

Averaging time of Allan variance, returned as a vector, or a matrix.

# Version History

**Introduced in R2019a**

## See Also

`gyroparams` | `imuSensor`

# angdiff

Difference between two angles

## Syntax

`delta = angdiff(alpha,beta)`

`delta = angdiff(alpha)`

## Description

`delta = angdiff(alpha,beta)` calculates the difference between the angles `alpha` and `beta`. This function subtracts `alpha` from `beta` with the result wrapped on the interval `[-pi,pi]`. You can specify the input angles as single values or as arrays of angles that have the same number of values.

`delta = angdiff(alpha)` returns the angular difference between adjacent elements of `alpha` along the first dimension whose size does not equal 1. If `alpha` is a vector of length *n*, the first entry is subtracted from the second, the second from the third, etc. The output, `delta`, is a vector of length *n-1*. If `alpha` is an *m*-by-*n* matrix with *m* greater than 1, the output, `delta`, will be a matrix of size *m-1*-by-*n*. If `alpha` is a scalar, `delta` returns as an empty vector.

## Examples

### Calculate Difference Between Two Angles

```
d = angdiff(pi,2*pi)
```

```
d = 3.1416
```

### Calculate Difference Between Two Angle Arrays

```
d = angdiff([pi/2 3*pi/4 0],[pi pi/2 -pi])
```

```
d = 1×3

    1.5708   -0.7854   -3.1416
```

### Calculate Angle Differences of Adjacent Elements

```
angles = [pi pi/2 pi/4 pi/2];
d = angdiff(angles)
```

```
d = 1×3
```

```
   -1.5708   -0.7854    0.7854
```

## Input Arguments

**`alpha` — Angle in radians**
scalar | vector | matrix | multidimensional array

Angle in radians, specified as a scalar, vector, matrix, or multidimensional array. This is the angle that is subtracted from `beta` when specified. If `alpha` is a scalar, `delta` returns as an empty vector.

Example: `pi/2`

**`beta` — Angle in radians**
scalar | vector | matrix | multidimensional array

Angle in radians, specified as a scalar, vector, matrix, or multidimensional array of the same size as `alpha`. This is the angle that `alpha` is subtracted from when specified.

Example: `pi/2`

## Output Arguments

**`delta` — Difference between two angles**
scalar | vector | matrix | multidimensional array

Angular difference between two angles, returned as a scalar, vector, or array. `delta` is wrapped to the interval `[-pi,pi]`. If `alpha` is a scalar, `delta` returns as an empty vector.

# Version History

**Introduced in R2015a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

# axang2quat

Convert axis-angle rotation to quaternion

## Syntax

```
quat = axang2quat(axang)
```

## Description

`quat = axang2quat(axang)` converts a rotation given in axis-angle form, `axang`, to quaternion, `quat`.

## Examples

### Convert Axis-Angle Rotation to Quaternion

```
axang = [1 0 0 pi/2];
quat = axang2quat(axang)
```

```
quat = 1×4

    0.7071    0.7071         0         0
```

## Input Arguments

**axang — Rotation given in axis-angle form**
*n*-by-4 matrix

Rotation given in axis-angle form, specified as an *n*-by-4 matrix of *n* axis-angle rotations. The first three elements of every row specify the rotation axis, and the last element defines the rotation angle (in radians).

Example: `[1 0 0 pi/2]`

## Output Arguments

**quat — Unit quaternion**
*n*-by-4 matrix

Unit quaternion, returned as an *n*-by-4 matrix containing *n* quaternions. Each quaternion, one per row, is of the form $q = [w\ x\ y\ z]$, with $w$ as the scalar number.

Example: `[0.7071 0.7071 0 0]`

# Version History

**Introduced in R2015a**

## Extended Capabilities

### C/C++ Code Generation
Generate C and C++ code using MATLAB® Coder™.

## See Also
`quat2axang` | `quaternion`

# axang2rotm

Convert axis-angle rotation to rotation matrix

## Syntax

```
rotm = axang2rotm(axang)
```

## Description

`rotm = axang2rotm(axang)` converts a rotation given in axis-angle form, `axang`, to an orthonormal rotation matrix, `rotm`. When using the rotation matrix, premultiply it with the coordinates to be rotated (as opposed to postmultiplying).

## Examples

### Convert Axis-Angle Rotation to Rotation Matrix

```
axang = [0 1 0 pi/2];
rotm = axang2rotm(axang)
```

```
rotm = 3×3

    0.0000         0    1.0000
         0    1.0000         0
   -1.0000         0    0.0000
```

## Input Arguments

**axang — Rotation given in axis-angle form**
*n*-by-4 matrix

Rotation given in axis-angle form, specified as an *n*-by-4 matrix of *n* axis-angle rotations. The first three elements of every row specify the rotation axis, and the last element defines the rotation angle (in radians).

Example: `[1 0 0 pi/2]`

## Output Arguments

**`rotm` — Rotation matrix**
3-by-3-by-*n* matrix

Rotation matrix, returned as a 3-by-3-by-*n* matrix containing *n* rotation matrices. Each rotation matrix has a size of 3-by-3 and is orthonormal. When using the rotation matrix, premultiply it with the coordinates to be rotated (as opposed to postmultiplying).

Example: `[0 0 1; 0 1 0; -1 0 0]`

## Version History

**Introduced in R2015a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`rotm2axang` | `so2` | `so3`

# axang2tform

Convert axis-angle rotation to homogeneous transformation

## Syntax

```
tform = axang2tform(axang)
```

## Description

`tform = axang2tform(axang)` converts a rotation given in axis-angle form, `axang`, to a homogeneous transformation matrix, `tform`. When using the transformation matrix, premultiply it with the coordinates to be transformed (as opposed to postmultiplying).

## Examples

### Convert Axis-Angle Rotation to Homogeneous Transformation

```
axang = [1 0 0 pi/2];
tform = axang2tform(axang)
```

```
tform = 4×4

    1.0000         0         0         0
         0    0.0000   -1.0000         0
         0    1.0000    0.0000         0
         0         0         0    1.0000
```

## Input Arguments

**axang — Rotation given in axis-angle form**
*n*-by-4 matrix

Rotation given in axis-angle form, specified as an *n*-by-4 matrix of *n* axis-angle rotations. The first three elements of every row specify the rotation axis, and the last element defines the rotation angle (in radians).

Example: `[1 0 0 pi/2]`

## Output Arguments

**`tform` — Homogeneous transformation**
4-by-4-by-*n* matrix

Homogeneous transformation matrix, specified by a 4-by-4-by-*n* matrix of *n* homogeneous transformations. When using the transformation matrix, premultiply it with the coordinates to be formed (as opposed to postmultiplying).

Example: `[0 0 1 0; 0 1 0 0; -1 0 0 0; 0 0 0 1]`

# Version History

**Introduced in R2015a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`tform2axang` | `se2` | `se3`

# buildMap

Build occupancy map from lidar scans

## Syntax

```
map = buildMap(scans,poses,mapResolution,maxRange)
```

## Description

`map = buildMap(scans,poses,mapResolution,maxRange)` creates a `occupancyMap` map by inserting lidar `scans` at the given `poses`. Specify the resolution of the resulting map, `mapResolution`, and the maximum range of the lidar sensor, `maxRange`.

## Examples

### Build Occupancy Map from Lidar Scans and Poses

The `buildMap` function takes in lidar scan readings and associated poses to build an occupancy grid as `lidarScan` objects and associated `[x y theta]` poses to build an `occupancyMap`.

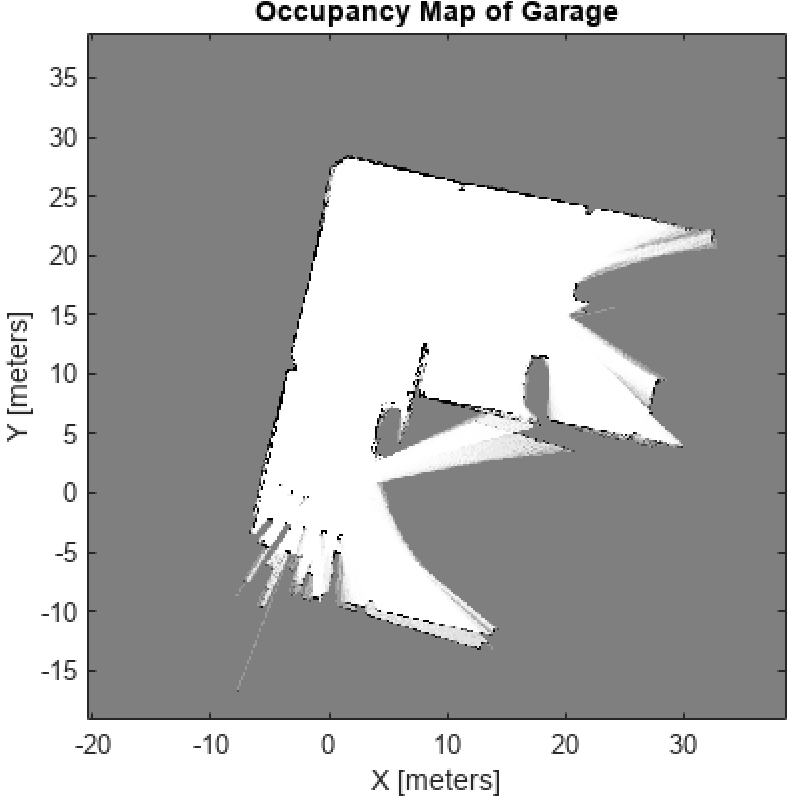
Load scan and pose estimates collected from sensors on a robot in a parking garage. The data collected is correlated using a `lidarSLAM` algorithm, which performs scan matching to associate scans and adjust poses over the full robot trajectory. Check to make sure scans and poses are the same length.

```
load scansAndPoses.mat
length(scans) == length(poses)
```

```
ans = logical
   1
```

Build the map. Specify the scans and poses in the `buildMap` function and include the desired map resolution (10 cells per meter) and the max range of the lidar (19.2 meters). Each scan is added at the associated poses and probability values in the occupancy grid are updated.

```
occMap = buildMap(scans,poses,10,19.2);
figure
show(occMap)
title('Occupancy Map of Garage')
```




**Perform SLAM Using Lidar Scans**

Use a `lidarSLAM` object to iteratively add and compare lidar scans and build an optimized pose graph of the robot trajectory. To get an occupancy map from the associated poses and scans, use the `buildMap` function.

**Load Data and Set Up SLAM Algorithm**

Load a cell array of `lidarScan` objects. The lidar scans were collected in a parking garage on a Husky® robot from ClearPath Robotics®. Typically, lidar scans are taken at a high frequency and each scan is not needed for SLAM. Therefore, down sample the scans by selecting only every 40th scan.

```
load garage_fl1_southend.mat scans
scans = scans(1:40:end);
```

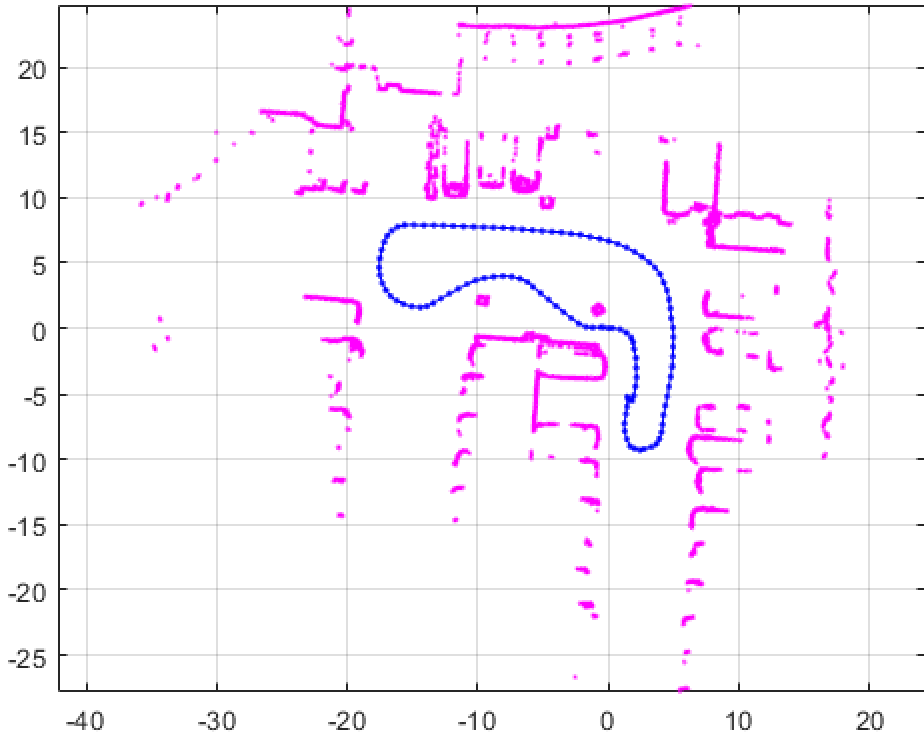
To set up the SLAM algorithm, specify the lidar range, map resolution, loop closure threshold, and search radius. Tune these parameters for your specific robot and environment. Create the `lidarSLAM` object with these parameters.

```
maxRange = 19.2; % meters
resolution = 10; % cells per meter

slamObj = lidarSLAM(resolution,maxRange);
slamObj.LoopClosureThreshold = 360;
slamObj.LoopClosureSearchRadius = 8;
```

### Add Scans Iteratively

Using a `for` loop, add scans to the SLAM object. The object uses scan matching to compare each added scan to previously added ones. To improve the map, the object optimizes the pose graph whenever it detects a loop closure. Every 10 scans, display the stored poses and scans.

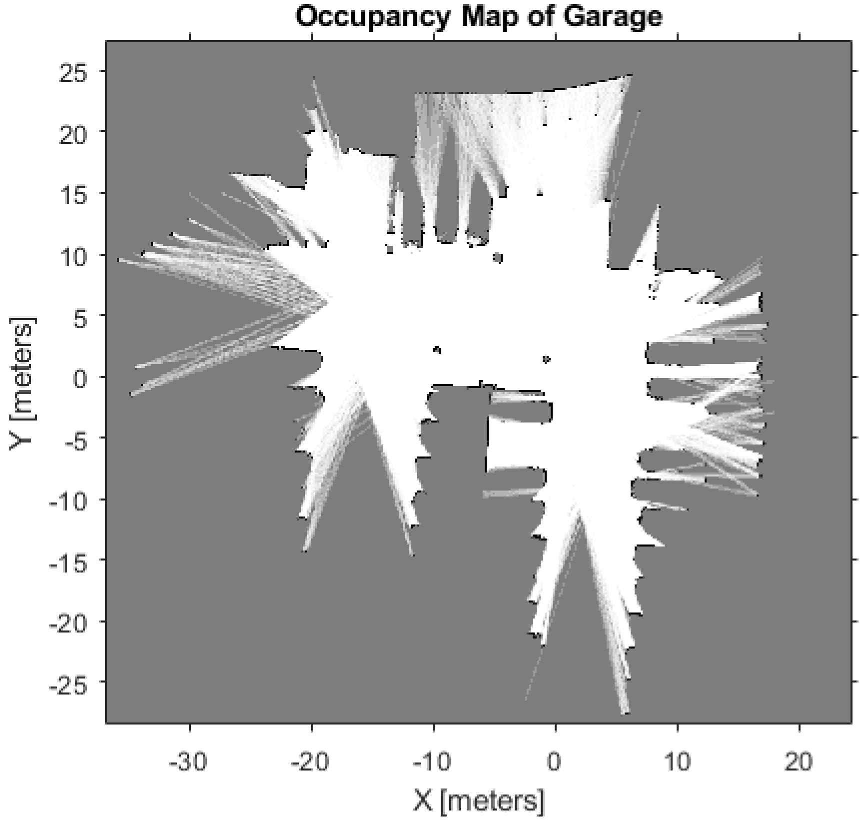
```
for i = 1:numel(scans)

    addScan(slamObj,scans{i});

    if rem(i,10) == 0
        show(slamObj);
    end
end
```




### View Occupancy Map

After adding all the scans to the SLAM object, build an `occupancyMap` map by calling `buildMap` with the scans and poses. Use the same map resolution and max range you used with the SLAM object.

```
[scansSLAM,poses] = scansAndPoses(slamObj);
occMap = buildMap(scansSLAM,poses,resolution,maxRange);
figure
show(occMap)
title('Occupancy Map of Garage')
```




## Input Arguments

**scans — Lidar scans**

cell array of `lidarScan` objects

Lidar scans used to build the map, specified as a cell array of `lidarScan` objects.

**poses — Poses of lidar scans**

*n*-by-3 matrix

Poses of lidar scans, specified as an *n*-by-3 matrix. Each row is an `[x y theta]` vector representing the *xy*-position and orientation angle of a scan.

**mapResolution — Resolution of occupancy grid**

positive integer

Resolution of the output `occupancyMap` map, specified as a positive integer in cells per meter.

**maxRange — Maximum range of lidar sensor**

positive scalar

Maximum range of lidar sensor, specified as a positive scalar in meters. Points in the `scans` outside this range are ignored.

#### Name-Value Pair Arguments

Specify optional pairs of arguments as `Name1=Value1,...,NameN=ValueN`, where `Name` is the argument name and `Value` is the corresponding value. Name-value arguments must appear after other arguments, but the order of the pairs does not matter.

*Before R2021a, use commas to separate each name and value, and enclose* `Name` *in quotes.*

Example: `['MapWidth',10]`

**`MapWidth` — Width of occupancy grid**
positive scalar

Width of the occupancy grid, specified as the comma-separated pair consisting of `'MapWidth'` and a positive scalar. If this value is not specified, the map is automatically scaled to fit all laser scans.

**`MapHeight` — Height of occupancy grid**
positive scalar

Height of occupancy grid, specified as the comma-separated pair consisting of `'MapHeight'` and a positive scalar. If this value is not specified, the map is automatically scaled to fit all laser scans.

### Output Arguments

**`map` — Occupancy Map**
`occupancyMap` object

Occupancy map, returned as a `occupancyMap` object.

## Version History

**Introduced in R2019b**

### See Also

**Functions**
`matchScans` | `matchScansGrid` | `lidarScan` | `transformScan`

**Classes**
`lidarSLAM` | `occupancyMap`

**Topics**
"Implement Simultaneous Localization And Mapping (SLAM) with Lidar Scans"
"Implement Online Simultaneous Localization And Mapping (SLAM) with Lidar Scans"

# cart2hom

Convert Cartesian coordinates to homogeneous coordinates

## Syntax

```
hom = cart2hom(cart)
```

## Description

`hom = cart2hom(cart)` converts a set of points in Cartesian coordinates to homogeneous coordinates.

## Examples

### Convert 3-D Cartesian Points to Homogeneous Coordinates

```
c = [0.8147 0.1270 0.6324; 0.9058 0.9134 0.0975];
h = cart2hom(c)
```

```
h = 2×4

    0.8147    0.1270    0.6324    1.0000
    0.9058    0.9134    0.0975    1.0000
```

## Input Arguments

**`cart` — Cartesian coordinates**
*n*-by-*k* matrix

Cartesian coordinates, specified as an *n*-by-*k* matrix, containing *n* points. Each row of `cart` represents a point in *k*-dimensional space. *k* must be greater than or equal to 1.

Example: `[0.8147 0.1270 0.6324; 0.9058 0.9134 0.0975]`

## Output Arguments

**`hom` — Homogeneous points**
*n*-by-(*k*+1) matrix

Homogeneous points, returned as an *n*-by-(*k*+1) matrix, containing *n* points. *k* must be greater than or equal to 1.

Example: `[0.2785 0.9575 0.1576 0.5; 0.5469 0.9649 0.9706 0.5]`

# Version History

**Introduced in R2015a**

#### R2023a: `cart2hom` Supports 2-D Cartesian Coordinates

The `cart` argument now accepts 2-D Cartesian coordinates and `cart2hom` outputs 2-D homogeneous points.

## Extended Capabilities

#### C/C++ Code Generation
Generate C and C++ code using MATLAB® Coder™.

## See Also
`hom2cart`

# checkMapCollision

Check for collision between 3-D occupancy map and geometry

## Syntax

```
collisionStatus = checkMapCollision(map,geometry)
[collisionStatus,details] = checkMapCollision(map,geometry,options)
```

## Description

Check for collision between a 3-D occupancy map and a convex collision geometry. The `checkMapCollision` function can search for collisions in two phases: first, a broad-phase search using a broad-phase search using simple bounding volumes, and then by a narrow-phase collision check if the simple volumes collide. For the broad-phase search, the function checks between simple primitives consisting of axially-aligned bounding boxes (AABB). For the narrow-phase, the function checks between occupied cells, represented by a `collisionBox` objects, and the input collision geometry object.

`collisionStatus = checkMapCollision(map,geometry)` checks if a 3-D occupancy map, `map`, and a collision geometry, `geometry`, are in collision.

`[collisionStatus,details] = checkMapCollision(map,geometry,options)` specifies the additional collision-checking options `options`, and returns the collision details `details`.

## Examples

### Check Collision Between 3-D Map and Collision Geometries

Create a 3-D occupancy map.

```
map = occupancyMap3D;
```

Specify 25 random coordinates in the occupancy map as occupied.

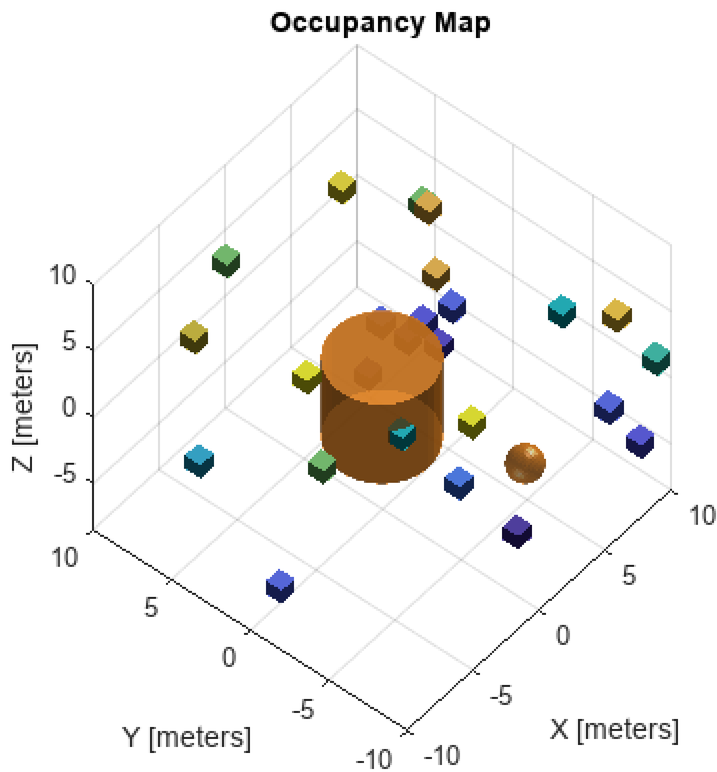
```
rng(0)
pt = (rand(25,3)-.5)*20;
setOccupancy(map,pt,1);
```

Create a collision sphere and a collision cylinder object.

```
sphere = collisionSphere(1);
cylinder = collisionCylinder(3,6);
sphere.Pose = trvec2tform([6.1 -4 -7.5]);
```

Visualize the occupancy map and collision geometry in the same figure.

```
exampleHelperPlotCylinderAndSphere(map,cylinder,sphere)
```




Perform only the broad-phase collision check for both the sphere and cylinder by setting the `CheckNarrowPhase` property of an `occupancyMap3DCollisionOptions` object to `false`. Return voxel information and the distance to the nearest occupied voxels.

```
bpOpts = occupancyMap3DCollisionOptions(CheckNarrowPhase=false,ReturnDistance=true,ReturnVoxels=t
[bpIsCollidingCylinder,bpResultsCylinder] = checkMapCollision(map,cylinder,bpOpts);
```

Check the voxel distances for the collision geometries. Note that, because the cylinder is in collision with voxels, the distance values are `NaN`. Because the sphere is not in collision with any voxels, its distance results are non-`NaN` values.

```
bpDistCylinder = bpResultsCylinder.DistanceInfo.Distance
```

```
bpDistCylinder = NaN
```

```
bpWitnessptsCylinder = bpResultsCylinder.DistanceInfo.WitnessPoints
```

```
bpWitnessptsCylinder = 3×2

   NaN   NaN
   NaN   NaN
   NaN   NaN
```

Because the cylinder is in collision with the voxels, the distance results contain `NaN` values. Since the sphere is not in collision with the voxels, the distance results consist of non-`NaN` values.

```
[bpIsCollidingSphere,bpResultsSphere] = checkMapCollision(map,sphere,bpOpts);
bpDistSphere = bpResultsSphere.DistanceInfo.Distance
```

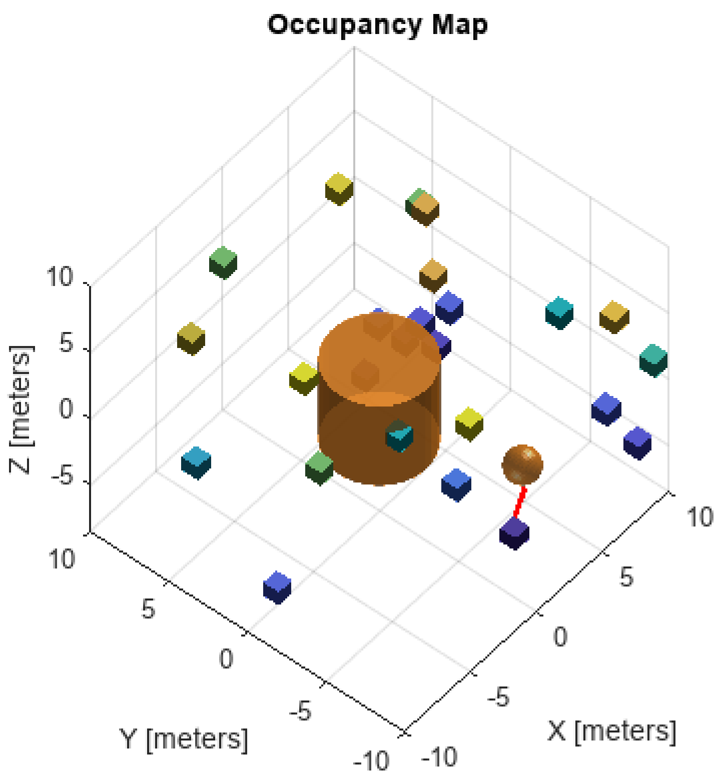
```
bpDistSphere = 2.3259
```

```
bpWitnessptsSphere = bpResultsSphere.DistanceInfo.WitnessPoints
```

```
bpWitnessptsSphere = 3×2

    3.0000    5.1000
   -6.0000   -5.0000
   -7.5000   -7.5000
```

Plot a line between the sphere and the closest voxel to it using its witness points.

```
figure
exampleHelperPlotCylinderAndSphere(map,cylinder,sphere)
hold on
plot3(bpWitnessptsSphere(1,:),bpWitnessptsSphere(2,:),bpWitnessptsSphere(3,:),LineWidth=2,Color=
hold off
```




Now perform a narrow-phase check, by using an `occupancyMap3DCollisionOptions` object with the `CheckNarrowPhase` property set to `true`.

```
npOpts = occupancyMap3DCollisionOptions(CheckNarrowPhase=true,ReturnDistance=true,ReturnVoxels=t
[npIsCollidingSphere,bpResultsSphere] = checkMapCollision(map,sphere,npOpts);
```

Return the voxel distance and witness point coordinates for the sphere. The distance and witness points are slightly more accurate this time, because the narrow phase uses the distance between the primitive and the voxel, whereas the broad phase before uses the distance between the axis-aligned bounding box (AABB) of the collision object and the voxel.

```
npDist = bpResultsSphere.DistanceInfo.Distance
```

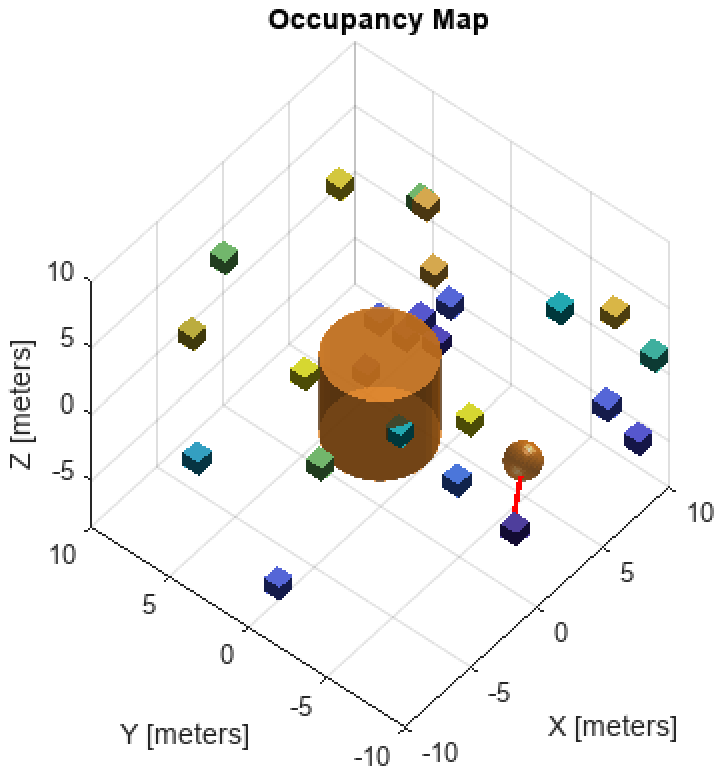
```
npDist = 2.6892
```

```
npWitnesspts = bpResultsSphere.DistanceInfo.WitnessPoints
```

```
npWitnesspts = 3×2

    3.0000    5.2596
   -6.0000   -4.5419
   -7.5000   -7.5000
```

Visualize the occupancy map again and plot line showing the shortest distance between the voxel and sphere. The line between the witness points visually appears accurate after performing the narrow-phase check.

```
exampleHelperPlotCylinderAndSphere(map,cylinder,sphere)
hold on
plot3(npWitnesspts(1,:),npWitnesspts(2,:),npWitnesspts(3,:),LineWidth=2,Color='r')
hold off
```



## Input Arguments

**map — 3-D occupancy map**
occupancyMap3D object

3-D occupancy map, specified as an occupancyMap3D object.

Example: occupancyMap3D(10)

**geometry — Collision geometry**
collision geometry object

Collision geometry, specified as one of these objects:

- collisionBox
- collisionCapsule
- collisionCylinder
- collisionMesh
- collisionSphere

Example: collisionBox(1,1,3)

**options — Collision-checking options**
occupancyMap3DCollisionOptions object

Collision-checking options, specified as an occupancyMap3DCollisionOptions object.

Example:
occupancyMap3DCollisionOptions(CheckNarrowPhase=false,ReturnDistance=true);

## Output Arguments

**collisionStatus — Collision status**
0 | 1

Collision status, returned as 0 or 1. If the geometry intersects with any occupied voxel, collisionStatus is 1. Otherwise, the value is 0.

Data Types: double

**details — Collision details**
structure

Collision details, returned as a structure that can contain up to two fields, DistanceInfo and VoxelInfo:

- DistanceInfo — This field is present when the ReturnDistance property of options is true. The field is a structure that contains these fields.
  - Distance — If the NarrowPhase property of options is set to true, this field contains the minimum distance between the collision geometry and the nearest voxel or occupied cell, represented as a collisionBox object. If NarrowPhase is false, then Distance is the minimum distance between the AABBs of the collision geometry and the nearest voxel.

For collision geometries that are not in collision, `Distance` is returned as a numeric scalar. For collision geometries that are in collision, `Distance` is returned as `NaN`.

- `WitnessPoints` — Witness points between the collision geometry and the nearest voxel. If the collision geometry is not in collision, `WitnessPoints` is returned as returned as a 3-by-2 matrix, where each column represents the witness points in the form $\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$. If the collision geometry is in collision, `WitnessPoints` is returned as `nan(3,2)`.

- `VoxelInfo` — This field is present when the `ReturnVoxels` property of `options` is `true`. The field is a structure that contains these fields.

  - `Location` — Center(s) of the colliding voxels. The format of this field depends on the value of the `Exhaustive` property of `options`:

    - `true` — *N*-by-3 matrix, where *N* is the total number of colliding voxels. Each row is a coordinate in the form [*X Y Z*].
    - `false` — Three-element row vector that contains the first collision voxel as a coordinate in the form [*X Y Z*], or as an empty vector if there is no collision.

  - `Size` — Edge lengths of the colliding voxels. The format of this field depends on the value of the `Exhaustive` property of `options`:

    - `true` — *N*-element column vector, where *N* is the total number of colliding voxels. The edge length of each element defines the size of the voxel centered at the corresponding location in `Location`.
    - `false` — Edge length of the first colliding voxel, returned as a numeric scalar if there is a collision, or as an empty vector if there is no collision.

## Version History

**Introduced in R2022b**

#### R2023a: Code Generation Support

`checkMapCollision` now supports code generation.

Note that `checkMapCollision` does not support code generation using the `packNGo` function if you set the `packType` argument to `"flat"`.

## Extended Capabilities

#### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

`checkMapCollision` does not support code generation using the `packNGo` function if you set the `packType` argument to `"flat"`.

## See Also

`occupancyMap3D` | `occupancyMap3DCollisionOptions`

# connect

Connect poses for given connection type

## Syntax

```
[pathSegments,pathCosts] = connect(connectionObj,start,goal)
[pathSegments,pathCosts] = connect(connectionObj,start,
goal,'PathSegments','all')
```

## Description

`[pathSegments,pathCosts] = connect(connectionObj,start,goal)` connects the start and goal poses using the specified `dubinsConnection` object. The path segment object with the lowest cost is returned.

`[pathSegments,pathCosts] = connect(connectionObj,start, goal,'PathSegments','all')` returns all possible path segments as a cell array with their associated costs.

## Examples

### Connect Poses Using Dubins Connection Path

Create a `dubinsConnection` object.

```
dubConnObj = dubinsConnection;
```

Define start and goal poses as `[x y theta]` vectors.

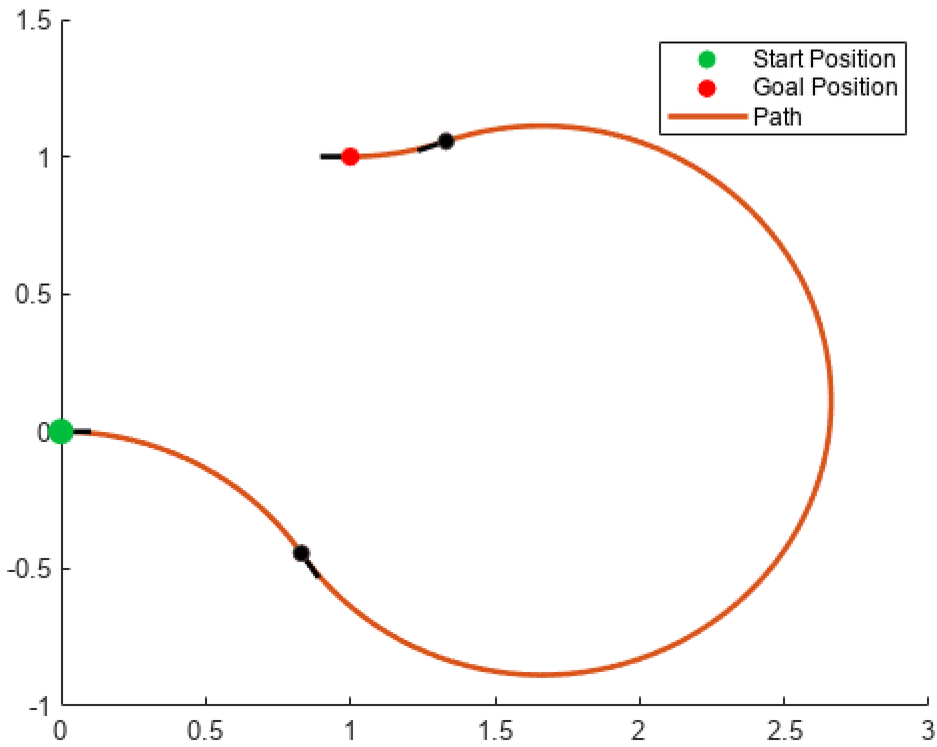
```
startPose = [0 0 0];
goalPose = [1 1 pi];
```

Calculate a valid path segment to connect the poses.

```
[pathSegObj, pathCosts] = connect(dubConnObj,startPose,goalPose);
```

Show the generated path.

```
show(pathSegObj{1})
```




### Connect Poses Using ReedsShepp Connection Path

Create a `reedsSheppConnection` object.

```
reedsConnObj = reedsSheppConnection;
```

Define start and goal poses as `[x y theta]` vectors.

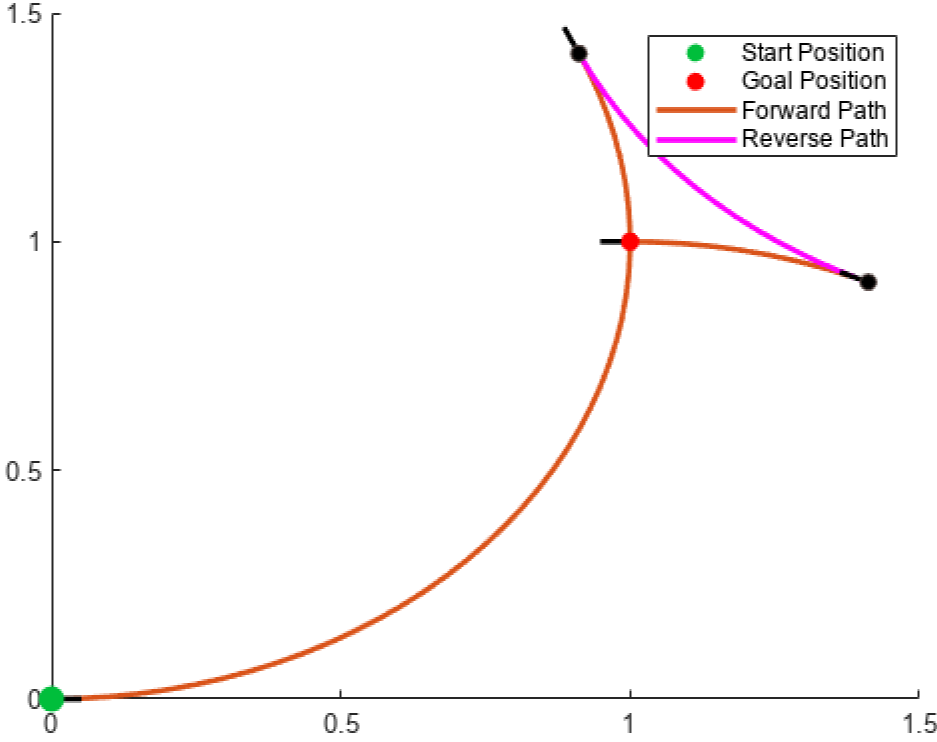
```
startPose = [0 0 0];
goalPose = [1 1 pi];
```

Calculate a valid path segment to connect the poses.

```
[pathSegObj,pathCosts] = connect(reedsConnObj,startPose,goalPose);
```

Show the generated path.

```
show(pathSegObj{1})
```




## Input Arguments

**`connectionObj` — Path connection type**
`dubinsPathSegment` object | `reedsSheppPathSegment` object

Path connection type, specified as a `dubinsConnection` or `reedsSheppConnection` object. This object defines the parameters of the connection, including the minimum turning radius of the robot and the valid motion types.

**`start` — Initial pose of robot**
[*x*, *y*, *Θ*] vector or matrix

This property is read-only.

Initial pose of the robot at the start of the path segment, specified as an [*x*, *y*, *Θ*] vector or matrix. Each row of the matrix corresponds to a different start pose.

*x* and *y* are in meters. *Θ* is in radians.

The `connect` function supports:

- Singular start pose with singular goal pose.
- Multiple start pose with singular goal pose.

- Singular start pose with multiple goal pose.
- Multiple start pose with multiple goal pose.

The output `pathSegments` cell array size reflects the singular or multiple pose options.

**`goal` — Goal pose of robot**
[*x*, *y*, *Θ*] vector or matrix

This property is read-only.

Goal pose of the robot at the end of the path segment, specified as an [*x*, *y*, *Θ*] vector or matrix. Each row of the matrix corresponds to a different goal pose.

*x* and *y* are in meters. *Θ* is in radians.

The `connect` function supports:

- Singular start pose with singular goal pose.
- Multiple start pose with singular goal pose.
- Singular start pose with multiple goal pose.
- Multiple start pose with multiple goal pose.

The output `pathSegments` cell array size reflects the singular or multiple pose options.

## Output Arguments

**`pathSegments` — Path segments**
cell array of objects

Path segments, specified as a cell array of objects. The type of object depends on the input `connectionObj`. The size of the cell array depends on whether you use singular or multiple `start` and `goal` poses. By default, the function returns the path with the lowest cost for each `start` and `goal` pose. When call `connect` using the `'PathSegments','all'` name-value pair, the cell array contains all valid path segments between the specified `start` and `goal` poses.

**`pathCosts` — Cost of path segment**
positive numeric scalar | positive numeric vector | positive numeric matrix

Cost of path segments, specified as a positive numeric scalar, vector, or matrix. Each element of the cost vector or matrix corresponds to a path segment in `pathSegment`. By default, the function returns the path with the lowest cost for each start and goal pose.

Example: `[7.6484,7.5122]`

# Version History

**Introduced in R2019b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Functions**
`interpolate` | `show`

**Objects**
`dubinsConnection` | `dubinsPathSegment` | `reedsSheppConnection` |
`reedsSheppPathSegment`

# createPlanningTemplate

Create sample implementation for path planning interface

## Syntax

```
createPlanningTemplate
createPlanningTemplate("StateValidator")
```

## Description

`createPlanningTemplate` creates a planning template for a subclass of the `nav.StateSpace` class. The function opens a file in the MATLAB® Editor. Save your custom implementation and ensure the file is available on the MATLAB path. Alternative syntax: `createPlanningTemplate("StateSpace")`

`createPlanningTemplate("StateValidator")` creates a template for a subclass of the `nav.StateValidator` class.

## Examples

### Create Custom State Space for Path Planning

This example shows how to use the `createPlanningTemplate` function to generate a template for customizing your own state space definition and sampler to use with path planning algorithms. A simple implementation is provided with the template.

Call the create template function. This function generates a class definition file for you to modify for your own implementation.

```
createPlanningTemplate
```

**Class and Property Definition**

The first part of the template specifies the class definition and any properties for the class. Derive from the `nav.StateSpace` class. For this example, create a property for the uniform and normal distributions. You can specify any additional user-defined properties here.

```
classdef MyCustomStateSpace < nav.StateSpace & ...
        matlabshared.planning.internal.EnforceScalarHandle
     properties
        UniformDistribution
        NormalDistribution
        % Specify additional properties here
end
```

Save your custom state space class and ensure your file name matches the class name.

### Class Constructor

Use the constructor to set the name of the state space, the number of state variables, and define its boundaries. Alternatively, you can add input arguments to the function and pass the variables in when you create an object.

- For each state variable, define the `[min max]` values for the state bounds.
- Call the constructor of the base class.
- For this example, you specify the normal and uniform distribution property values using predefined `NormalDistribution` and `UniformDistribution` classes.
- Specify any other user-defined property values here.

```
methods
    function obj = MyCustomStateSpace
        spaceName = "MyCustomStateSpace";
        numStateVariables = 3;
        stateBounds = [-100 100;  % [min max]
                       -100 100;
                       -100 100];

        obj@nav.StateSpace(spaceName, numStateVariables, stateBounds);

        obj.NormalDistribution = matlabshared.tracking.internal.NormalDistribution(numStateVarial
        obj.UniformDistribution = matlabshared.tracking.internal.UniformDistribution(numStateVar
        % User-defined property values here
    end
```

### Copy Semantics

Specify the `copy` method definition. Copy all the values of your user-defined variables into a new object, so `copyObj` is a deep copy. The default behavior given in this example creates a new copy of the object with the same name, state bounds, and distributions.

```
function copyObj = copy(obj)
    copyObj = feval(class(obj));
    copyObj.StateBounds = obj.StateBounds;
    copyObj.UniformDistribution = obj.UniformDistribution.copy;
    copyObj.NormalDistribution = obj.NormalDistribution.copy;
end
```

### Enforce State Bounds

Specify how to ensure states are always within the state bounds. For this example, the state values get saturated at the minimum or maximum values for the state bounds.

```
function boundedState = enforceStateBounds(obj, state)
    nav.internal.validation.validateStateMatrix(state, nan, obj.NumStateVariables, "enforceState
    boundedState = state;
    boundedState = min(max(boundedState, obj.StateBounds(:,1)'), ...
        obj.StateBounds(:,2)');

end
```

### Sample Uniformly

Specify the behavior for sampling across a uniform distribution. support multiple syntaxes to constrain the uniform distribution to a nearby state within a certain distance and sample multiple states.

```
STATE = sampleUniform(OBJ)
STATE = sampleUniform(OBJ,NUMSAMPLES)
STATE = sampleUniform(OBJ,NEARSTATE,DIST)
STATE = sampleUniform(OBJ,NEARSTATE,DIST,NUMSAMPLES)
```

For this example, use a validation function to process a `varargin` input that handles the varying input arguments.

```
 function state = sampleUniform(obj, varargin)
    narginchk(1,4);
    [numSamples, stateBounds] = obj.validateSampleUniformInput(varargin{:});

    obj.UniformDistribution.RandomVariableLimits = stateBounds;
    state = obj.UniformDistribution.sample(numSamples);
 end
```

### Sample from Gaussian Distribution

Specify the behavior for sampling across a Gaussian distribution. Support multiple syntaxes for sampling a single state or multiple states.

```
STATE = sampleGaussian(OBJ, MEANSTATE, STDDEV)
STATE = sampleGaussian(OBJ, MEANSTATE, STDDEV, NUMSAMPLES)
```

```
function state = sampleGaussian(obj, meanState, stdDev, varargin)
    narginchk(3,4);

    [meanState, stdDev, numSamples] = obj.validateSampleGaussianInput(meanState, stdDev, varargi

    obj.NormalDistribution.Mean = meanState;
    obj.NormalDistribution.Covariance = diag(stdDev.^2);

    state = obj.NormalDistribution.sample(numSamples);
    state = obj.enforceStateBounds(state);

end
```

### Interpolate Between States

Define how to interpolate between two states in your state space. Use an input, `fraction`, to determine how to sample along the path between two states. For this example, define a basic linear interpolation method using the difference between states.

```
function interpState = interpolate(obj, state1, state2, fraction)
    narginchk(4,4);
    [state1, state2, fraction] = obj.validateInterpolateInput(state1, state2, fraction);

    stateDiff = state2 - state1;
    interpState = state1 + fraction' * stateDiff;
end
```

### Calculate Distance Between States

Specify how to calculate the distance between two states in your state space. Use the `state1` and `state2` inputs to define the start and end positions. Both inputs can be a single state (row vector) or multiple states (matrix of row vectors). For this example, calculate the distance based on the Euclidean distance between each pair of state positions.

```
function dist = distance(obj, state1, state2)

    narginchk(3,3);

    nav.internal.validation.validateStateMatrix(state1, nan, obj.NumStateVariables, "distance", "
    nav.internal.validation.validateStateMatrix(state2, size(state1,1), obj.NumStateVariables, "d

    stateDiff = bsxfun(@minus, state2, state1);
    dist = sqrt( sum( stateDiff.^2, 2 ) );
end
```

Terminate the methods and class sections.

```
    end
end
```

Save your state space class definition. You can now use the class constructor to create an object for your state space.

### Create Custom State Space Validator for Path Planning

This example shows how to use the `createPlanningTemplate` function to generate a template for customizing your own state validation class. State validation is used with path planning algorithms to ensure valid paths. The template function provides a basic implementation for example purposes.

Call the create template function. This function generates a class definition file for you to modify for your own implementation. Save this file.

```
createPlanningTemplate("StateValidator")
```

### Class and Property Definition

The first part of the template specifies the class definition and any properties for the class. Derive from the `nav.StateValidator` class. You can specify any additional user-defined properties here.

```
classdef MyCustomStateValidator < nav.StateValidator & ...
        matlabshared.planning.internal.EnforceScalarHandle
    properties
       % User-defined properties
    end
```

Save your custom state validator class and ensure your file name matches the class name.

### Class Constructor

Use the constructor to set the name of the state space validator and specify the state space object. Set a default value for the state space if one is not provided. Call the constructor of the base class. Initialize any other user-defined properties. This example uses a default of `MyCustomStateSpace`, which was illustrated in the previous example.

```
methods
        function obj = MyCustomStateValidator(space)
            narginchk(0,1)

            if nargin == 0
                space = MyCustomStateSpace;
            end

            obj@nav.StateValidator(space);

           % Initialize user-defined properties
        end
```

#### Copy Semantics

Specify the `copy` method definition. Copy all the values of your user-defined variables into a new object, so `copyObj` is a deep copy. The default behavior given in this example creates a new copy of the object with the same type.

```
        function copyObj = copy(obj)
            copyObj = feval(class(obj), obj.StateSpace);
        end
```

#### Check State Validity

Define how a given state is validated. The `state` input can either be a single row vector, or a matrix of row vectors for multiple states. Customize this function for any special validation behavior for your state space like collision checking against obstacles.

```
        function isValid = isStateValid(obj, state)
            narginchk(2,2);
            nav.internal.validation.validateStateMatrix(state, nan, obj.StateSpace.NumStateVarial
                "isStateValid", "state");

            bounds = obj.StateSpace.StateBounds';
            inBounds = state >= bounds(1,:) & state <= bounds(2,:);
            isValid = all(inBounds, 2);

        end
```

#### Check Motion Validity

Define how to generate the motion between states and determine if it is valid. For this example, use `linspace` to evenly interpolate between states and check if these states are valid using `isStateValid`. Customize this function to sample between states or consider other analytical methods for determining if a vehicle can move between given states.

```
        function [isValid, lastValid] = isMotionValid(obj, state1, state2)
            narginchk(3,3);
            state1 = nav.internal.validation.validateStateVector(state1, ...
                obj.StateSpace.NumStateVariables, "isMotionValid", "state1");
            state2 = nav.internal.validation.validateStateVector(state2, ...
                obj.StateSpace.NumStateVariables, "isMotionValid", "state2");

            if (~obj.isStateValid(state1))
                error("statevalidator:StartStateInvalid", "The start state of the motion is inva
            end
```

```
            % Interpolate at a fixed interval between states and check state validity
            numInterpPoints = 100;
            interpStates = obj.StateSpace.interpolate(state1, state2, linspace(0,1,numInterpPoin
            interpValid = obj.isStateValid(interpStates);

            % Look for invalid states. Set lastValid state to index-1.
            firstInvalidIdx = find(~interpValid, 1);
            if isempty(firstInvalidIdx)
                isValid = true;
                lastValid = state2;
            else
                isValid = false;
                lastValid = interpStates(firstInvalidIdx-1,:);
            end

        end
```

Terminate the methods and class sections.

```
    end
end
```

Save your state space validator class definition. You can now use the class constructor to create an object for validation of states for a given state space.

# Version History

**Introduced in R2019b**

## See Also

`nav.StateSpace` | `nav.StateValidator` | `stateSpaceSE2` | `validatorOccupancyMap`

# ecompass

Orientation from magnetometer and accelerometer readings

## Syntax

```
orientation = ecompass(accelerometerReading,magnetometerReading)
orientation = ecompass(accelerometerReading,magnetometerReading,
orientationFormat)
orientation = ecompass(accelerometerReading,magnetometerReading,
orientationFormat,'ReferenceFrame',RF)
```

## Description

`orientation = ecompass(accelerometerReading,magnetometerReading)` returns a `quaternion` that can rotate quantities from a parent (NED) frame to a child (sensor) frame.

`orientation = ecompass(accelerometerReading,magnetometerReading, orientationFormat)` specifies the orientation format as `quaternion` or rotation matrix.

`orientation = ecompass(accelerometerReading,magnetometerReading, orientationFormat,'ReferenceFrame',RF)` also allows you to specify the reference frame `RF` of the `orientation` output. Specify `RF` as `'NED'` (North-East-Down) or `'ENU'` (East-North-Up). The default value is `'NED'`.

## Examples

### Determine Declination of Boston

Use the known magnetic field strength and proper acceleration of a device pointed true north in Boston to determine the magnetic declination of Boston.

Define the known acceleration and magnetic field strength in Boston.

```
magneticFieldStrength = [19.535 -5.109 47.930];
properAcceleration = [0 0 9.8];
```

Pass the magnetic field strength and acceleration to the `ecompass` function. The `ecompass` function returns a quaternion rotation operator. Convert the quaternion to Euler angles in degrees.

```
q = ecompass(properAcceleration,magneticFieldStrength);
e = eulerd(q,'ZYX','frame');
```

The angle, `e`, represents the angle between true north and magnetic north in Boston. By convention, magnetic declination is negative when magnetic north is west of true north. Negate the angle to determine the magnetic declination.

```
magneticDeclinationOfBoston = -e(1)
```

```
magneticDeclinationOfBoston = -14.6563
```

### Return Rotation Matrix

The `ecompass` function fuses magnetometer and accelerometer data to return a quaternion that, when used within a quaternion rotation operator, can rotate quantities from a parent (NED) frame to a child frame. The `ecompass` function can also return rotation matrices that perform equivalent rotations as the quaternion operator.

Define a rotation that can take a parent frame pointing to magnetic north to a child frame pointing to geographic north. Define the rotation as both a quaternion and a rotation matrix. Then, convert the quaternion and rotation matrix to Euler angles in degrees for comparison.

Define the magnetic field strength in microteslas in Boston, MA, when pointed true north.

```
m = [19.535 -5.109 47.930];
a = [0 0 9.8];
```

Determine the quaternion and rotation matrix that is capable of rotating a frame from magnetic north to true north. Display the results for comparison.

```
q = ecompass(a,m);
quaterionEulerAngles = eulerd(q,'ZYX','frame')
```

```
quaterionEulerAngles = 1×3

   14.6563         0         0
```

```
r = ecompass(a,m,'rotmat');
theta = -asin(r(1,3));
psi = atan2(r(2,3)/cos(theta),r(3,3)/cos(theta));
rho = atan2(r(1,2)/cos(theta),r(1,1)/cos(theta));
rotmatEulerAngles = rad2deg([rho,theta,psi])
```

```
rotmatEulerAngles = 1×3

   14.6563         0         0
```

### Determine Gravity Vector

Use `ecompass` to determine the gravity vector based on data from a rotating IMU.

Load the inertial measurement unit (IMU) data.

```
load 'rpy_9axis.mat' sensorData Fs
```

Determine the orientation of the sensor body relative to the local NED frame over time.

```
orientation = ecompass(sensorData.Acceleration,sensorData.MagneticField);
```

To estimate the gravity vector, first rotate the accelerometer readings from the sensor body frame to the NED frame using the `orientation` quaternion vector.

```
gravityVectors = rotatepoint(orientation,sensorData.Acceleration);
```

Determine the gravity vector as an average of the recovered gravity vectors over time.

```
gravityVectorEstimate = mean(gravityVectors,1)
```

```
gravityVectorEstimate = 1×3

    0.0000   -0.0000   10.2102
```

### Track Spinning Platform

Fuse modeled accelerometer and gyroscope data to track a spinning platform using both idealized and realistic data.

#### Generate Ground-Truth Trajectory

Describe the ground-truth orientation of the platform over time. Use the `kinematicTrajectory` System object™ to create a trajectory for a platform that has no translation and spins about its *z*-axis.

```
duration = 12;
fs = 100;
numSamples = fs*duration;

accelerationBody = zeros(numSamples,3);

angularVelocityBody = zeros(numSamples,3);
zAxisAngularVelocity = [linspace(0,4*pi,4*fs),4*pi*ones(1,4*fs),linspace(4*pi,0,4*fs)]';
angularVelocityBody(:,3) = zAxisAngularVelocity;

trajectory = kinematicTrajectory('SampleRate',fs);

[~,orientationNED,~,accelerationNED,angularVelocityNED] = trajectory(accelerationBody,angularVelo
```

#### Model Receiving IMU Data

Use an `imuSensor` System object to mimic data received from an IMU that contains an ideal magnetometer and an ideal accelerometer.

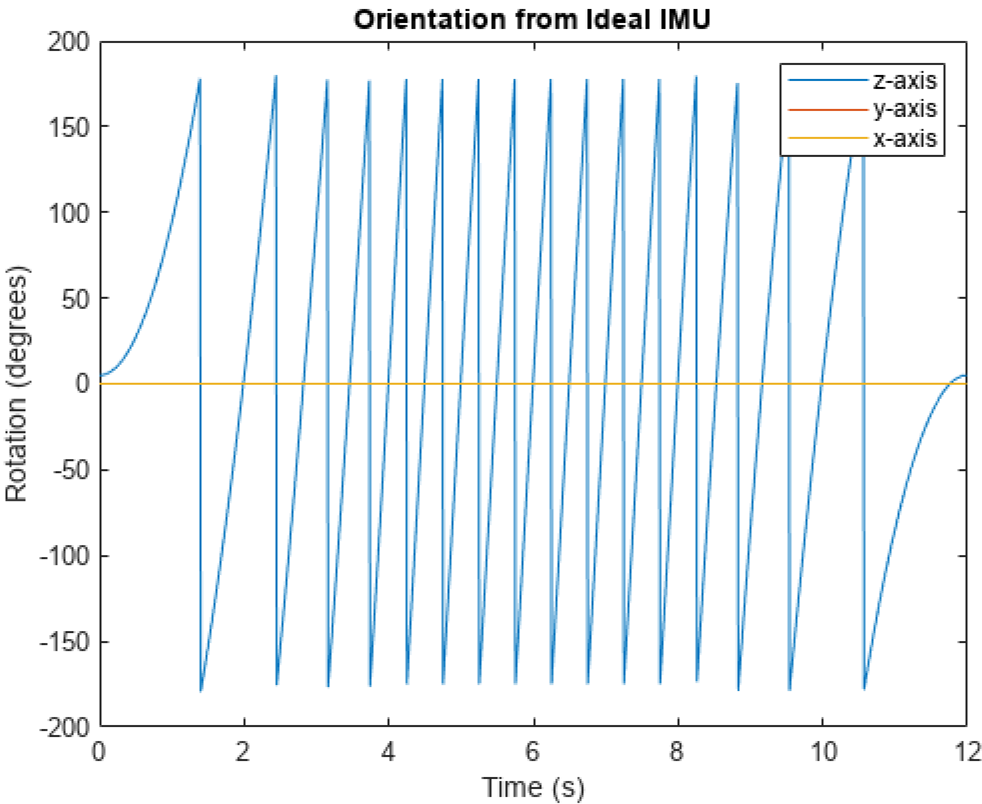
```
IMU = imuSensor('accel-mag','SampleRate',fs);
[accelerometerData,magnetometerData] = IMU(accelerationNED, ...
                                           angularVelocityNED, ...
                                           orientationNED);
```

#### Fuse IMU Data to Estimate Orientation

Pass the accelerometer data and magnetometer data to the `ecompass` function to estimate orientation over time. Convert the orientation to Euler angles in degrees and plot the result.

```
orientation = ecompass(accelerometerData,magnetometerData);
orientationEuler = eulerd(orientation,'ZYX','frame');

timeVector = (0:numSamples-1).'/fs;

figure(1)
```

```
plot(timeVector,orientationEuler)
legend('z-axis','y-axis','x-axis')
xlabel('Time (s)')
ylabel('Rotation (degrees)')
title('Orientation from Ideal IMU')
```

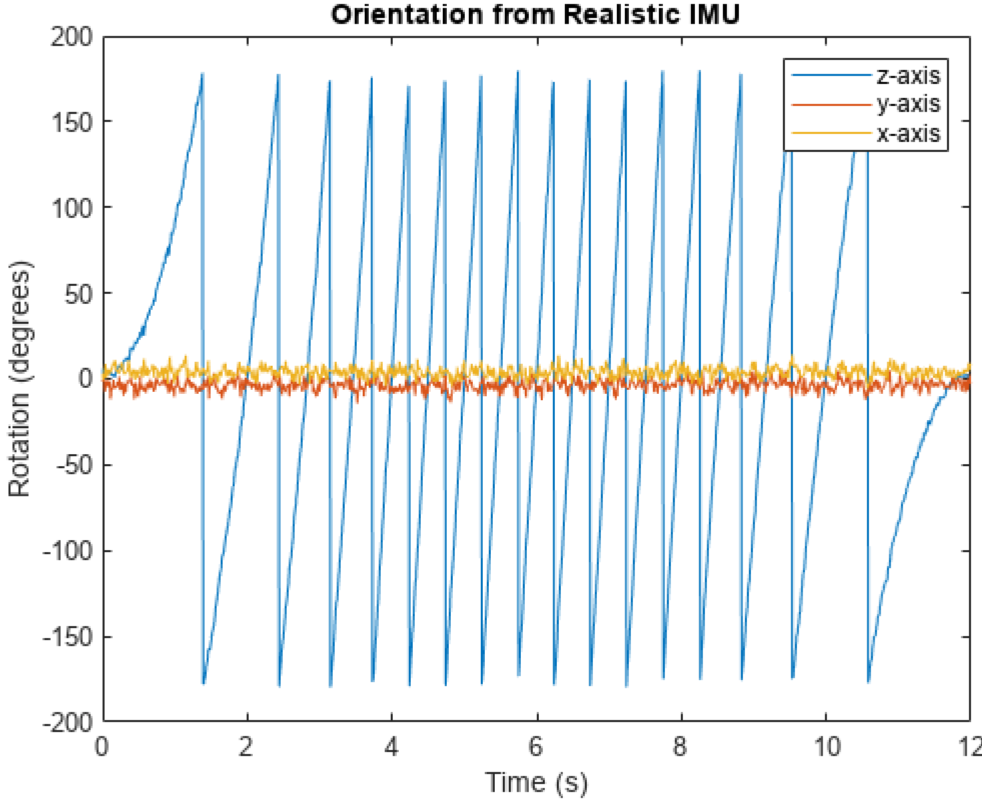



#### Repeat Experiment with Realistic IMU Sensor Model

Modify parameters of the `IMU` System object to approximate realistic IMU sensor data. Reset the `IMU` and then call it with the same ground-truth acceleration, angular velocity, and orientation. Use `ecompass` to fuse the IMU data and plot the results.

```
IMU.Accelerometer = accelparams( ...
    'MeasurementRange',20, ...
    'Resolution',0.0006, ...
    'ConstantBias',0.5, ...
    'AxesMisalignment',2, ...
    'NoiseDensity',0.004, ...
    'BiasInstability',0.5);
IMU.Magnetometer = magparams( ...
    'MeasurementRange',200, ...
    'Resolution',0.01);
reset(IMU)

[accelerometerData,magnetometerData] = IMU(accelerationNED,angularVelocityNED,orientationNED);

orientation = ecompass(accelerometerData,magnetometerData);
orientationEuler = eulerd(orientation,'ZYX','frame');
```

```
figure(2)
plot(timeVector,orientationEuler)
legend('z-axis','y-axis','x-axis')
xlabel('Time (s)')
ylabel('Rotation (degrees)')
title('Orientation from Realistic IMU')
```




## Input Arguments

**`accelerometerReading` — Accelerometer readings in sensor body coordinate system (m/s²)**
*N*-by-3 matrix

Accelerometer readings in sensor body coordinate system in m/s², specified as an *N*-by-3 matrix. The columns of the matrix correspond to the *x*-, *y*-, and *z*-axes of the sensor body. The rows in the matrix, *N*, correspond to individual samples. The accelerometer readings are normalized before use in the function.

Data Types: `single` | `double`

**`magnetometerReading` — Magnetometer readings in sensor body coordinate system (µT)**
*N*-by-3 matrix

Magnetometer readings in sensor body coordinate system in µT, specified as an *N*-by-3 matrix. The columns of the matrix correspond to the *x*-, *y*-, and *z*-axes of the sensor body. The rows in the matrix, *N*, correspond to individual samples. The magnetometer readings are normalized before use in the function.

Data Types: `single` | `double`

**`orientationFormat` — Format used to describe orientation**
`'quaternion'` (default) | `'rotmat'`

Format used to describe orientation, specified as `'quaternion'` or `'rotmat'`.

Data Types: `char` | `string`

## Output Arguments

**`orientation` — Orientation that rotates quantities from global coordinate system to sensor body coordinate system**
*N*-by-1 vector of quaternions (default) | 3-by-3-by-*N* array

Orientation that can rotate quantities from a global coordinate system to a body coordinate system, returned as a vector of quaternions or an array. The size and type of the `orientation` depends on the format used to describe orientation:

- `'quaternion'` –– *N*-by-1 vector of quaternions with the same underlying data type as the input
- `'rotmat'` –– 3-by-3-by-*N* array the same data type as the input

Data Types: `quaternion` | `single` | `double`

## Algorithms

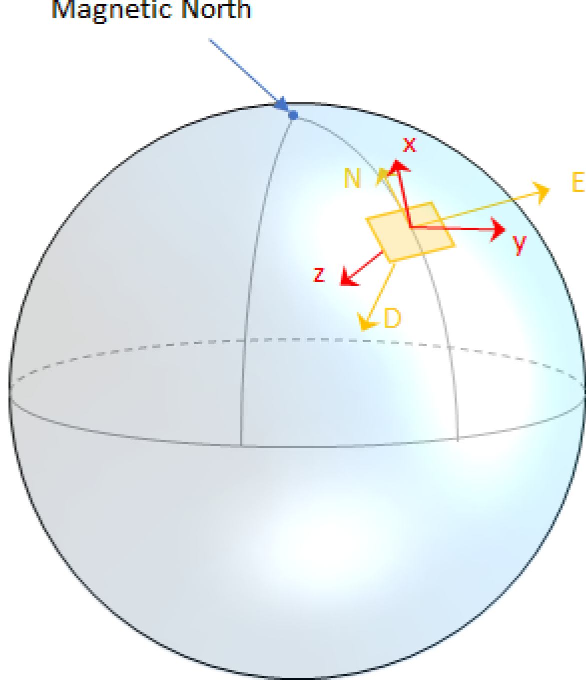
The `ecompass` function returns a quaternion or rotation matrix that can rotate quantities from a parent (NED for example) frame to a child (sensor) frame. For both output orientation formats, the rotation operator is determined by computing the rotation matrix.

The rotation matrix is first calculated with an intermediary:

$$R = \left[ (a \times m) \times a \;\; a \times m \;\; a \right]$$

and then normalized column-wise. $a$ and $m$ are the `accelerometerReading` input and the `magnetometerReading` input, respectively.

To understand the rotation matrix calculation, consider an arbitrary point on the Earth and its corresponding local NED frame. Assume a sensor body frame, $[x,y,z]$, with the same origin.



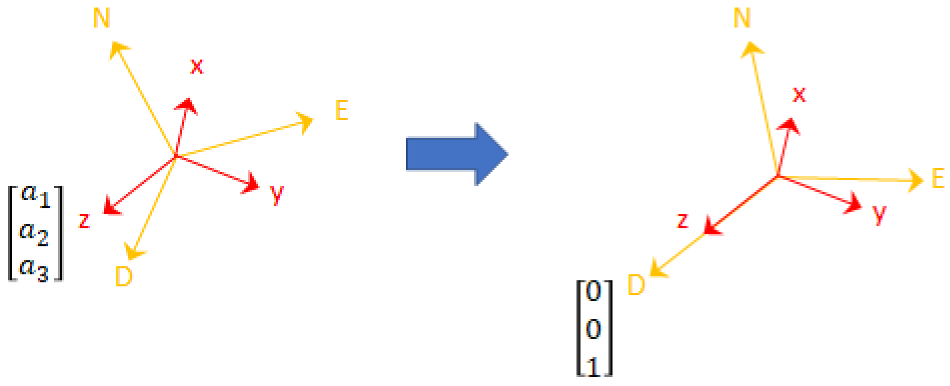

Recall that orientation of a sensor body is defined as the rotation operator (rotation matrix or quaternion) required to rotate a quantity from a parent (NED) frame to a child (sensor body) frame:

$$\begin{bmatrix} R \end{bmatrix}\begin{bmatrix} p_{\text{parent}} \end{bmatrix} = \begin{bmatrix} p_{\text{child}} \end{bmatrix}$$

where

- $R$ is a 3-by-3 rotation matrix, which can be interpreted as the orientation of the child frame.
- $p_{\text{parent}}$ is a 3-by-1 vector in the parent frame.
- $p_{\text{child}}$ is a 3-by-1 vector in the child frame.

For a stable sensor body, an accelerometer returns the acceleration due to gravity. If the sensor body is perfectly aligned with the NED coordinate system, all acceleration due to gravity is along the *z*-axis, and the accelerometer reads [0 0 1]. Consider the rotation matrix required to rotate a quantity from the NED coordinate system to a quantity indicated by the accelerometer.

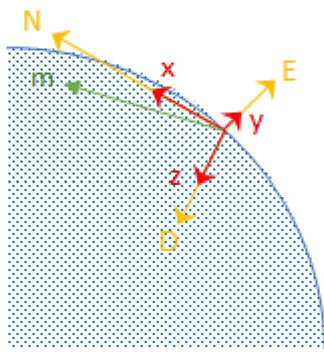


$$\begin{bmatrix} r_{11} & r_{21} & r_{31} \\ r_{12} & r_{22} & r_{32} \\ r_{13} & r_{23} & r_{33} \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix}$$

The third column of the rotation matrix corresponds to the accelerometer reading:

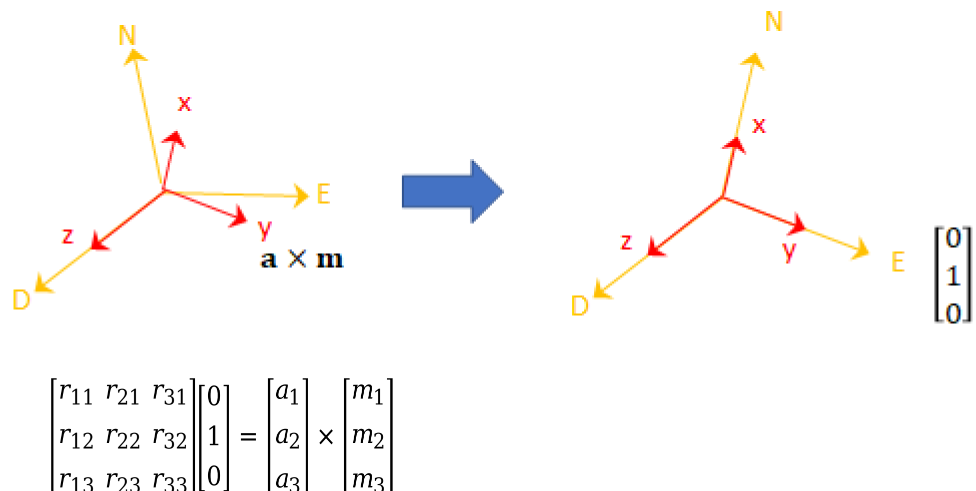
$$\begin{bmatrix} r_{31} \\ r_{32} \\ r_{33} \end{bmatrix} = \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix}$$

A magnetometer reading points toward magnetic north and is in the *N*-*D* plane. Again, consider a sensor body frame aligned with the NED coordinate system.




By definition, the *E*-axis is perpendicular to the *N*-*D* plane, therefore $D \times N = E$, within some amplitude scaling. If the sensor body frame is aligned with NED, both the acceleration vector from the accelerometer and the magnetic field vector from the magnetometer lie in the *N*-*D* plane. Therefore $a \times m = y$, again with some amplitude scaling.

Consider the rotation matrix required to rotate NED to the child frame, [*x* *y* *z*].




$$\begin{bmatrix} r_{11} & r_{21} & r_{31} \\ r_{12} & r_{22} & r_{32} \\ r_{13} & r_{23} & r_{33} \end{bmatrix} \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} = \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix} \times \begin{bmatrix} m_1 \\ m_2 \\ m_3 \end{bmatrix}$$

The second column of the rotation matrix corresponds to the cross product of the accelerometer reading and the magnetometer reading:

$$\begin{bmatrix} r_{21} \\ r_{22} \\ r_{23} \end{bmatrix} = \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix} \times \begin{bmatrix} m_1 \\ m_2 \\ m_3 \end{bmatrix}$$

By definition of a rotation matrix, column 1 is the cross product of columns 2 and 3:

$$\begin{bmatrix} r_{11} \\ r_{12} \\ r_{13} \end{bmatrix} = \begin{bmatrix} r_{21} \\ r_{22} \\ r_{23} \end{bmatrix} \times \begin{bmatrix} r_{31} \\ r_{32} \\ r_{33} \end{bmatrix}$$
$$= (a \times m) \times a$$

Finally, the rotation matrix is normalized column-wise:

$$R_{ij} = \frac{R_{ij}}{\sqrt{\sum_{i=1}^{3} R_{ij}^2}} \quad , \forall j$$

**Note** The `ecompass` algorithm uses magnetic north, not true north, for the NED coordinate system.

# Version History

**Introduced in R2018b**

## References

[1] Open Source Sensor Fusion. https://github.com/memsindustrygroup/Open-Source-Sensor-Fusion/tree/master/docs

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`ahrsfilter` | `imufilter`

# enu2lla

Transform local east-north-up coordinates to geodetic coordinates

## Syntax

```
lla = enu2lla(xyzENU,lla0,method)
```

## Description

`lla = enu2lla(xyzENU,lla0,method)` transforms the local east-north-up (ENU) Cartesian coordinates `xyzENU` to geodetic coordinates `lla`. Specify the origin of the local ENU system as the geodetic coordinates `lla0`.

---

**Note**

- The latitude and longitude values in the geodetic coordinate system use the World Geodetic System of 1984 (WGS84) standard.
- Specify altitude as height in meters above the WGS84 reference ellipsoid.

---

## Examples

### Transform ENU Coordinates to Geodetic Coordinates

Specify the geodetic coordinates of the local origin in Zermatt, Switzerland.

```
lla0 = [46.017 7.750 1673]; % [lat0 lon0 alt0]
```

Specify the ENU coordinates of a point of interest, in meters. In this case, the point of interest is the Matterhorn.

```
xyzENU = [-7134.8 -4556.3 2852.4]; % [xEast yNorth zUp]
```

Transform the local ENU coordinates to geodetic coordinates using flat earth approximation.

```
lla = enu2lla(xyzENU,lla0,'flat')
```

```
lla = 1×3
10^3 ×

    0.0460    0.0077    4.5254
```

## Input Arguments

**xyzENU — Local ENU Cartesian coordinates**
three-element row vector | *n*-by-3 matrix

Local ENU Cartesian coordinates, specified as a three-element row vector or an *n*-by-3 matrix. *n* is the number of points to transform. Specify each point in the form [*xEast yNorth zUp*]. *xEast*, *yNorth*, and *zUp* are the respective *x*-, *y*-, and *z*-coordinates, in meters, of the point in the local ENU system.

Example: `[-7134.8 -4556.3 2852.4]`

Data Types: `double`

**`lla0` — Origin of local ENU system in geodetic coordinates**
three-element row vector | *n*-by-3 matrix

Origin of the local ENU system in the geodetic coordinates, specified as a three-element row vector or an *n*-by-3 matrix. *n* is the number of origin points. Specify each point in the form `[lat0 lon0 alt0]`. *lat0* and *lon0* specify the latitude and longitude of the origin, respectively, in degrees. *alt0* specifies the altitude of the origin in meters.

Example: `[46.017 7.750 1673]`

Data Types: `double`

**`method` — Transformation method**
`'flat'` | `'ellipsoid'`

Transformation method, specified as `'flat'` or `'ellipsoid'`. This argument specifies whether the function assumes the planet is flat or ellipsoidal.

The flat Earth transformation method has these limitations:

- Assumes that the flight path and bank angle are zero.
- Assumes that the flat Earth *z*-axis is normal to the Earth at only the initial geodetic latitude and longitude. This method has higher accuracy over small distances from the initial geodetic latitude and longitude, and closer to the equator. The method calculates a longitude with higher accuracy when the variation in latitude is smaller.
- Latitude values of +90 and -90 degree may return unexpected values because of singularity at the poles.

Data Types: `char` | `string`

## Output Arguments

**`lla` — Geodetic coordinates**
three-element row vector | *n*-by-3 matrix

Geodetic coordinates, returned as a three-element row vector or an *n*-by-3 matrix. *n* is the number of transformed points. Each point is in the form `[lat lon alt]`. *lat* and *lon* specify the latitude and longitude, respectively, in degrees. *alt* specifies the altitude in meters.

Data Types: `double`

# Version History

**Introduced in R2021a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Functions**
`lla2enu` | `lla2ned` | `ned2lla`

# eul2quat

Convert Euler angles to quaternion

## Syntax

```
quat = eul2quat(eul)
quat = eul2quat(eul,sequence)
```

## Description

`quat = eul2quat(eul)` converts a given set of Euler angles, `eul`, to the corresponding quaternion, `quat`. The default order for Euler angle rotations is `"ZYX"`.

`quat = eul2quat(eul,sequence)` converts a set of Euler angles into a quaternion. The Euler angles are specified in the axis rotation sequence, `sequence`. The default order for Euler angle rotations is `"ZYX"`.

## Examples

### Convert Euler Angles to Quaternion

```
eul = [0 pi/2 0];
qZYX = eul2quat(eul)
```

```
qZYX = 1×4

    0.7071         0    0.7071         0
```

### Convert Euler Angles to Quaternion Using Default ZYZ Axis Order

```
eul = [pi/2 0 0];
qZYZ = eul2quat(eul,"ZYZ")
```

```
qZYZ = 1×4

    0.7071         0         0    0.7071
```

## Input Arguments

**`eul` — Euler rotation angles**
*n*-by-3 matrix

Euler rotation angles in radians, specified as an *n*-by-3 array of intrinsic Euler rotation angles. Each row represents one Euler angle set in the sequence defined by the `sequence` argument. For example, with the default sequence `"ZYX"`, each row of `eul` is of the form `[zAngle yAngle xAngle]`.

Example: `[0 0 1.5708]`

**sequence — Axis-rotation sequence**
"ZYX" (default) | "ZYZ" | "ZXY" | "ZXZ" | "YXY" | "YZX" | "YXZ" | "YZY" | "XYX" | "XYZ" | "XZX" | "XZY"

Axis-rotation sequence for the Euler angles, specified as one of these string scalars:

- "ZYX" (default)
- "ZYZ"
- "ZXY"
- "ZXZ"
- "YXY"
- "YZX"
- "YXZ"
- "YZY"
- "XYX"
- "XYZ"
- "XZX"
- "XZY"

Each character indicates the corresponding axis. For example, if the sequence is "ZYX", then the three specified Euler angles are interpreted in order as a rotation around the *z*-axis, a rotation around the *y*-axis, and a rotation around the *x*-axis. When applying this rotation to a point, it will apply the axis rotations in the order *x*, then *y*, then *z*.

Data Types: `string` | `char`

## Output Arguments

**quat — Unit quaternion**
*n*-by-4 matrix

Unit quaternion, returned as an *n*-by-4 matrix containing *n* quaternions. Each quaternion, one per row, is of the form $q = [w\ x\ y\ z]$, with *w* as the scalar number.

Example: `[0.7071 0.7071 0 0]`

# Version History

**Introduced in R2015a**

### R2023a: Additional Euler sequence support

`eul2quat` supports additional Euler sequences for the `sequences` argument. These are all the supported Euler sequences:

- "ZYX"

- "ZYZ"
- "ZXY"
- "ZXZ"
- "YXY"
- "YZX"
- "YXZ"
- "YZY"
- "XYX"
- "XYZ"
- "XZX"
- "XZY"

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

`quat2eul` | `quaternion`

# eul2rotm

Convert Euler angles to rotation matrix

## Syntax

```
rotm = eul2rotm(eul)
rotm = eul2rotm(eul,sequence)
```

## Description

`rotm = eul2rotm(eul)` converts a set of Euler angles, `eul`, to the corresponding rotation matrix, `rotm`. When using the rotation matrix, premultiply it with the coordinates to be rotated (as opposed to postmultiplying). The default order for Euler angle rotations is `"ZYX"`.

`rotm = eul2rotm(eul,sequence)` converts Euler angles to a rotation matrix, `rotm`. The Euler angles are specified in the axis rotation sequence, `sequence`. The default order for Euler angle rotations is `"ZYX"`.

## Examples

### Convert Euler Angles to Rotation Matrix

```
eul = [0 pi/2 0];
rotmZYX = eul2rotm(eul)
```

```
rotmZYX = 3×3

    0.0000         0    1.0000
         0    1.0000         0
   -1.0000         0    0.0000
```

### Convert Euler Angles to Rotation Matrix Using ZYZ Axis Order

```
eul = [0 pi/2 pi/2];
rotmZYZ = eul2rotm(eul,'ZYZ')
```

```
rotmZYZ = 3×3

    0.0000   -0.0000    1.0000
    1.0000    0.0000         0
   -0.0000    1.0000    0.0000
```

## Input Arguments

### `eul` — Euler rotation angles

*n*-by-3 matrix

Euler rotation angles in radians, specified as an *n*-by-3 array of intrinsic Euler rotation angles. Each row represents one Euler angle set in the sequence defined by the `sequence` argument. For example, with the default sequence `"ZYX"`, each row of `eul` is of the form `[zAngle yAngle xAngle]`.

Example: `[0 0 1.5708]`

### `sequence` — Axis-rotation sequence

`"ZYX"` (default) | `"ZYZ"` | `"ZXY"` | `"ZXZ"` | `"YXY"` | `"YZX"` | `"YXZ"` | `"YZY"` | `"XYX"` | `"XYZ"` | `"XZX"` | `"XZY"`

Axis-rotation sequence for the Euler angles, specified as one of these string scalars:

- `"ZYX"` (default)
- `"ZYZ"`
- `"ZXY"`
- `"ZXZ"`
- `"YXY"`
- `"YZX"`
- `"YXZ"`
- `"YZY"`
- `"XYX"`
- `"XYZ"`
- `"XZX"`
- `"XZY"`

Each character indicates the corresponding axis. For example, if the sequence is `"ZYX"`, then the three specified Euler angles are interpreted in order as a rotation around the *z*-axis, a rotation around the *y*-axis, and a rotation around the *x*-axis. When applying this rotation to a point, it will apply the axis rotations in the order *x*, then *y*, then *z*.

Data Types: `string` | `char`

## Output Arguments

### `rotm` — Rotation matrix

3-by-3-by-*n* matrix

Rotation matrix, returned as a 3-by-3-by-*n* matrix containing *n* rotation matrices. Each rotation matrix has a size of 3-by-3 and is orthonormal. When using the rotation matrix, premultiply it with the coordinates to be rotated (as opposed to postmultiplying).

Example: `[0 0 1; 0 1 0; -1 0 0]`

# Version History

**Introduced in R2015a**

**R2023a: Additional Euler sequence support**

`eul2rotm` supports additional Euler sequences for the `sequences` argument. These are all the supported Euler sequences:

- `"ZYX"`
- `"ZYZ"`
- `"ZXY"`
- `"ZXZ"`
- `"YXY"`
- `"YZX"`
- `"YXZ"`
- `"YZY"`
- `"XYX"`
- `"XYZ"`
- `"XZX"`
- `"XZY"`

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

`rotm2eul` | `so2` | `so3`

# eul2tform

Convert Euler angles to homogeneous transformation

## Syntax

```
tform = eul2tform(eul)
tform = eul2tform(eul,sequence)
```

## Description

`tform = eul2tform(eul)` converts a set of Euler angles, `eul`, into a homogeneous transformation matrix, `tform`. When using the transformation matrix, premultiply it with the coordinates to be transformed (as opposed to postmultiplying). The default order for Euler angle rotations is `"ZYX"`.

`tform = eul2tform(eul,sequence)` converts Euler angles to a homogeneous transformation. The Euler angles are specified in the axis rotation sequence, `sequence`. The default order for Euler angle rotations is `"ZYX"`.

## Examples

### Convert Euler Angles to Homogeneous Transformation Matrix

```
eul = [0 pi/2 0];
tformZYX = eul2tform(eul)
```

```
tformZYX = 4×4

    0.0000         0    1.0000         0
         0    1.0000         0         0
   -1.0000         0    0.0000         0
         0         0         0    1.0000
```

### Convert Euler Angles to Homogeneous Transformation Matrix Using ZYZ Axis Order

```
eul = [0 pi/2 pi/2];
tformZYZ = eul2tform(eul,'ZYZ')
```

```
tformZYZ = 4×4

    0.0000   -0.0000    1.0000         0
    1.0000    0.0000         0         0
   -0.0000    1.0000    0.0000         0
         0         0         0    1.0000
```

## Input Arguments

**`eul` — Euler rotation angles**
*n*-by-3 matrix

Euler rotation angles in radians, specified as an *n*-by-3 array of intrinsic Euler rotation angles. Each row represents one Euler angle set in the sequence defined by the `sequence` argument. For example, with the default sequence `"ZYX"`, each row of `eul` is of the form `[zAngle yAngle xAngle]`.

Example: `[0 0 1.5708]`

**`sequence` — Axis-rotation sequence**
`"ZYX"` (default) | `"ZYZ"` | `"ZXY"` | `"ZXZ"` | `"YXY"` | `"YZX"` | `"YXZ"` | `"YZY"` | `"XYX"` | `"XYZ"` | `"XZX"` | `"XZY"`

Axis-rotation sequence for the Euler angles, specified as one of these string scalars:

- `"ZYX"` (default)
- `"ZYZ"`
- `"ZXY"`
- `"ZXZ"`
- `"YXY"`
- `"YZX"`
- `"YXZ"`
- `"YZY"`
- `"XYX"`
- `"XYZ"`
- `"XZX"`
- `"XZY"`

Each character indicates the corresponding axis. For example, if the sequence is `"ZYX"`, then the three specified Euler angles are interpreted in order as a rotation around the *z*-axis, a rotation around the *y*-axis, and a rotation around the *x*-axis. When applying this rotation to a point, it will apply the axis rotations in the order *x*, then *y*, then *z*.

Data Types: `string` | `char`

## Output Arguments

**`tform` — Homogeneous transformation**
4-by-4-by-*n* matrix

Homogeneous transformation matrix, specified by a 4-by-4-by-*n* array of *n* homogeneous transformation matrices. When using the transformation matrix, premultiply it with the coordinates to be rotated (as opposed to postmultiplying).

Example: `[0 0 1 0; 0 1 0 0; -1 0 0 0; 0 0 0 1]`

# Version History

**Introduced in R2015a**

#### R2023a: Additional Euler sequence support

`eul2tform` supports additional Euler sequences for the `sequences` argument. These are all the supported Euler sequences:

- `"ZYX"`
- `"ZYZ"`
- `"ZXY"`
- `"ZXZ"`
- `"YXY"`
- `"YZX"`
- `"YXZ"`
- `"YZY"`
- `"XYX"`
- `"XYZ"`
- `"XZX"`
- `"XZY"`

## Extended Capabilities

#### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`tform2eul` | `se2` | `se3`

# exportOccupancyMap3D

Export 3-D occupancy map as octree or binary tree file

## Syntax

`exportOccupancyMap3D(map3D,filename)`

## Description

`exportOccupancyMap3D(map3D,filename)` exports the 3-D occupancy map, `map3D`, into either an octree file (`.ot`) that contains all the occupancy data, or a binary tree file (`.bt`) that contains only the maximum-likelihood information at the specified location, `filename`

## Examples

### Create and Export 3-D Occupancy Map

Create an `occupancyMap3D` object.

```
map3D = occupancyMap3D;
```

Create a ground plane and set occupancy values to 0.

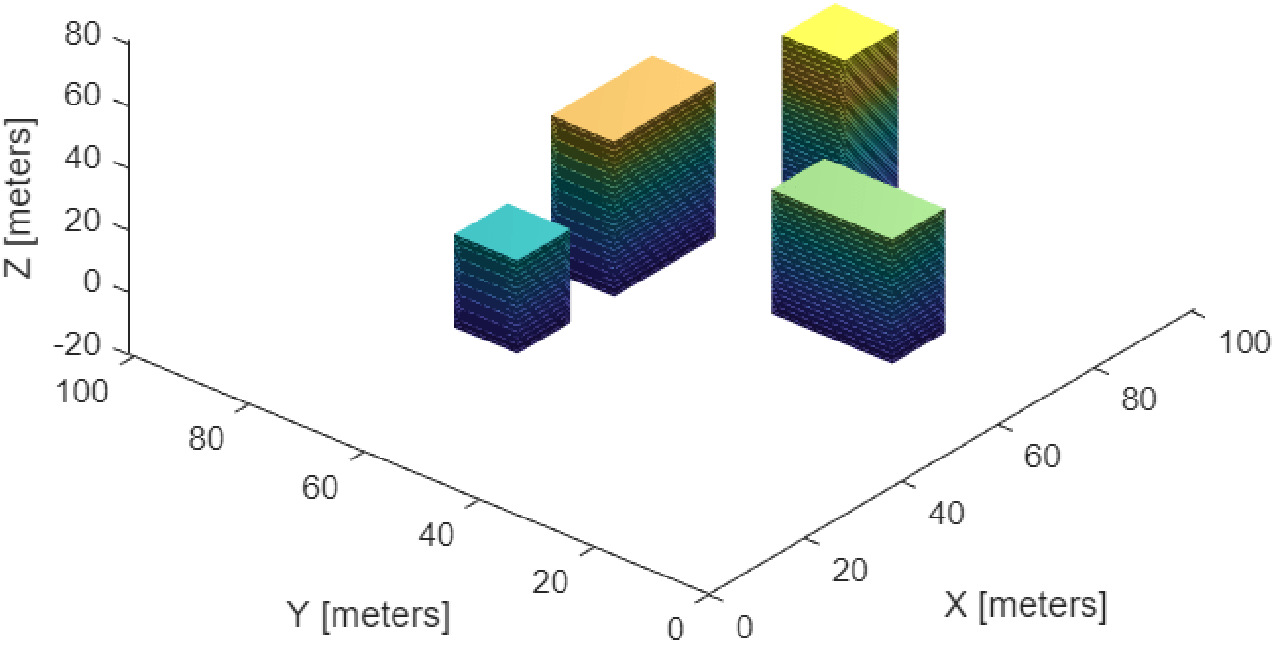
```
[xGround,yGround,zGround] = meshgrid(0:100,0:100,0);
xyzGround = [xGround(:) yGround(:) zGround(:)];
occval = 0;
setOccupancy(map3D,xyzGround,occval)
```

Create obstacles in specific world locations of the map.

```
[xBuilding1,yBuilding1,zBuilding1] = meshgrid(20:30,50:60,0:30);
[xBuilding2,yBuilding2,zBuilding2] = meshgrid(50:60,10:30,0:40);
[xBuilding3,yBuilding3,zBuilding3] = meshgrid(40:60,50:60,0:50);
[xBuilding4,yBuilding4,zBuilding4] = meshgrid(70:80,35:45,0:60);

xyzBuildings = [xBuilding1(:) yBuilding1(:) zBuilding1(:);...
                xBuilding2(:) yBuilding2(:) zBuilding2(:);...
                xBuilding3(:) yBuilding3(:) zBuilding3(:);...
                xBuilding4(:) yBuilding4(:) zBuilding4(:)];
```

Update the obstacles with new probability values and display the map.

```
obs = 0.65;
updateOccupancy(map3D,xyzBuildings,obs)
show(map3D)
```




Check if the map file named `citymap.ot` already exist in the current directory and delete it before creating the map file.

```
if exist("citymap.ot",'file')
    delete("citymap.ot")
end
```

Export the map as an octree file.

```
filePath = fullfile(pwd,"citymap.ot");
exportOccupancyMap3D(map3D,filePath)
```

## Input Arguments

**map3D — 3-D occupancy map**
occupancyMap3D object

3-D occupancy map, specified as a `occupancyMap3D` object.

**filename — Absolute or relative path to octree or binary tree file**
string scalar | character vector

Absolute or relative path to octree file (.ot) or binary tree file (.bt), specified as a string scalar or character vector.

Example: "path/to/file/map.ot"

Data Types: char | string

# Version History

**Introduced in R2020a**

## See Also

**Classes**
occupancyMap3D | lidarSLAM | occupancyMap

**Functions**
insertPointCloud | inflate | setOccupancy | show

# extractNMEASentence

Verify and extract NMEA sentence data into string array

## Syntax

```
[isValid,splitString] = extractNMEASentence(unparsedData,'MessageID')
```

## Description

`[isValid,splitString] = extractNMEASentence(unparsedData,'MessageID')` verifies the checksum of an unparsed NMEA sentence, identified using its Message ID, and extracts the NMEA fields from NMEA sentence data into a string array, `splitString`.

## Examples

### Extract NMEA Fields of NMEA Sentence

Provide unparsed GGA, GSA, and RMC sentences as the input.

```
unparsedGGALine = '$GPGGA,111357.771,5231.364,N,01324.240,E,1,12,1.0,0.0,M,0.0,M,,*69';
unparsedGSALine = '$GPGSA,A,3,01,02,03,04,05,06,07,08,09,10,11,12,1.0,1.0,1.0*30';
unparsedRMCLine = '$GPRMC,111357.771,A,5231.364,N,01324.240,E,10903,221.5,020620,000.0,W*44';
```

Create a string array to include the three sentences

```
unparsedNMEAData = [unparsedGGALine,newline,unparsedGSALine,newline,unparsedRMCLine]
```

```
unparsedNMEAData =
    '$GPGGA,111357.771,5231.364,N,01324.240,E,1,12,1.0,0.0,M,0.0,M,,*69
     $GPGSA,A,3,01,02,03,04,05,06,07,08,09,10,11,12,1.0,1.0,1.0*30
     $GPRMC,111357.771,A,5231.364,N,01324.240,E,10903,221.5,020620,000.0,W*44'
```

Specify GSA as the Message ID to extract the NMEA fields from the NMEA sentence into string array.

```
[isValid, splitString] = extractNMEASentence(unparsedNMEAData,'GSA')
```

```
isValid = logical
   1

splitString = 1x19 string
    "GP"    "GSA"    "A"    "3"    "01"    "02"    "03"    "04"    "05"    "06"    "07"    "08"
```

## Input Arguments

**`unparsedData` — Unparsed NMEA data from the device**
string | character array

The unparsed NMEA data as obtained from the device.

**`MessageID` — Message ID of the unparsed NMEA sentence**
string | character array

The Message ID to identify the unparsed NMEA sentence.

## Output Arguments

**`isValid` — Validity of unparsed NMEA sentence based on checksum**
`0` | `1`

Determine the validity of unparsed NMEA sentence based on checksum. A value of `1` indicates that the checksum is valid. A value of `0` indicates that the checksum is invalid; however, the fields of NMEA sentence appear in the `splitString` output if the specified MessageID is matching.

Data Types: `logical`

**`splitString` — Output data as split strings**
string array

Output data as split strings based on the structure that you defined. If the specified MessageID is not found in the NMEA sentence, the function returns an empty `splitString`.

Data Types: `string`

# Version History

**Introduced in R2021b**

## See Also

**Objects**
`nmeaParser`

# flush

Flush all GPS data accumulated in the buffers and reset properties

## Syntax

```
flush(gps)
```

## Description

`flush(gps)` clears the buffers and resets the values of `SamplesRead` and `SamplesAvailable` properties.

## Examples

### Read Data from GPS Receiver as Matrix

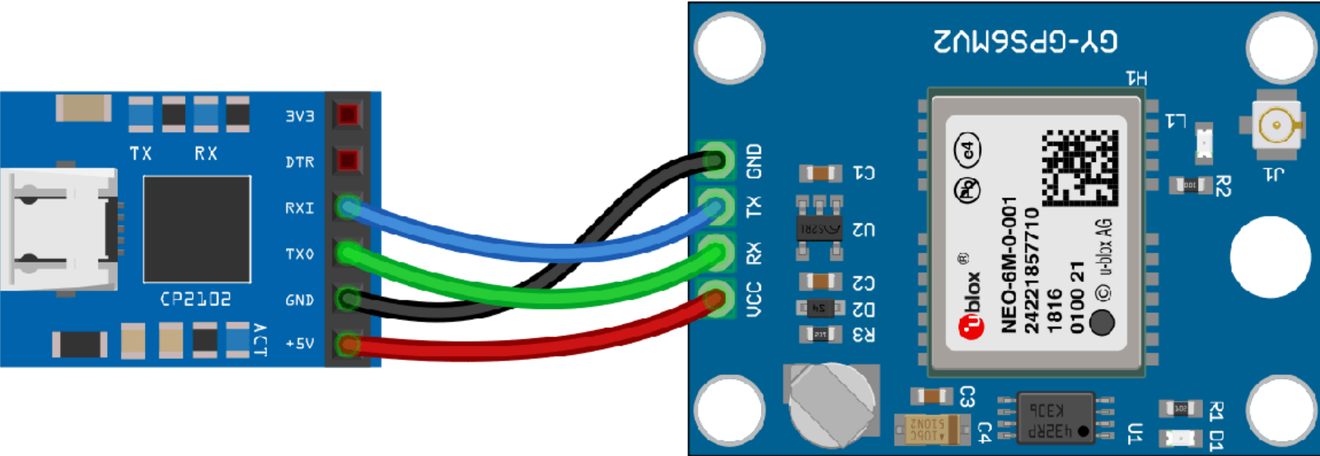
Read data from the GPS receiver connected to the host computer using `serialport` object.

**Required Hardware**

To run this example, you need:

- UBlox Neo-6M GPS module
- GPS antenna
- USB to UART module
- USB cable
- Connecting wires

**Hardware Connection**



Connect the pins on the UBlox Neo-6M GPS module to the pins on your USB to UART module. The connections are:

- VCC - +5V
- RX - TXO
- TX - RXI
- GND - GND

Connect the GPS antenna to the GPS module. Connect the USB to UART module to the host computer with a USB cable. GPS Fix can be easily acquired in locations that have a clear view of the sky. Wait for the GPS module to acquire satelite signals (Fix).This can be verified by checking the Fix LED (D1) of your GPS module.

### Create GPS Object

Connect to the GPS receiver using `serialport` object. Specify the port name and the baud rate. Specify the output format of the data as matrix.

```
s = serialport('COM4',9600);
gps = gpsdev(s,'OutputFormat',"matrix")
```

```
gps = 
  gpsdev with properties:

                         SerialPort: COM4
                           BaudRate: 9600 (bits/s)

                     SamplesPerRead: 1
                           ReadMode: "latest"
                        SamplesRead: 0
Show all properties all functions
```

### Read the GPS data

Read the GPS data and return them as matrices.

```
[lla,speed,course,dops,gpsReceiverTime,timestamp,overruns] = read(gps)
```

```
lla = 1×3

   NaN   NaN   NaN


speed = NaN

course = NaN

dops = 1×3

   NaN   NaN   NaN


gpsReceiverTime = datetime
   NaT
```

```
timestamp = datetime
   22-Mar-2021 03:41:00.274

overruns = 1
```

Display number of samples read and the samples available in the host buffer.

```
gps.SamplesRead
```

```
ans = 1
```

```
gps.SamplesAvailable
```

```
ans = 0
```

Flush all GPS data accumulated in the buffers and reset the `SamplesRead` and `SamplesAvailable` properties.

```
flush(gps)
```

Display number of samples read and the samples available in the host buffer.

```
gps.SamplesRead
```

```
ans = 0
```

```
gps.SamplesAvailable
```

```
ans = 0
```

**Clean Up**

When the connection is no longer needed, clear the associated object.

```
delete(gps);
clear gps;
clear s;
```

## Input Arguments

**gps — GPS sensor**
`gpsdev` object

The GPS sensor, specified as a `gpsdev` object.

# Version History

**Introduced in R2020b**

## See Also

**Objects**
`gpsdev`

**Functions**
`release` | `writeBytes` | `read` | `info`

# gnssconstellation

Satellite locations at specified time

## Syntax

```
[satPos,satVel] = gnssconstellation(t)
[satPos,satVel,satID] = gnssconstellation(t,navData)
[satPos,satVel,satID] = gnssconstellation(t,navData,GNSSFileType=
gnssFileType)
```

## Description

`[satPos,satVel] = gnssconstellation(t)` returns the satellite positions and velocities at the `datetime` `t`. The function returns positions and velocities in the Earth-centered Earth-fixed (ECEF) coordinate system in meters and meters per second, respectively. If the time zone for the datetime is not specified, it is assumed to be UTC.

`[satPos,satVel,satID] = gnssconstellation(t,navData)` returns the satellite positions, velocities, and IDs at time `t` in the specified RINEX navigation message data `navData`.

`[satPos,satVel,satID] = gnssconstellation(t,navData,GNSSFileType= gnssFileType)` additionally specifies the GNSS file type from which you obtained the navigation message data. This syntax enables you to process navigation data obtained from either a RINEX file, a SEM almanac file, or a YUMA almanac file.

**Note** The `gnssconstellation` function determines the satellite position and satellite velocities by propagating the current orbital parameters specified by the RINEX file, SEM almanac file, or YUMA almanac file to the query time. To get more accurate satellite positions and velocities, ensure you are using the navigation file released for the time that you are querying at.

## Examples

### Get Current Satellite Positions and Velocities

Get the current satellite positions and velocities from the GNSS satellites. Access the orbital parameters from IS-GPS-200M Interface Specification and calculate the position and velocities in ECEF coordinates for the given time. Display the satellite positions.

```
t = datetime('now','TimeZone','Local');
[satPos,satVel] = gnssconstellation(t);
disp(satPos)
```

```
   1.0e+07 *

    1.5471    0.2129    2.1483
   -0.5458   -2.5847   -0.2746
   -0.2505    2.5080   -0.8374
   -0.9852    1.7558   -1.7322
```

```
   -0.3225   -1.6035   -2.0926
   -1.3709   -0.8182   -2.1226
    2.1641   -1.5312    0.1631
   -1.0429    2.0216    1.3710
    2.2526   -0.6297    1.2584
    1.8177   -0.6393   -1.8280
   -2.0437   -1.4728   -0.8416
   -2.5193   -0.7627    0.3543
    0.1882    1.6470    2.0752
    1.1375    2.0723   -1.2107
   -1.5264   -0.8670    1.9931
   -1.5026    0.2541    2.1753
    0.8398   -1.9723   -1.5682
    0.4023    2.6246   -0.0638
   -2.2921    0.8699    1.0217
    0.7713   -1.9934    1.5766
    1.3802    0.8088   -2.1201
    1.7782   -1.8869    0.5760
   -0.3053   -1.6701    2.0425
    2.2953    1.2649   -0.4307
    2.5237    0.6059    0.5639
   -1.6018    0.8219   -1.9526
   -2.3653   -0.0546   -1.2069
```

### Get Satellite Look Angles for Receiver Position

Use the `lookangles` function to get the azimuth and elevation angles of satellites for given satellite and receiver positions. Specify a mask angle of 5 degrees. Get the satellite positions using the `gnssconstellation` function.

Specify a receiver position in geodetic coordinates (latitude, longitude, altitude).

```
recPos = [42 -71 50];
```

Get the satellite positions for the current time.

```
t = datetime('now');
gpsSatPos = gnssconstellation(t);
```

Specify a mask angle of 5 degrees.

```
maskAngle = 5;
```

Get the azimuth and elevation look angles for the satellite positions. The `vis` output indicates which satellites are visible. Get the total using `nnz`.

```
[az,el,vis] = lookangles(recPos,gpsSatPos,maskAngle);
fprintf('%d satellites visible at %s.\n',nnz(vis),t);
```

```
8 satellites visible at 04-Mar-2023 01:25:04.
```

#### Retrieve Satellite Positions, Velocities, and IDs from RINEX File

Read one set of GPS satellites from the GPS navigation message in a RINEX file.

```
filename = "GODS00USA_R_20211750000_01D_GN.rnx";
data = rinexread(filename);
gpsData = data.GPS;
[~,satIdx] = unique(gpsData.SatelliteID);
gpsData = gpsData(satIdx,:);
```

Get the satellite positions, velocities, and IDs at the first time step.

```
t = gpsData.Time(1);
[satPos,satVel,satID] = gnssconstellation(t,gpsData)
```

```
satPos = 31×3
10^7 ×

   -1.5630   -0.1882    2.1186
    1.3808    2.1970   -0.4861
   -2.0061    0.7606    1.5492
   -2.5625   -0.0140   -0.7096
    1.4896    0.5448   -2.1487
    0.6129    2.5407    0.4615
   -1.0081    1.3751   -1.9877
   -2.5811   -0.6135   -0.3246
   -1.9289    0.8690   -1.6134
    0.9542   -2.2526    1.0113
      ⋮

satVel = 31×3
10^3 ×

   -0.8888   -2.5914   -0.8416
    0.0362    0.7543    3.1043
    1.1203   -1.6505    2.2591
   -0.8301   -0.4385    2.9967
   -1.6023    2.1607   -0.5493
   -0.3948   -0.4708    3.1591
   -1.0322   -2.4133   -1.1748
    0.4370   -0.1710   -3.1339
   -1.9860   -0.5032    2.1087
    0.9968   -0.8308   -2.8502
      ⋮

satID = 31×1

     1
     2
     3
     4
     5
     6
     7
     8
     9
    10
```

⋮

#### Retrieve Satellite Positions, Velocities, and IDs from SEM Almanac File

Read GPS navigation message data from a SEM almanac file.

```
data = semread("semalmanac_2022-4-10.al3")
```

```
data=31×16 timetable
            Time            GPSWeekNumber    GPSTimeOfApplicability    PRNNumber    SVN    Averag
    ____________________    _____________    ______________________    _________    ___    ______

    12-Apr-2022 16:50:54        2205               2.3347e+05              1        63
    12-Apr-2022 16:50:54        2205               2.3347e+05              2        61
    12-Apr-2022 16:50:54        2205               2.3347e+05              3        69
    12-Apr-2022 16:50:54        2205               2.3347e+05              4        74
    12-Apr-2022 16:50:54        2205               2.3347e+05              5        50
    12-Apr-2022 16:50:54        2205               2.3347e+05              6        67
    12-Apr-2022 16:50:54        2205               2.3347e+05              7        48
    12-Apr-2022 16:50:54        2205               2.3347e+05              8        72
    12-Apr-2022 16:50:54        2205               2.3347e+05              9        68
    12-Apr-2022 16:50:54        2205               2.3347e+05             10        73
    12-Apr-2022 16:50:54        2205               2.3347e+05             11        78
    12-Apr-2022 16:50:54        2205               2.3347e+05             12        58
    12-Apr-2022 16:50:54        2205               2.3347e+05             13        43
    12-Apr-2022 16:50:54        2205               2.3347e+05             14        77
    12-Apr-2022 16:50:54        2205               2.3347e+05             15        55
    12-Apr-2022 16:50:54        2205               2.3347e+05             16        56
      ⋮
```

Get the satellite positions, velocities, and IDs at the first time step.

```
t = data.Time(1);
[satPos,satVel,satID] = gnssconstellation(t,data,GNSSFileType="SEM")
```

```
satPos = 31×3
10^7 ×

    1.3899   -2.2151    0.3074
   -1.6755    0.5872   -1.9147
    1.5377   -1.2781   -1.7528
    0.6332   -1.6385   -1.9887
   -2.5716    0.5413    0.4215
   -1.0251   -1.1336   -2.1646
    0.2694   -2.3585    1.1775
    1.3414   -0.7139    2.1761
   -0.3881   -2.2626   -1.3395
    1.5043    1.1879    1.8656
      ⋮
```

```
satVel = 31×3
10^3 ×
```

```
    0.0014    0.4854    3.2261
    0.8625   -2.4217   -1.4348
    2.2113    0.0321    1.9394
    1.4081    2.1049   -1.2936
   -0.5761   -0.2150   -3.1036
    1.2999   -2.4327    0.6643
    0.9229   -1.1620   -2.6758
    1.5581    2.2893   -0.1743
    1.1480    1.2668   -2.4877
   -2.3150    0.2417    1.6982
      ⋮

satID = 31×1

     1
     2
     3
     4
     5
     6
     7
     8
     9
    10
     ⋮
```

**Retrieve Satellite Positions, Velocities, and IDs from YUMA Almanac File**

Read GPS navigation message data from a YUMA almanac file.

```
data = yumaread("yumaAlmanac_2022-9-27.alm")
```

data=31×13 timetable

| Time | PRN | Health | Eccentricity | TimeOfApplicability | OrbitalIncli |
|---|---|---|---|---|---|
| 29-Sep-2022 16:38:06 | 1 | 0 | 0.012008 | 4.055e+05 | 0.98891 |
| 29-Sep-2022 16:38:06 | 2 | 0 | 0.02 | 4.055e+05 | 0.96685 |
| 29-Sep-2022 16:38:06 | 3 | 0 | 0.0044999 | 4.055e+05 | 0.97519 |
| 29-Sep-2022 16:38:06 | 4 | 0 | 0.0020423 | 4.055e+05 | 0.96187 |
| 29-Sep-2022 16:38:06 | 5 | 0 | 0.0060811 | 4.055e+05 | 0.96224 |
| 29-Sep-2022 16:38:06 | 6 | 0 | 0.0024514 | 4.055e+05 | 0.98822 |
| 29-Sep-2022 16:38:06 | 7 | 0 | 0.016406 | 4.055e+05 | 0.95104 |
| 29-Sep-2022 16:38:06 | 8 | 0 | 0.0075631 | 4.055e+05 | 0.96192 |
| 29-Sep-2022 16:38:06 | 9 | 0 | 0.0025387 | 4.055e+05 | 0.95495 |
| 29-Sep-2022 16:38:06 | 10 | 0 | 0.0079675 | 4.055e+05 | 0.97498 |
| 29-Sep-2022 16:38:06 | 11 | 0 | 0.00075054 | 4.055e+05 | 0.96415 |
| 29-Sep-2022 16:38:06 | 12 | 0 | 0.0085082 | 4.055e+05 | 0.96755 |
| 29-Sep-2022 16:38:06 | 13 | 0 | 0.0065126 | 4.055e+05 | 0.96921 |
| 29-Sep-2022 16:38:06 | 14 | 0 | 0.002305 | 4.055e+05 | 0.95095 |
| 29-Sep-2022 16:38:06 | 15 | 0 | 0.014625 | 4.055e+05 | 0.93093 |
| 29-Sep-2022 16:38:06 | 16 | 0 | 0.012809 | 4.055e+05 | 0.96738 |
| ⋮ | | | | | |

Get the satellite positions, velocities, and IDs at the first time step.

```
t = data.Time(1);
[satPos,satVel,satID] = gnssconstellation(t,data,GNSSFileType="YUMA")
```

```
satPos = 31×3
10^7 ×

   -1.3549    2.2358   -0.3793
    1.4926   -2.1942   -0.1952
   -1.2477    1.2357   -2.0018
   -0.4096    2.0385   -1.6467
    2.2427   -0.7207    1.2218
    1.4711    0.4089   -2.1680
   -0.0841    2.0989    1.6373
   -1.0615    1.1949    2.1111
    0.5989    2.4816   -0.7333
   -1.9686   -1.1518    1.4018
      ⋮

satVel = 31×3
10^3 ×

   -0.4388    0.2295    3.2113
    0.0460    0.4065   -3.1646
   -2.4900   -0.3576    1.3500
   -0.9647   -1.8691   -2.0833
    1.5583    0.3175   -2.6224
   -1.6003    2.2475   -0.6531
   -1.3741    1.5034   -2.0994
   -1.2344   -2.3991    0.7711
   -0.6518   -0.7124   -2.9785
    1.7466    0.0160    2.4627
      ⋮

satID = 31×1

     1
     2
     3
     4
     5
     6
     7
     8
     9
    10
      ⋮
```

## Input Arguments

### t — Current time for satellite simulation

scalar `datetime` array

Current time for the satellite simulation, specified as a scalar `datetime` array.

The default time zone for a `datetime` array is UTC. For information on specifying a different time zone, see `datetime`.

GPS start time is January 6, 1980 at 00:00 (UTC). Specifying any `datetime` prior to this time will use the GPS start time.

Example: `datetime('now','TimeZone','Local');`

Data Types: `datetime`

**navData — Navigation data**
timetable

Navigation data, specified as a timetable. For a RINEX file, you can obtain this timetable from the structure returned by the `rinexread` function. For a SEM almanac file, you can use the timetable returned by the `semread` function. For a YUMA almanac file, you can use the timetable returned by the `yumaread` function.

**Read Navigation Data from RINEX File**

The `gnssconstellation` function can process the GPS or Galileo data read from a RINEX file. The contents of the structure returned by the `rinexread` function vary depending on the type of satellite system described by the RINEX file. For more information on the contents of the structure, see the `rinexread` function “More About” on page 1-239 section.

To read GPS navigation message data from a RINEX file, extract the GPS field from the returned structure. For example:

```
rinexData = rinexread("GODS00USA_R_20211750000_01D_GN.rnx");
navData = rinexData.GPS;
```

To read Galileo navigation message data from a RINEX file, extract the Galileo field from the returned structure. For example:

```
rinexData = rinexread("GODS00USA_R_20211750000_01D_EN.rnx");
navData = rinexData.Galileo;
```

**Read Navigation Data from SEM Almanac File**

The `gnssconstellation` function can process the GPS data read from a SEM almanac file. The timetable returned by the `semread` function contains the parameters of each satellite in the almanac file associated with the specified date. For more information on the contents of the timetable, see the `“data” on page 1-0` argument of the `semread` function.

Because `semread` returns a timetable, you can directly specify `navData` as the `semread` output argument. For example:

```
navData = semread("semalmanac_2022-1-18.al3")
```

**Read Navigation Data from YUMA Almanac File**

The `gnssconstellation` function can process the GPS and QZSS data read from a YUMA almanac file. The timetable returned by the `yumaread` function contains the parameters of each satellite in the almanac file associated with the specified date. For more information on the contents of the timetable, see the `“data” on page 1-0` argument of the `yumaread` function.

Because `yumaread` returns a timetable, you can directly specify `navData` as the `yumaread` output argument. For example:

```
navData = yumaread("yumaAlmanac_2022-4-20.alm")
```

**`gnssFileType` — GNSS file type**
`"RINEX"` | `"SEM"` | `"YUMA"`

GNSS file type, specified as `"RINEX"`, `"SEM"`, or `"YUMA"`. Specify the GNSS file type as `"RINEX"` when specifying the navigation data as a timetable obtained from the structure returned by the `rinexread` function. Specify the GNSS file type as `"SEM"` when specifying the navigation data as a timetable returned by the `semread` function. Specify the GNSS file type as `"YUMA"` when specifying the navigation data as a timetable returned by the `yumaread` function.

Example: `GNSSFileType="RINEX"`

Example: `GNSSFileType="SEM"`

Example: `GNSSFileType="YUMA"`

Data Types: `char` | `string`

## Output Arguments

**`satPos` — Satellite positions**
*N*-by-3 matrix of scalars

Satellite positions in the Earth-centered Earth-fixed (ECEF) coordinate system in meters, returned as an *N*-by-3 matrix of scalars. *N* is the number of satellites in the constellation.

Data Types: `single` | `double`

**`satVel` — Satellite velocities**
*N*-by-3 matrix of scalar

Satellite velocities in the Earth-centered Earth-fixed (ECEF) coordinate system in meters per second, returned as an *N*-by-3 matrix of scalars. *N* is the number of satellites in the constellation.

Data Types: `single` | `double`

**`satID` — Satellite identification numbers**
*N*-element column vector

Satellite identification numbers, returned as an *N*-element column vector. *N* is the number of satellites in the constellation.

Data Types: `single` | `double`

## More About

### Orbital Parameters

The initial satellite positions and velocities are defined by orbital parameters in Table A.2-2 in GPS SPS Performance Standard, and are given in Earth-centered Earth-fixed (ECEF) coordinates. To get accurate position and velocity calculations, ensure that you are using the correct orbital parameters for the corresponding querying time.

Position calculations use equations from Table 30-II in the same IS-GPS-200M Interface Specification.

Velocity calculations use equations 8.21–8.27 in *Principles of GNSS, Inertial, and Multisensor Integrated Navigation Systems* [1].

# Version History

**Introduced in R2021a**

## References

[1] Groves, Paul D. *Principles of GNSS, Inertial, and Multisensor Integrated Navigation Systems*. Boston: Artech House, 2013.

[2] International GNSS Service (IGS), Daily 30-Second GPS Broadcast Ephemeris Data, NASA Crustal Dynamics Data Information System (CDDIS), Greenbelt, MD, USA, Jun. 24, 2021. Accessed Jun. 25, 2021. https://dx.doi.org/10.5067/GNSS/gnss_daily_n_001.

[3] United States Coast Guard. "GPS Almanacs, NANUs, and OPS Advisories Archives." US Coast Guard Navigation Center. Accessed May 6, 2022. https://www.navcen.uscg.gov/archives.

[4] QZSS almanac archives, Quasi-Zenith Satellite System(QZSS). "QZSS (Quasi-Zenith Satellite System) - Cabinet Office (Japan)" Accessed September 20, 2022. https://sys.qzss.go.jp/dod/en/archives/pnt.html.

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

Only MEX functions are supported for code generation.

## See Also

**Objects**
`gnssSensor` | `gpsSensor` | `imuSensor`

**Functions**
`skyplot` | `lookangles` | `pseudoranges` | `receiverposition` | `rinexread` | `rinexinfo` | `semread` | `yumaread`

**Topics**
“Estimate GNSS Receiver Position with Simulated Satellite Constellations”

# headingFromXY

Compute heading angle from *XY*-points of path

## Syntax

```
heading = headingFromXY(path)
```

## Description

`heading = headingFromXY(path)` computes the heading angle `heading` based on the *XY*-points of the path `path`.

## Examples

### Compute Heading from XY-Points of Path

Create a binary occupancy map using the `mapClutter` function.

```
rng("default")
map = mapClutter(5,MapSize=[20,20],MapResolution=1);
```

Create a `plannerAStarGrid` object using the map. Plan a path.

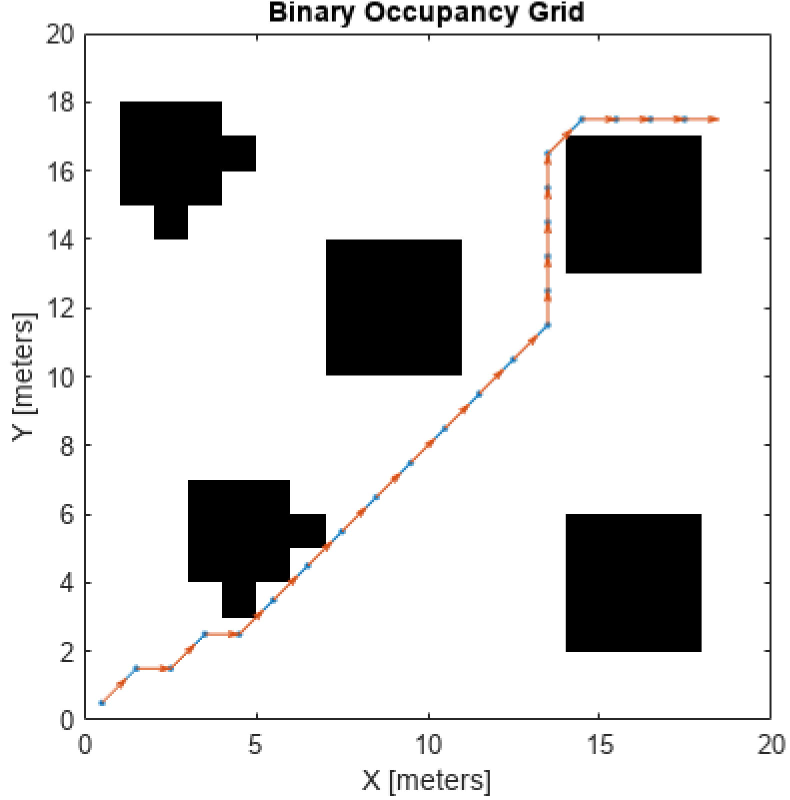
```
planner = plannerAStarGrid(map);
pathXY = plan(planner,[1 1],[18 18],"world");
```

Compute the heading angle (orientation of the robot) from the path.

```
heading = headingFromXY(pathXY);
```

Visualize the heading angle on the path.

```
show(map)
hold on
plot(pathXY(:,1),pathXY(:,2),".-")
quiver(pathXY(:,1),pathXY(:,2),cos(heading),sin(heading),0.2)
```




## Input Arguments

**path — Path**
*N*-by-2 matrix

Path, specified as an *N*-by-2 matrix, where the first column represents the *X*-coordinate and the second column represents the *Y*-coordinate of each point on the path.

Data Types: `single` | `double`

## Output Arguments

**heading — Heading angle**
*N*-element column vector

Heading angle, returned as an *N*-element column vector, in radians. Element *N* is the same as the element (*N*-1).

# Version History

**Introduced in R2023a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Functions

`velocityCommand`

### Objects

`controllerTEB` | `plannerAStarGrid` | `mobileRobotPRM`

# hom2cart

Convert homogeneous coordinates to Cartesian coordinates

## Syntax

```
cart = hom2cart(hom)
```

## Description

`cart = hom2cart(hom)` converts a set of homogeneous points to Cartesian coordinates.

## Examples

### Convert Homogeneous Points to 3-D Cartesian Points

```
h = [0.2785 0.9575 0.1576 0.5; 0.5469 0.9649 0.9706 0.5];
c = hom2cart(h)
```

```
c = 2×3

    0.5570    1.9150    0.3152
    1.0938    1.9298    1.9412
```

## Input Arguments

**`hom` — Homogeneous points**
*n*-by-*k* matrix

Homogeneous points, returned as an *n*-by-*k* matrix, containing *n* points. *k* must be greater than or equal to 2.

Example: `[0.2785 0.9575 0.1576 0.5; 0.5469 0.9649 0.9706 0.5]`

## Output Arguments

**`cart` — Cartesian coordinates**
*n*-by-(*k*-1) matrix

Cartesian coordinates, specified as an *n*-by-(*k*-1) matrix, containing *n* points. Each row of `cart` represents a point in *k*-dimensional space. *k* must be greater than or equal to 1.

Example: `[0.8147 0.1270 0.6324; 0.9058 0.9134 0.0975]`

# Version History

**Introduced in R2015a**

#### R2023a: `hom2cart` Supports 2-D Homogeneous Points

The `hom` argument now accepts 2-D homogeneous points and `hom2cart` outputs 2-D Cartesian coordinates.

## Extended Capabilities

#### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`cart2hom`

# importFactorGraph

Import factor graph from g2o log file

## Syntax

```
graph = importFactorGraph(filename)
```

## Description

`graph = importFactorGraph(filename)` imports a factor graph from the specified G2o file `filename`.

## Examples

### Import Factor Graph from G2o Log File

Import a factor graph from a G2o log file.

```
G = importFactorGraph("factorGraphLog.g2o");
```

## Input Arguments

**`filename` — Name of G2o log file**
string scalar | character vector

Name of the G2o log file to import a factor graph from, specified as a string scalar or character vector. The specified G2o log file must contain either only `'EDGE_SE2'` and `'VERTEX_SE2'` tokens, or only `'EDGE_SE3:QUAT'` and `'VERTEX_SE3:QUAT'` tokens.

## Output Arguments

**`graph` — Factor graph imported from G2o file**
`factorGraph` object

Factor graph imported from the G2o file, returned as a `factorGraph` object.

# Version History

**Introduced in R2022a**

## See Also

**Objects**
`factorGraph` | `factorGraphSolverOptions`

# estimateGravityRotation

Estimate gravity rotation using IMU measurements and factor graph optimization

## Syntax

`[gRot,info] = estimateGravityRotation(poses,gyroscopeReadings,accelerometerReadings,Name=Value)`

## Description

The `estimateGravityRotation` function estimates the gravity rotation that helps transform input poses to the local navigation reference frame of IMU using IMU measurements and factor graph optimization. The gravity rotation transforms the gravity vector from the local navigation reference frame of IMU to the pose reference frame.

The accelerometer measurements contain constant gravity acceleration that does not contribute to motion. You must remove this from the measurements for accurate fusion with other sensor data. The input pose reference frame may not always match the local navigation reference frame of IMU, North-East-Down (NED) or East-North-Up (ENU) in which the gravity direction is known. So, it is necessary to transform the input poses to the local navigation frame to remove the known gravity effect. The estimated rotation helps align the input pose reference frame and local navigation reference frame of IMU.

`[gRot,info] = estimateGravityRotation(poses,gyroscopeReadings,accelerometerReadings,Name=Value)` estimates the rotation required to transform the gravity vector from the local navigation reference frame of IMU (NED or ENU) to the input pose reference frame.

---

**Note** Input poses must be in the initial IMU reference frame unless you specify the `SensorTransform` name-value argument, then the poses can be in a different frame.

---

## Examples

### Estimate Gravity Rotation and Direction Using IMU Measurements and Factor Graph Optimization

Specify input poses in the first camera pose reference frame.

```
poses = [0.1 0 0 0.7071 0 0 0.7071; ...
         0.1 0.4755 -0.1545 0.7071 0 0 0.7071];
```

Specify 10 gyroscope and accelerometer readings between consecutive camera frames.

```
accelReadings = repmat([97.9887 -3.0315 -22.0285],10,1);
gyroReadings = zeros(10,3);
```

Specify IMU parameters.

```
params = factorIMUParameters(SampleRate=100, ...
                             ReferenceFrame="NED");
```

Specify a transformation consisting of 3-D translation and rotation to transform input poses from the initial camera pose reference frame to the initial IMU pose reference frame. Initial sensor reference frame has first sensor pose at it's origin.

```
sensorTransform = se3(eul2rotm([-pi/2 0 0]),[0 0.1 0]);
```

Specify factor graph solver options.

```
opts = factorGraphSolverOptions(MaxIterations=50);
```

Estimate gravity rotation using IMU measurements between camera pose estimates.

```
[gRot,solutionInfo] = estimateGravityRotation(poses, ...
                      {gyroReadings},{accelReadings}, ...
                      IMUParameters=params, ...
                      SensorTransform=sensorTransform, ...
                      SolverOptions=opts)
```

```
gRot = 3×3

    0.0058   -0.6775   -0.7355
    0.1023    0.7320   -0.6736
    0.9947   -0.0713    0.0736


solutionInfo = struct with fields:
             InitialCost: 2.3123e+03
               FinalCost: 19.0067
      NumSuccessfulSteps: 23
    NumUnsuccessfulSteps: 18
               TotalTime: 0.0030
         TerminationType: 0
        IsSolutionUsable: 1
```

Use gravity rotation to transform gravity vector from local navigation frame to initial camera pose reference frame.

```
% gravity direction in NED frame is along Z-Axis.
gravityDirectionNED = [0; 0; 1];
% gravity direction in pose reference frame.
gravityDirection = gRot*gravityDirectionNED
```

```
gravityDirection = 3×1

   -0.7355
   -0.6736
    0.0736
```

```
% gravity vector in pose reference frame.
gravityMagnitude = 9.81;
gravity = gravityDirection*gravityMagnitude
```

```
gravity = 3×1
```

```
-7.2149
-6.6076
 0.7221
```

## Input Arguments

**`poses` — Camera or lidar poses**
*N*-by-7 matrix | array of `se3` objects | table | array of `rigidtform3d` objects

Camera or lidar poses, with similar metric units as IMU measurements estimated by stereo-visual-inertial or lidar-inertial systems, respectively, specified as one of these pose types:

- *N*-by-7 matrix, where each row is of the form [*x y z qw qx qy qz*]. Each row defines the *xyz*-position, in meters, and quaternion orientation, [*qw qx qy qz*].
- Array of `se3` objects.
- Camera pose table returned by the `poses` function of the `imageviewset` object.
- Array of `rigidtform3d` objects.

**`gyroscopeReadings` — Gyroscope readings between consecutive camera views or poses**
cell array of *N*-by-3 matrices

Gyroscope readings between consecutive camera views or poses, specified as a cell array of *N*-by-3 matrices, in radians per second. *N* is the number of samples, and the three columns of `gyroscopeReadings` represent the [*x y z*] measurements.

Data Types: `cell`

**`accelerometerReadings` — Accelerometer readings between consecutive camera views or poses**
cell array of *N*-by-3 matrices

Accelerometer readings between consecutive camera views or poses, specified as a cell array of *N*-by-3 matrices, in meters per second squared. *N* is the number of samples, and the three columns of `accelerometerReadings` represent the [*x y z*] measurements.

Data Types: `cell`

### Name-Value Pair Arguments

Specify optional pairs of arguments as `Name1=Value1,...,NameN=ValueN`, where `Name` is the argument name and `Value` is the corresponding value. Name-value arguments must appear after other arguments, but the order of the pairs does not matter.

Example: `estimateGravityRotation(poses,gyroscopeReadings,accelerometerReadings,IMUParameters=factorIMUParameters(SampleRate=100))` estimates the gravity rotation based on an IMU.

**`IMUParameters` — IMU parameters**
`factorIMUParameters()` (default) | `factorIMUParameters` object

IMU parameters, specified as a `factorIMUParameters` object.

Example: `IMUParameters=factorIMUParameters(SampleRate=100)`

**`SolverOptions` — Solver options**
`factorGraphSolverOptions()` (default) | `factorGraphSolverOptions` object

Solver options, specified as a `factorGraphSolverOptions` object.

Example: `SolverOptions=factorGraphSolverOptions(MaxIterations=50)`

**`SensorTransform` — Transformation consisting of 3-D translation and rotation to transform pose or point in input pose reference frame to initial IMU frame**
`se3()` (default) | `se3` object

Transformation consisting of 3-D translation and rotation to transform a quantity like a pose or a point in the input pose reference frame to the initial IMU sensor reference frame, specified as a `se3` object.

For example, if the input poses are camera poses in the initial camera sensor reference frame, then the sensor transform rotates and translates a pose or a point in the initial camera sensor reference frame to the initial IMU sensor reference frame. The initial sensor reference frame has the very first sensor pose at its origin.

Example: `SensorTransform=se3(eul2rotm([-pi/2,0,0]),[0,0.1,0])`

## Output Arguments

**`gRot` — Gravity rotation**
3-by-3 matrix | `se3` object | `rigidtform3d` object

Gravity rotation, returned as a 3-by-3 matrix, `se3` object, or `rigidtform3d` object similar to input pose type. It contains the rotation required to transform the gravity vector from the local navigation reference frame of IMU (NED or ENU) to the input pose reference frame.

**`info` — Factor graph optimization solution information**
structure

Factor graph optimization solution information, returned as a structure. The fields of the structure are:

| Field | Description |
| --- | --- |
| `InitialCost` | Initial cost of the non-linear least squares problem formulated by the factor graph before the optimization. |
| `FinalCost` | Final cost of the non-linear least squares problem formulated by the factor graph after the optimization.<br><br>**Note** Cost is the sum of error terms, known as residuals, where each residual is a function of a subset of factor measurements. |

| Field | Description |
|---|---|
| NumSuccessfulSteps | Number of iterations in which the solver decreases the cost. This value includes the initialization iteration at 0 in addition to the minimizer iterations. |
| NumUnsuccessfulSteps | Number of iterations in which the iteration is numerically invalid or the solver does not decrease the cost. |
| TotalTime | Total solver optimization time in seconds. |
| TerminationType | Termination type as an integer in the range [0, 2]:<br>• 0 — Solver found a solution that meets convergence criterion and decreases in cost after optimization.<br>• 1 — Solver could not find a solution that meets convergence criterion after running for the maximum number of iterations.<br>• 2 — Solver terminated due to an error. |
| IsSolutionUsable | Solution is usable if 1 (true), not usable if 0 (false). |

Use this information to check whether the optimization required for alignment has converged or not.

Data Types: struct

# Version History

**Introduced in R2023a**

## References

[1] Campos, Carlos, Richard Elvira, Juan J. Gomez Rodriguez, Jose M. M. Montiel, and Juan D. Tardos. "ORB-SLAM3: An Accurate Open-Source Library for Visual, Visual–Inertial, and Multimap SLAM." IEEE Transactions on Robotics 37, no. 6 (December 2021): 1874–90. https://doi.org/10.1109/TRO.2021.3075644.

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

factorIMU | factorIMUParameters | estimateGravityRotationAndPoseScale

# estimateGravityRotationAndPoseScale

Estimate gravity rotation and pose scale using IMU measurements and factor graph optimization

## Syntax

```
[gRot,scale,info] = estimateGravityRotationAndPoseScale(poses,
gyroscopeReadings,accelerometerReadings,Name=Value)
```

## Description

The `estimateGravityRotationAndPoseScale` function estimates the gravity rotation and pose scale that helps in transforming input poses to the local navigation reference frame of IMU using IMU measurements and factor graph optimization. The gravity rotation transforms the gravity vector from the local navigation reference frame of IMU to the pose reference frame. The pose scale brings input poses to the metric scale, similar to IMU measurements.

The accelerometer measurements contain constant gravity acceleration that does not contribute to motion. You must remove this from the measurements for accurate fusion with other sensor data. The input pose reference frame may not always match the local navigation reference frame of IMU, North-East-Down (NED) or East-North-Up (ENU) in which the gravity direction is known. So, it is necessary to transform the input poses to the local navigation frame to remove the known gravity effect. The estimated rotation helps in transforming the input pose reference frame to the local navigation reference frame of IMU.

Monocular camera sensor-based structure from motion (SfM) estimates poses at an unknown scale different from metric measurements obtained by an IMU. The accelerometer readings help estimate scale factor to bring input poses to metric scale similar to IMU measurements.

`[gRot,scale,info] = estimateGravityRotationAndPoseScale(poses,
gyroscopeReadings,accelerometerReadings,Name=Value)` estimates the rotation required to transform the gravity vector from the local navigation reference frame of IMU (NED or ENU) to the input pose reference frame. The function also estimates scale, so input poses at an unknown scale can be converted to metric units similar to those in the IMU measurements.

**Note** Input poses must be in the initial IMU reference frame unless you specify the `SensorTransform` name-value argument, then the poses can be in a different frame.

## Examples

### Estimate Gravity Rotation and Direction and Pose Scale Using IMU Measurements and Factor Graph Optimization

Specify input poses in the initial camera pose reference frame.

```
poses = [0.1 0 0 0.7071 0 0 0.7071; ...
         0.1 0.4755 -0.1545 0.7071 0 0 0.7071];
```

Specify 10 gyroscope and accelerometer readings between consecutive camera frames.

```
accelReadings = repmat([97.9887 -3.0315 -22.0285],10,1);
gyroReadings = zeros(10,3);
```

Specify IMU parameters.

```
params = factorIMUParameters(SampleRate=100, ...
                             ReferenceFrame="NED");
```

Specify a transformation consisting of 3-D translation and rotation to transform poses from the initial camera pose reference frame to the initial IMU pose reference frame.

```
sensorTransform = se3(eul2rotm([-pi/2 0 0]),[0 0.1 0]);
```

Specify factor graph solver options.

```
opts = factorGraphSolverOptions(MaxIterations=50);
```

Estimate the gravity rotation and pose scale using IMU measurements between camera frames.

```
[gRot,scale,solutionInfo] = estimateGravityRotationAndPoseScale(poses, ...
                            {gyroReadings},{accelReadings}, ...
                            IMUParameters=params, ...
                            SensorTransform=sensorTransform, ...
                            SolverOptions=opts)
```

```
gRot = 3×3

    0.9804   -0.0654   -0.1856
   -0.1765    0.1251   -0.9763
    0.0871    0.9900    0.1111


scale = 0.7357

solutionInfo = struct with fields:
             InitialCost: 2.3123e+03
               FinalCost: 27.9808
      NumSuccessfulSteps: 30
    NumUnsuccessfulSteps: 21
               TotalTime: 0.0267
         TerminationType: 1
        IsSolutionUsable: 1
```

Use gravity rotation to transform gravity vector from local navigation frame to initial camera pose reference frame.

```
% gravity direction in NED frame is along Z-Axis.
gravityDirectionNED = [0; 0; 1];
% gravity direction in pose reference frame.
gravityDirection = gRot*gravityDirectionNED
```

```
gravityDirection = 3×1

   -0.1856
   -0.9763
    0.1111
```

```
% gravity vector in pose reference frame.
gravityMagnitude = 9.81;
gravity = gravityDirection*gravityMagnitude

gravity = 3×1

   -1.8210
   -9.5777
    1.0900
```

## Input Arguments

**poses — Camera poses**
*N*-by-7 matrix | array of `se3` objects | table | array of `rigidtform3d` objects

Camera poses, at an unknown scale estimated by monocular camera-based structure from motion (SfM), specified as one of these pose types:

- *N*-by-7 matrix, where each row is of the form [*x y z qw qx qy qz*]. Each row defines the *xyz*-position, in meters, and quaternion orientation, [*qw qx qy qz*].
- Array of `se3` objects.
- Camera pose table returned by the `poses` function of the `imageviewset` object.
- Array of `rigidtform3d` objects.

**gyroscopeReadings — Gyroscope readings between consecutive camera views or poses**
cell array of *N*-by-3 matrices

Gyroscope readings between consecutive camera views or poses, specified as a cell array of *N*-by-3 matrices, in radians per second. *N* is the number of samples, and the three columns of `gyroscopeReadings` represent the [*x y z*] measurements.

Data Types: `cell`

**accelerometerReadings — Accelerometer readings between consecutive camera views or poses**
cell array of *N*-by-3 matrices

Accelerometer readings between consecutive camera views or poses, specified as a cell array of *N*-by-3 matrices, in meters per second squared. *N* is the number of samples, and the three columns of `accelerometerReadings` represent the [*x y z*] measurements.

Data Types: `cell`

### Name-Value Pair Arguments

Specify optional pairs of arguments as `Name1=Value1,...,NameN=ValueN`, where `Name` is the argument name and `Value` is the corresponding value. Name-value arguments must appear after other arguments, but the order of the pairs does not matter.

Example: `estimateGravityRotationAndPoseScale(poses,gyroscopeReadings,accelerometerReadings,IMUParameters=factorIMUParameters(SampleRate=100))` estimates the gravity rotation based on an IMU.

**`IMUParameters` — IMU parameters**
`factorIMUParameters()` (default) | `factorIMUParameters` object

IMU parameters, specified as a `factorIMUParameters` object.

Example: `IMUParameters=factorIMUParameters(SampleRate=100)`

**`SolverOptions` — Solver options**
`factorGraphSolverOptions()` (default) | `factorGraphSolverOptions` object

Solver options, specified as a `factorGraphSolverOptions` object.

Example: `SolverOptions=factorGraphSolverOptions(MaxIterations=50)`

**`SensorTransform` — Transformation consisting of 3-D translation and rotation to transform pose or point in input pose reference frame to initial IMU frame**
`se3()` (default) | `se3` object

Transformation consisting of 3-D translation and rotation to transform a quantity like a pose or a point in the input pose reference frame to the initial IMU sensor reference frame, specified as a `se3` object.

For example, if the input poses are camera poses in the initial camera sensor reference frame, then the sensor transform rotates and translates a pose or a point in the initial camera sensor reference frame to the initial IMU sensor reference frame. The initial sensor reference frame has the very first sensor pose at its origin.

Example: `SensorTransform=se3(eul2rotm([-pi/2,0,0]),[0,0.1,0])`

## Output Arguments

**`gRot` — Gravity rotation**
3-by-3 matrix | `se3` object | `rigidtform3d` object

Gravity rotation, returned as a 3-by-3 matrix, `se3` object, or `rigidtform3d` object similar to input pose type. It contains the rotation required to transform the gravity vector from the local navigation reference frame of IMU (NED or ENU) to the input pose reference frame.

**`scale` — Multiplier by which to scale input poses**
numeric scalar

Multiplier by which to scale the input poses, returned as a numeric scalar. Use this value to scale the input poses to the same metric units as the IMU measurements.

Data Types: `double`

**`info` — Factor graph optimization solution information**
structure

Factor graph optimization solution information, returned as a structure. The fields of the structure are:

| Field | Description |
| --- | --- |
| InitialCost | Initial cost of the non-linear least squares problem formulated by the factor graph before the optimization. |
| FinalCost | Final cost of the non-linear least squares problem formulated by the factor graph after the optimization.<br><br>**Note** Cost is the sum of error terms, known as residuals, where each residual is a function of a subset of factor measurements. |
| NumSuccessfulSteps | Number of iterations in which the solver decreases the cost. This value includes the initialization iteration at 0 in addition to the minimizer iterations. |
| NumUnsuccessfulSteps | Number of iterations in which the iteration is numerically invalid or the solver does not decrease the cost. |
| TotalTime | Total solver optimization time in seconds. |
| TerminationType | Termination type as an integer in the range [0, 2]:<br>• 0 — Solver found a solution that meets convergence criterion and decreases in cost after optimization.<br>• 1 — Solver could not find a solution that meets convergence criterion after running for the maximum number of iterations.<br>• 2 — Solver terminated due to an error. |
| IsSolutionUsable | Solution is usable if 1 (true), not usable if 0 (false). |

Use this information to check whether the optimization required for alignment has converged or not.

Data Types: struct

# Version History

**Introduced in R2023a**

## References

[1] Campos, Carlos, Richard Elvira, Juan J. Gomez Rodriguez, Jose M. M. Montiel, and Juan D. Tardos. “ORB-SLAM3: An Accurate Open-Source Library for Visual, Visual–Inertial, and Multimap SLAM.” IEEE Transactions on Robotics 37, no. 6 (December 2021): 1874–90. https://doi.org/10.1109/TRO.2021.3075644.

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

`factorIMU` | `factorIMUParameters` | `estimateGravityRotation`

# importOccupancyMap3D

Import octree or binary tree file as 3-D occupancy map

## Syntax

```
map3D = importOccupancyMap3D(mapPath)
```

## Description

`map3D = importOccupancyMap3D(mapPath)` imports the octree file (`.ot`) or binary tree file (`.bt`) specified at the relative or absolute file path, `mapPath`

## Examples

### Check Occupancy Status and Get Occupancy Values in 3-D Occupancy Map

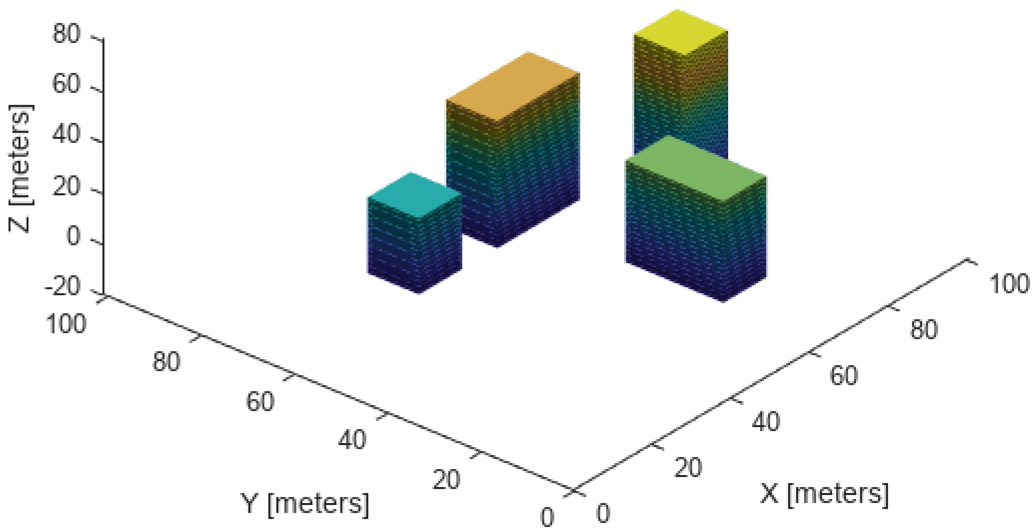
Import a 3-D occupancy map.

```
map3D = importOccupancyMap3D("citymap.ot")
```

```
map3D = 
  occupancyMap3D with properties:

    ProbabilitySaturation: [1.0000e-03 0.9990]
               Resolution: 1
        OccupiedThreshold: 0.6500
            FreeThreshold: 0.2000
```

Display the map.

```
show(map3D)
```




Check the occupancy statuses of different locations and get their occupancy values.

```
iOccVal1 = checkOccupancy(map3D,[50 15 0])
```

```
iOccVal1 = 0
```

```
OccVal1 = getOccupancy(map3D,[50 15 0])
```

```
OccVal1 = 0.0019
```

```
iOccVal2 = checkOccupancy(map3D,[50 15 15])
```

```
iOccVal2 = 1
```

```
OccVal2 = getOccupancy(map3D,[50 15 15])
```

```
OccVal2 = 0.6500
```

```
iOccVal3 = checkOccupancy(map3D,[50 15 45])
```

```
iOccVal3 = -1
```

```
OccVal3 = getOccupancy(map3D,[50 15 45])
```

```
OccVal3 = 0.5000
```

## Input Arguments

**`mapPath` — Absolute or relative path to octree or binary tree file**
string scalar | character vector

Absolute or relative path to octree file (`.ot`) or binary tree file (`.bt`) , specified as a string scalar or character vector.

Example: `"path/to/file/map.ot"`

Data Types: `char` | `string`

## Output Arguments

**`map3D` — 3-D occupancy map**
`occupancyMap3D` object

3-D occupancy map, specified as a `occupancyMap3D` object.

# Version History

**Introduced in R2020a**

## See Also

**Classes**
`occupancyMap3D` | `lidarSLAM` | `occupancyMap`

**Functions**
`insertPointCloud` | `inflate` | `setOccupancy` | `show`

# info

Read update rate, GPS lock information and number of satellites in view for the GPS receiver

## Syntax

```
gpsInfo = info(gps)
```

## Description

`gpsInfo = info(gps)` returns the update rate of the GPS receiver, GPS lock information and number of satellites from which the GPS can read signals. `info` gets updated after every execution of `read` command.

## Examples

### Read Information from GPS Receiver

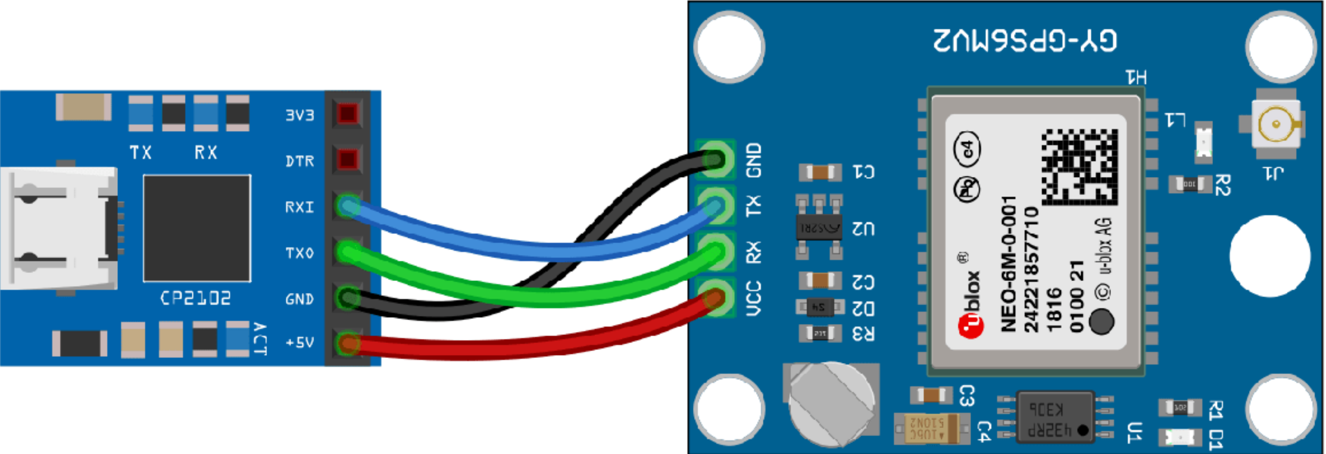
Read information from the GPS receiver connected to the host computer on a specific serial port.

#### Required Hardware

To run this example, you need:

- UBlox Neo-6M GPS module
- GPS antenna
- USB to UART module
- USB cable
- Connecting wires

#### Hardware Connection



Connect the pins on the UBlox Neo-6M GPS module to the pins on your USB to UART module. The connections are:

- VCC - +5V
- RX - TXO
- TX - RXI
- GND - GND

Connect the GPS antenna to the GPS module. Connect the USB to UART module to the host computer with a USB cable. GPS Fix can be easily acquired in locations that have a clear view of the sky. Wait for the GPS module to acquire satelite signals (Fix).This can be verified by checking the Fix LED (D1) of your GPS module.

**Create GPS Object**

Create a `gpsdev` object for the GPS receiver connected to a specific port.

```
gps = gpsdev('COM4')
```

```
gps =
  gpsdev with properties:

                         SerialPort: COM4
                           BaudRate: 9600 (bits/s)

                     SamplesPerRead: 1
                           ReadMode: "latest"
                        SamplesRead: 0
Show all properties all functions
```

**Read the GPS Module Information**

Read the GPS module information and return them as a structure.

```
gpsInfo = info(gps)
```

```
gpsInfo = struct with fields:
          UpdateRate: []
           GPSLocked: 0
    SatellitesInView: 0
```

**Clean Up**

When the connection is no longer needed, clear the associated object.

```
delete(gps);
clear gps;
```

## Input Arguments

**gps — GPS sensor**
gpsdev object

The GPS sensor, specified as a `gpsdev` object.

## Output Arguments

**`gpsInfo` — GPS module information**
structure

GPS module information such as update rate, and number of satellites. The output has three fields:

- `UpdateRate` — Update Rate of the GPS Module in Hz. Update Rate of GPS receiver is estimated from the difference in time at which two RMC sentences are obtained. This value might be slightly varying from actual Update Rate of the module.
- `GPSLocked` — This property specifies if GPS has enough information to get valid data. GPS signals are acquired easily in locations that have a clear view of the sky. It can be either a `0` or `1` (logical). If `GPSLocked` is `0`, the GPS does not have the lock to compute location or time information. If `GPSLocked` is `1`, GPS module has enough data to compute location or time information.
- `NumberOfSatellitesInView` — Number of satellites from which the GPS module can read the signals.

Data Types: `struct`

# Version History

**Introduced in R2020b**

## See Also

**Objects**
`gpsdev`

**Functions**
`flush` | `release` | `read` | `writeBytes`

# insfilter

Create inertial navigation filter

## Syntax

```
filter = insfilter
filter = insfilter('ReferenceFrame',RF)
```

## Description

`filter = insfilter` returns an `insfilterMARG` inertial navigation filter object that estimates pose based on accelerometer, gyroscope, GPS, and magnetometer measurements. See `insfilterMARG` for more details.

`filter = insfilter('ReferenceFrame',RF)` returns an `insfilterMARG` inertial navigation filter object that estimates pose relative to a reference frame specified by `RF`. Specify `RF` as `'NED'` (North-East-Down) or `'ENU'` (East-North-Up). The default value is `'NED'`. See `insfilterMARG` for more details.

## Examples

### Create Default INS Filter

The default INS filter is the `insfilterMARG` object. Call `insfilter` with no input arguments to create the default INS filter.

```
filter = insfilter
```

```
filter = 
  insfilterMARG with properties:

        IMUSampleRate: 100               Hz
    ReferenceLocation: [0 0 0]           [deg deg m]
                State: [22x1 double]
      StateCovariance: [22x22 double]

   Multiplicative Process Noise Variances
           GyroscopeNoise: [1e-09 1e-09 1e-09]       (rad/s)²
       AccelerometerNoise: [0.0001 0.0001 0.0001]    (m/s²)²
       GyroscopeBiasNoise: [1e-10 1e-10 1e-10]       (rad/s)²
    AccelerometerBiasNoise: [0.0001 0.0001 0.0001]    (m/s²)²

   Additive Process Noise Variances
    GeomagneticVectorNoise: [1e-06 1e-06 1e-06]    uT²
     MagnetometerBiasNoise: [0.1 0.1 0.1]          uT²
```

# Version History

**Introduced in R2018b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`imufilter` | `ahrsfilter` | `insfilterErrorState` | `insfilterAsync` | `insfilterNonholonomic` | `insfilterMARG`

# interpolate

Interpolate poses along path segment

## Syntax

```
poses = interpolate(pathSeg)
poses = interpolate(pathSeg,lengths)
[poses,directions] = interpolate( ___ )
```

## Description

`poses = interpolate(pathSeg)` interpolates along the path segment at the transitions between motion types.

`poses = interpolate(pathSeg,lengths)` interpolates along the path segment at the specified lengths along the path. Transitions between motion types are always included.

`[poses,directions] = interpolate( ___ )` also returns the direction of motion along the path for each section as a vector of 1s (forward) and –1s (reverse) using the previous inputs.

## Examples

### Interpolate Poses For Dubins Path

Create a `dubinsConnection` object.

```
dubConnObj = dubinsConnection;
```

Define start and goal poses as `[x y theta]` vectors.

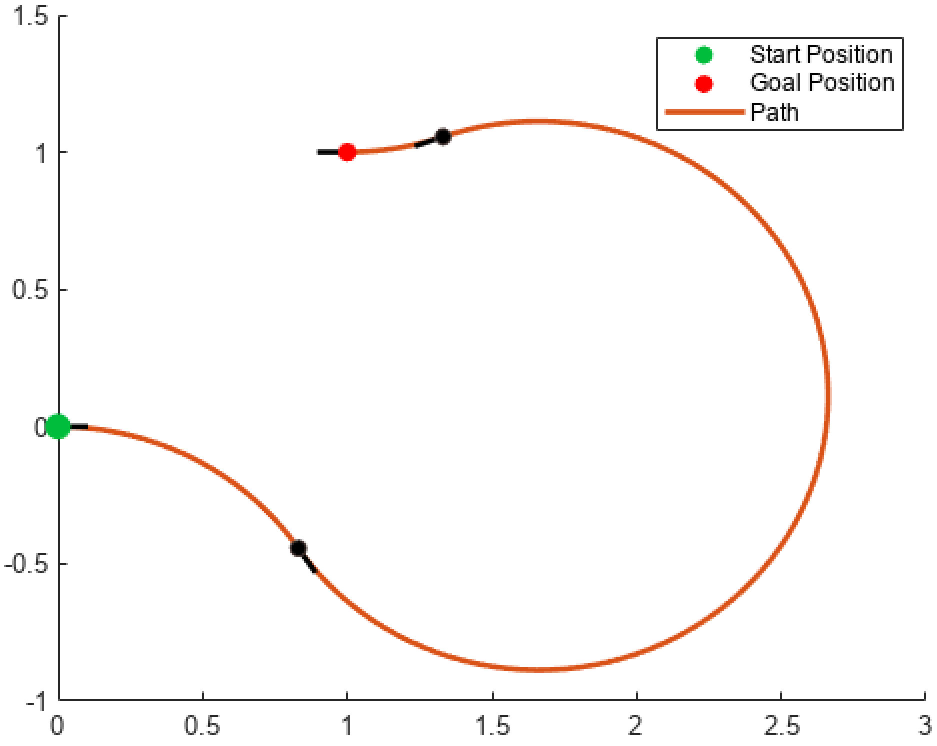
```
startPose = [0 0 0];
goalPose = [1 1 pi];
```

Calculate a valid path segment to connect the poses.

```
[pathSegObj,pathCosts] = connect(dubConnObj,startPose,goalPose);
```

Show the generated path.

```
show(pathSegObj{1})
```



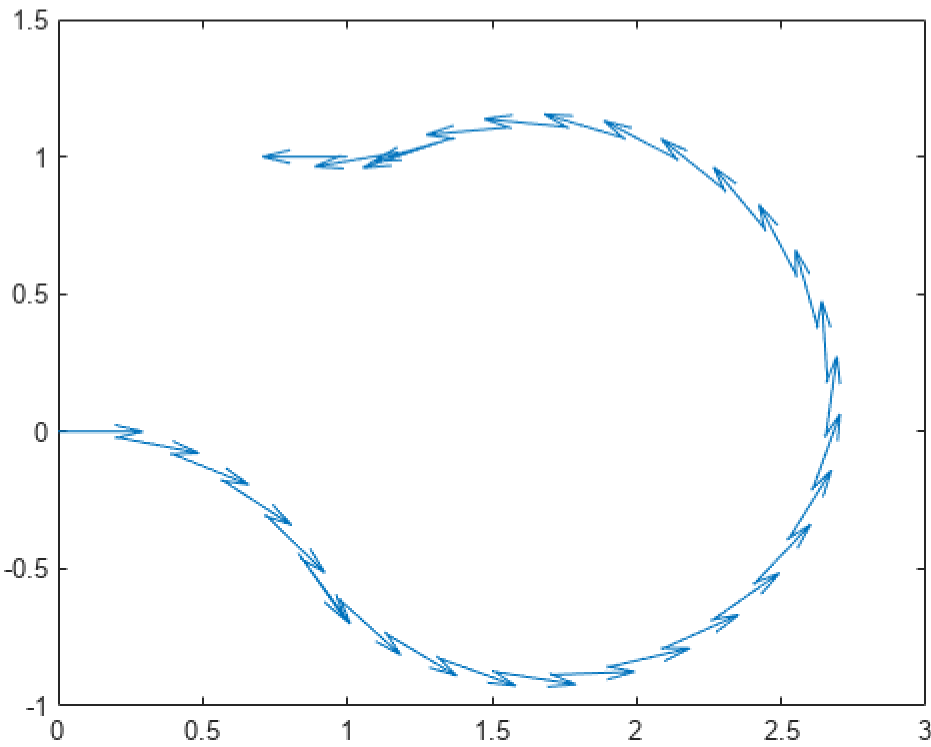

Interpolate poses along the path. Get a pose every 0.2 meters, including the transitions between turns.

```
length = pathSegObj{1}.Length;
poses = interpolate(pathSegObj{1},0:0.2:length)
```

```
poses = 32×3

         0         0         0
    0.1987   -0.0199    6.0832
    0.3894   -0.0789    5.8832
    0.5646   -0.1747    5.6832
    0.7174   -0.3033    5.4832
    0.8309   -0.4436    5.3024
    0.8418   -0.4595    5.3216
    0.9718   -0.6110    5.5216
    1.1293   -0.7337    5.7216
    1.3081   -0.8226    5.9216
      ⋮
```

Use the `quiver` function to plot these poses.

```
quiver(poses(:,1),poses(:,2),cos(poses(:,3)),sin(poses(:,3)),0.5)
```




## Input Arguments

**pathSeg — Path segment**
dubinsPathSegment object | reedsSheppPathSegment object

Path segment, specified as a `dubinsPathSegment` or `reedsSheppPathSegment` object.

**lengths — Lengths along path to interpolate at**
positive numeric vector

Lengths along path to interpolate at, specified as a positive numeric vector. For example, specify `[0:0.1:pathSegObj{1}.Length]` to interpolate at every 0.1 meters along the path. Transitions between motion types are always included.

## Output Arguments

**poses — Interpolated poses**
[*x*, *y*, *Θ*] matrix

This property is read-only.

Interpolated poses along the path segment, specified as an [*x*, *y*, *Θ*] matrix. Each row of the matrix corresponds to a different interpolated pose along the path.

*x* and *y* are in meters. *Θ* is in radians.

**`directions` — Directions of motion**
vector of 1s (forward) and –1s (reverse)

Directions of motion for each segment of the interpolated path, specified as a vector of 1s (forward) and –1s (reverse).

# Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Functions

`connect` | `show`

### Objects

`dubinsConnection` | `dubinsPathSegment` | `reedsSheppConnection` | `reedsSheppPathSegment`

# lla2enu

Transform geodetic coordinates to local east-north-up coordinates

## Syntax

```
xyzENU = lla2enu(lla,lla0,method)
```

## Description

`xyzENU = lla2enu(lla,lla0,method)` transforms the geodetic coordinates `lla` to local east-north-up (ENU) Cartesian coordinates `xyzENU`. Specify the origin of the local ENU system as the geodetic coordinates `lla0`.

**Note**

- The latitude and longitude values in the geodetic coordinate system use the World Geodetic System of 1984 (WGS84) standard.
- Specify altitude as height in meters above the WGS84 reference ellipsoid.

## Examples

### Transform Geodetic Coordinates to ENU Coordinates

Specify the geodetic coordinates of the local origin in Zermatt, Switzerland.

```
lla0 = [46.017 7.750 1673]; % [lat0 lon0 alt0]
```

Specify the geodetic coordinates of a point of interest. In this case, the point of interest is the Matterhorn.

```
lla = [45.976 7.658 4531]; % [lat lon alt]
```

Transform the geodetic coordinates to local ENU coordinates using flat earth approximation.

```
xyzENU = lla2enu(lla,lla0,'flat')
```

```
xyzENU = 1×3
10³ ×

   -7.1244   -4.5572    2.8580
```

## Input Arguments

**`lla` — Geodetic coordinates**
three-element row vector | *n*-by-3 matrix

Geodetic coordinates, specified as a three-element row vector or an *n*-by-3 matrix. *n* is the number of points to transform. Specify each point in the form `[lat lon alt]`. *lat* and *lon* specify the latitude and longitude respectively in degrees. *alt* specifies the altitude in meters.

Example: `[45.976 7.658 4531]`

Data Types: `double`

**`lla0` — Origin of local ENU system in geodetic coordinates**
three-element row vector | *n*-by-3 matrix

Origin of the local ENU system in the geodetic coordinates, specified as a three-element row vector or an *n*-by-3 matrix. *n* is the number of origin points. Specify each point in the form `[lat0 lon0 alt0]`. *lat0* and *lon0* specify the latitude and longitude of the origin, respectively, in degrees. *alt0* specifies the altitude of the origin in meters.

Example: `[46.017 7.750 1673]`

Data Types: `double`

**`method` — Transformation method**
`'flat'` | `'ellipsoid'`

Transformation method, specified as `'flat'` or `'ellipsoid'`. This argument specifies whether the function assumes the planet is flat or ellipsoidal.

The flat Earth transformation method has these limitations:

- Assumes that the flight path and bank angle are zero.
- Assumes that the flat Earth *z*-axis is normal to the Earth at only the initial geodetic latitude and longitude. This method has higher accuracy over small distances from the initial geodetic latitude and longitude, and closer to the equator. The method calculates a longitude with higher accuracy when the variation in latitude is smaller.
- Latitude values of +90 and -90 degree may return unexpected values because of singularity at the poles.

Data Types: `char` | `string`

## Output Arguments

**`xyzENU` — Local ENU Cartesian coordinates**
three-element row vector | *n*-by-3 matrix

Local ENU Cartesian coordinates, returned as a three-element row vector or an *n*-by-3 matrix. *n* is the number of transformed points. Each point is in the form `[xEast yNorth zUp]`. *xEast*, *yNorth*, and *zUp* are the respective *x*-, *y*-, and *z*-coordinates, in meters, of the point in the local ENU system.

Data Types: `double`

# Version History

**Introduced in R2021a**

## Extended Capabilities

### C/C++ Code Generation
Generate C and C++ code using MATLAB® Coder™.

## See Also

### Functions
`enu2lla` | `lla2ned` | `ned2lla`

# lla2ned

Transform geodetic coordinates to local north-east-down coordinates

## Syntax

```
xyzNED = lla2ned(lla,lla0,method)
```

## Description

`xyzNED = lla2ned(lla,lla0,method)` transforms the geodetic coordinates `lla` to local north-east-down (NED) Cartesian coordinates `xyzNED`. Specify the origin of the local NED system as the geodetic coordinates `lla0`.

**Note**

- The latitude and longitude values in the geodetic coordinate system use the World Geodetic System of 1984 (WGS84) standard.
- Specify altitude as height in meters above the WGS84 reference ellipsoid.

## Examples

### Transform Geodetic Coordinates to NED Coordinates

Specify the geodetic coordinates of the local origin in Zermatt, Switzerland.

```
lla0 = [46.017 7.750 1673]; % [lat0 lon0 alt0]
```

Specify the geodetic coordinates of a point of interest. In this case, the point of interest is the Matterhorn.

```
lla = [45.976 7.658 4531]; % [lat lon alt]
```

Transform the geodetic coordinates to local NED coordinates using flat earth approximation.

```
xyzNED = lla2ned(lla,lla0,'flat')
```

```
xyzNED = 1×3
10³ ×

   -4.5572   -7.1244   -2.8580
```

## Input Arguments

**`lla` — Geodetic coordinates**
three-element row vector | *n*-by-3 matrix

Geodetic coordinates, specified as a three-element row vector or an *n*-by-3 matrix. *n* is the number of points to transform. Specify each point in the form `[lat lon alt]`. *lat* and *lon* specify the latitude and longitude respectively in degrees. *alt* specifies the altitude in meters.

Example: `[45.976 7.658 4531]`

Data Types: `double`

**`lla0` — Origin of local NED system in geodetic coordinates**
three-element row vector | *n*-by-3 matrix

Origin of the local NED system with the geodetic coordinates, specified as a three-element row vector or an *n*-by-3 matrix. *n* is the number of origin points. Specify each point in the form `[lat0 lon0 alt0]`. *lat0* and *lon0* specify the latitude and longitude respectively in degrees. *alt0* specifies the altitude in meters.

Example: `[46.017 7.750 1673]`

Data Types: `double`

**`method` — Transformation method**
`'flat'` | `'ellipsoid'`

Transformation method, specified as `'flat'` or `'ellipsoid'`. This argument specifies whether the function assumes the planet is flat or ellipsoidal.

The flat Earth transformation method has these limitations:

- Assumes that the flight path and bank angle are zero.
- Assumes that the flat Earth *z*-axis is normal to the Earth at only the initial geodetic latitude and longitude. This method has higher accuracy over small distances from the initial geodetic latitude and longitude, and closer to the equator. The method calculates a longitude with higher accuracy when the variation in latitude is smaller.
- Latitude values of +90 and -90 degree may return unexpected values because of singularity at the poles.

Data Types: `char` | `string`

## Output Arguments

**`xyzNED` — Local NED Cartesian coordinates**
three-element row vector | *n*-by-3 matrix

Local NED Cartesian coordinates, returned as a three-element row vector or an *n*-by-3 matrix. *n* is the number of transformed points. Each point is in the form `[xNorth yEast zDown]`. *xNorth*, *yEast*, and *zDown* are the respective *x*-, *y*-, and *z*-coordinates, in meters, of the point in the local NED system.

Data Types: `double`

# Version History

**Introduced in R2021a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Functions

`enu2lla` | `lla2enu` | `ned2lla`

# lookangles

Satellite look angles from receiver and satellite positions

## Syntax

```
[az,el,vis] = lookangles(recPos,satPos)
[az,el,vis] = lookangles(recPos,satPos,maskAngle)
```

## Description

`[az,el,vis] = lookangles(recPos,satPos)` returns the look angles and visibilities of satellite positions for a given receiver position. The azimuth `az` and elevation `el` are the look angles in degrees in the Earth-centered Earth-fixed (ECEF) coordinate system. The visibility of the satellites `vis` is a logical array that the function calculates using the default receiver mask angle of 10 degrees.

`[az,el,vis] = lookangles(recPos,satPos,maskAngle)` returns the look angles and visibilities of satellites with a specified mask angle `maskAngle` in degrees.

## Examples

### Get Satellite Look Angles for Receiver Position

Use the `lookangles` function to get the azimuth and elevation angles of satellites for given satellite and receiver positions. Specify a mask angle of 5 degrees. Get the satellite positions using the `gnssconstellation` function.

Specify a receiver position in geodetic coordinates (latitude, longitude, altitude).

```
recPos = [42 -71 50];
```

Get the satellite positions for the current time.

```
t = datetime('now');
gpsSatPos = gnssconstellation(t);
```

Specify a mask angle of 5 degrees.

```
maskAngle = 5;
```

Get the azimuth and elevation look angles for the satellite positions. The `vis` output indicates which satellites are visible. Get the total using `nnz`.

```
[az,el,vis] = lookangles(recPos,gpsSatPos,maskAngle);
fprintf('%d satellites visible at %s.\n',nnz(vis),t);
```

```
8 satellites visible at 04-Mar-2023 01:25:04.
```

## Input Arguments

### `recPos` — Receiver position

three-element vector of the form `[lat lon alt]`

Receiver position in geodetic coordinates, specified as a three-element vector of the form *[latitude longitude altitude]*

Data Types: `single` | `double`

### `satPos` — Satellite positions

*N*-by-3 matrix of scalars

Satellite positions in the Earth-centered Earth-fixed (ECEF) coordinate system in meters, specified as an *N*-by-3 matrix of scalars. *N* is the number of satellites in the constellation.

Data Types: `single` | `double`

### `maskAngle` — Elevation mask angle

positive scalar

Elevation mask angle of the receiver, specified as a positive scalar in degrees.

Data Types: `single` | `double`

## Output Arguments

### `az` — Azimuth angles for visible satellite positions

*n*-element vector of angles

Azimuth angles for visible satellite positions, returned as an *n*-element vector of angles. *n* is the number of visible satellite positions in the plot. Azimuth angles are measured in degrees, clockwise-positive from the north direction looking down.

Example: `[25 45 182 356]`

Data Types: `double`

### `el` — Elevation angles for visible satellite positions

*n*-element vector of angles

Elevation angles for visible satellite positions, returned as an *n*-element vector of angles. *n* is the number of visible satellite positions in the plot. Elevation angles are measured from the horizon line with 90 degrees being directly up.

Example: `[45 90 27 74]`

Data Types: `double`

### `vis` — Satellite visibility

*n*-element `logical` array

Satellite visibility, returned as an *n*-element `logical` array. Each element indicates whether the satellite position given by `az` and `el` is visible.

Data Types: `logical`

# Version History

**Introduced in R2021a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
`gnssSensor` | `gpsSensor` | `imuSensor`

**Functions**
`skyplot` | `gnssconstellation` | `pseudoranges` | `receiverposition`

# ned2lla

Transform local north-east-down coordinates to geodetic coordinates

## Syntax

```
lla = ned2lla(xyzNED,lla0,method)
```

## Description

`lla = ned2lla(xyzNED,lla0,method)` transforms the local north-east-down (NED) Cartesian coordinates `xyzNED` to geodetic coordinates `lla`. Specify the origin of the local NED system as the geodetic coordinates `lla0`.

---

**Note**

- The latitude and longitude values in the geodetic coordinate system use the World Geodetic System of 1984 (WGS84) standard.
- Specify altitude as height in meters above the WGS84 reference ellipsoid.

---

## Examples

### Transform NED Coordinates to Geodetic Coordinates

Specify the geodetic coordinates of the local origin in Zermatt, Switzerland.

```
lla0 = [46.017 7.750 1673]; % [lat0 lon0 alt0]
```

Specify the NED coordinates of a point of interest, in meters. In this case, the point of interest is the Matterhorn.

```
xyzNED = [-4556.3 -7134.8 -2852.4]; % [xNorth yEast zDown]
```

Transform the local NED coordinates to geodetic coordinates using flat earth approximation.

```
lla = ned2lla(xyzNED,lla0,'flat')
```

```
lla = 1×3
10^3 ×

    0.0460    0.0077    4.5254
```

## Input Arguments

**`xyzNED` — Local NED Cartesian coordinates**
three-element row vector | *n*-by-3 matrix

Local NED Cartesian coordinates, specified as a three-element row vector or an *n*-by-3 matrix. *n* is the number of points to transform. Specify each point in the form `[xNorth yEast zDown]`. *xNorth*, *yEast*, and *zDown* are the respective *x*-, *y*-, and *z*-coordinates, in meters, of the point in the local NED system.

Example: `[-4556.3 -7134.8 -2852.4]`

Data Types: `double`

#### `lla0` — Origin of local NED system in geodetic coordinates
three-element row vector | *n*-by-3 matrix

Origin of the local NED system with the geodetic coordinates, specified as a three-element row vector or an *n*-by-3 matrix. *n* is the number of origin points. Specify each point in the form `[lat0 lon0 alt0]`. *lat0* and *lon0* specify the latitude and longitude respectively in degrees. *alt0* specifies the altitude in meters.

Example: `[46.017 7.750 1673]`

Data Types: `double`

#### `method` — Transformation method
`'flat'` | `'ellipsoid'`

Transformation method, specified as `'flat'` or `'ellipsoid'`. This argument specifies whether the function assumes the planet is flat or ellipsoidal.

The flat Earth transformation method has these limitations:

- Assumes that the flight path and bank angle are zero.
- Assumes that the flat Earth *z*-axis is normal to the Earth at only the initial geodetic latitude and longitude. This method has higher accuracy over small distances from the initial geodetic latitude and longitude, and closer to the equator. The method calculates a longitude with higher accuracy when the variation in latitude is smaller.
- Latitude values of +90 and -90 degree may return unexpected values because of singularity at the poles.

Data Types: `char` | `string`

### Output Arguments

#### `lla` — Geodetic coordinates
three-element row vector | *n*-by-3 matrix

Geodetic coordinates, returned as a three-element row vector or an *n*-by-3 matrix. *n* is the number of transformed points. Each point is in the form `[lat lon alt]`. *lat* and *lon* specify the latitude and longitude, respectively, in degrees. *alt* specifies the altitude in meters.

Data Types: `double`

## Version History
**Introduced in R2021a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Functions

`enu2lla` | `lla2enu` | `lla2ned`

# copy

Create copy of path object

## Syntax

```
path2 = copy(path1)
```

## Description

`path2 = copy(path1)` creates a copy of the path object, `path2`, from the path object, `path1`.

## Examples

### Create Copy of navPath Object

Create a `navPath` object.

```
path = navPath
```

```
path =
  navPath with properties:

      StateSpace: [1x1 stateSpaceSE2]
          States: [0x3 double]
       NumStates: 0
    MaxNumStates: Inf
```

Create copy of `navPath` object.

```
pathNew = copy(path)
```

```
pathNew =
  navPath with properties:

      StateSpace: [1x1 stateSpaceSE2]
          States: [0x3 double]
       NumStates: 0
    MaxNumStates: Inf
```

## Input Arguments

**`path1` — path object**
`navPath` object

Path object, specified as a `navPath` object.

## Output Arguments

**`path2` — path object**
`navPath` object

Path object, returned as a `navPath` object.

# Version History

**Introduced in R2019b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
`navPath`

**Functions**
`append` | `interpolate` | `pathLength`

# magcal

Magnetometer calibration coefficients

## Syntax

```
[A,b,expmfs] = magcal(D)
[A,b,expmfs] = magcal(D,fitkind)
```

## Description

`[A,b,expmfs] = magcal(D)` returns the coefficients needed to correct uncalibrated magnetometer data `D`.

To produce the calibrated magnetometer data `C`, use equation `C = (D-b)*A`. The calibrated data `C` lies on a sphere of radius `expmfs`.

`[A,b,expmfs] = magcal(D,fitkind)` constrains the matrix `A` to be the type specified by `fitkind`. Use this syntax when only the soft- or hard-iron effect needs to be corrected.

## Examples

### Correct Data Lying on Ellipsoid

Generate uncalibrated magnetometer data lying on an ellipsoid.

```
c = [-50; 20; 100]; % ellipsoid center
r = [30; 20; 50]; % semiaxis radii

[x,y,z] = ellipsoid(c(1),c(2),c(3),r(1),r(2),r(3),20);
D = [x(:),y(:),z(:)];
```

Correct the magnetometer data so that it lies on a sphere. The option for the calibration is set by default to 'auto'.

```
[A,b,expmfs] = magcal(D); % calibration coefficients
expmfs % Dipaly expected  magnetic field strength in uT
```

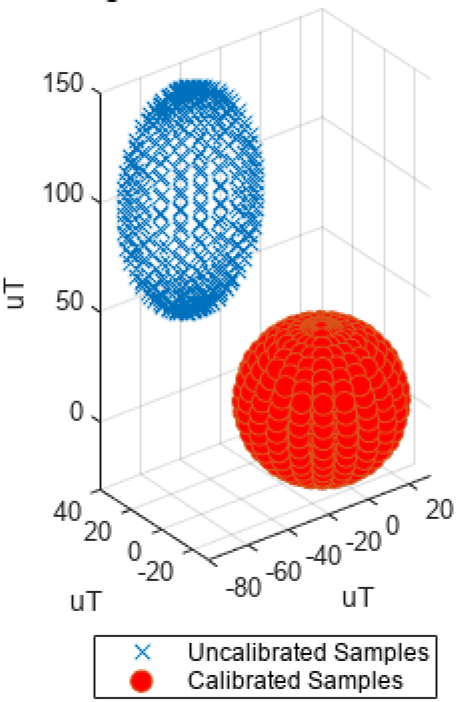
```
expmfs = 31.0723
```

```
C = (D-b)*A; % calibrated data
```

Visualize the uncalibrated and calibrated magnetometer data.

```
figure(1)
plot3(x(:),y(:),z(:),'LineStyle','none','Marker','X','MarkerSize',8)
hold on
grid(gca,'on')
plot3(C(:,1),C(:,2),C(:,3),'LineStyle','none','Marker', ...
            'o','MarkerSize',8,'MarkerFaceColor','r')
axis equal
xlabel('uT')
```

```
ylabel('uT')
zlabel('uT')
legend('Uncalibrated Samples', 'Calibrated Samples','Location', 'southoutside')
title("Uncalibrated vs Calibrated" + newline + "Magnetometer Measurements")
hold off
```




## Input Arguments

### D — Raw magnetometer data

*N*-by-3 matrix (default)

Input matrix of raw magnetometer data, specified as a *N*-by-3 matrix. Each column of the matrix corresponds to the magnetometer measurements in the first, second and third axes, respectively. Each row of the matrix corresponds to a single three-axis measurement.

Data Types: `single` | `double`

### `fitkind` — Matrix output type

'auto' (default) | 'eye' | 'diag' | 'sym'

Matrix type for output `A`. The matrix type of `A` can be constrained to:

- `'eye'` – identity matrix
- `'diag'` – diagonal

- `'sym'` – symmetric
- `'auto'` – whichever of the previous options gives the best fit

## Output Arguments

### A — Correction matrix for soft-iron effect
3-by-3 matrix

Correction matrix for the soft-iron effect, returned as a 3-by-3 matrix.

### b — Correction vector for hard-iron effect
3-by-1 vector

Correction vector for the hard-iron effect, returned as a 3-by-1 array.

### `expmfs` — Expected magnetic field strength
scalar

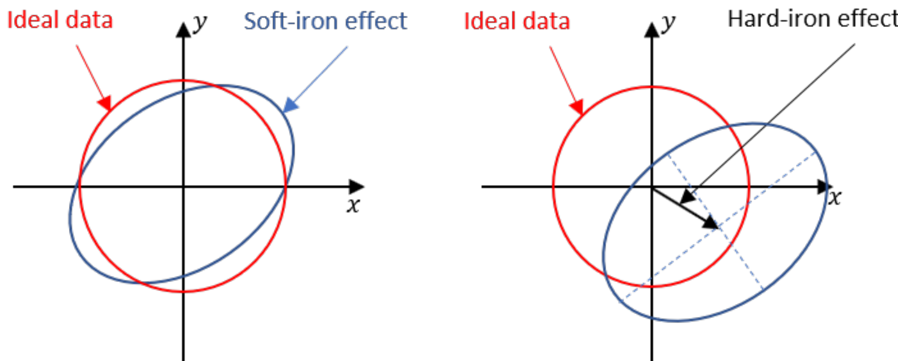
Expected magnetic filed strength, returned as a scalar.

## More About

### Soft- and Hard-Iron Effects

Because a magnetometer usually rotates through a full range of 3-D rotation, the ideal measurements from a magnetometer should form a perfect sphere centered at the origin if the magnetic field is unperturbed. However, due to distorting magnetic fields from the sensor circuit board and the surrounding environment, the spherical magnetic measurements can be perturbed. In general, two effects exist.

1. The soft-iron effect is described as the distortion of the ellipsoid from a sphere and the tilt of the ellipsoid, as shown in the left figure. This effect is caused by disturbances that influence the magnetic field but may not generate their own magnetic field. For example, metals such as nickel and iron can cause this kind of distortion.
2. The hard-iron effect is described as the offset of the ellipsoid center from the origin. This effect is produced by materials that exhibit a constant, additive field to the earth's magnetic field. This constant additive offset is in addition to the soft-iron effect as shown in the figure on the right.




The underlying algorithm in `magcal` determines the best-fit ellipsoid to the raw sensor readings and attempts to "invert" the ellipsoid to produce a sphere. The goal is to generate a correction matrix `A` to

account for the soft-iron effect and a vector `b` to account for the hard-iron effect. The three output options, 'eye', 'diag' and 'sym' correspond to three parameter-solving algorithms, and the 'auto' option chooses among these three options to give the best fit.

# Version History

**Introduced in R2019a**

### R2022b: `magcal` supports code generation

The `magcal` supports C/C++ code generation.

## References

[1] Ozyagcilar, T. "Calibrating an eCompass in the Presence of Hard and Soft-iron Interference." *Freescale Semiconductor Ltd*. 1992, pp. 1-17.

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Classes**
`magparams`

**Objects**
`imuSensor`

# mapClutter

Generate map with randomly scattered obstacles

## Syntax

```
map = mapClutter
map = mapClutter(numObst)
map = mapClutter(numObst,shapes)
map = mapClutter( ___ ,Name,Value)
```

## Description

`map = mapClutter` generates a 2-D occupancy map as a `binaryOccupancyMap` object `map`, with a width and height of 50 meters and a resolution of 5 cells per meter. The map contains 20 randomly distributed obstacles of types `Box` and `Circle`. Generated obstacles have random sizes.

`map = mapClutter(numObst)` generates a 2-D occupancy map, of the default size and resolution, with a specified number of randomly distributed obstacles, `numObst`, of default shapes.

`map = mapClutter(numObst,shapes)` generates a 2-D occupancy map, of the default size and resolution, with a specified number of obstacles, `numObst`, of specified shapes, `shapes`.

`map = mapClutter( ___ ,Name,Value)` specifies options using one or more name-value pair arguments in addition to any combination of input arguments from previous syntaxes. For example, `'MapSize',[50 30]` generates a randomly distributed obstacle map with a width of 50 meters and height of 30 meters.

## Examples

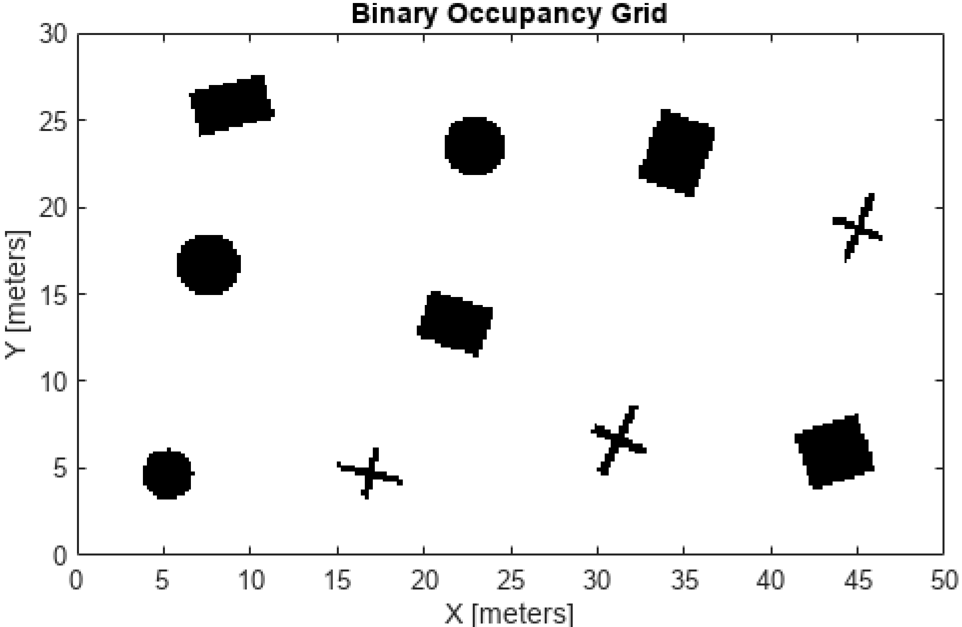
### Generate Randomly Distributed Obstacle Map

Generate a 2-D occupancy map with ten randomly scattered obstacles of types `Box`, `Circle`, and `Plus`. Specify the size of the map as 50 meters wide and 30 meters high with a resolution of 5 cells per meters.

```
map = mapClutter(10,{'Box','Plus','Circle'},'MapSize',[50 30],'MapResolution',5);
```

Visualize the generated obstacle map.

```
show(map)
```




## Input Arguments

**`numObst` — Number of obstacles**
`20` (default) | positive integer

Number of obstacles, specified as a positive integer.

Data Types: `single` | `double`

**`shapes` — Obstacle shapes**
`{'Box','Circle'}` (default) | string scalar | character vector | string array | cell array of character vectors

Obstacle shapes, specified as a string scalar, character vector, string array, or cell array of character vectors. The only valid shapes are `Box`, `Circle`, and `Plus`.

When you specify a string scalar or a character vector, the function generates a map with obstacles of only the specified shape.

Example: `"Box"`

Example: `'Box'`

When you specify a string array or a cell array of character vectors, the function generates a map with obstacles of each specified shape.

Example: ["Box","Plus"]

Example: {'Box','Plus','Circle'}

Data Types: cell | string | char

### Name-Value Pair Arguments

Specify optional pairs of arguments as Name1=Value1,...,NameN=ValueN, where Name is the argument name and Value is the corresponding value. Name-value arguments must appear after other arguments, but the order of the pairs does not matter.

*Before R2021a, use commas to separate each name and value, and enclose* Name *in quotes.*

Example: 'MapSize',[50 40] generates a randomly distributed obstacle map with a width of 50 meters and height of 40 meters.

#### MapSize — Width and height of generated map
[50 50] (default) | two-element vector of positive real finite numbers

Width and height of the generated map, specified as the comma-separated pair consisting of 'MapSize' and a two-element vector of positive real finite numbers of the form [*Width*,*Height*]. Specify both values in meters.

Example: 'MapSize',[50 30]

Data Types: single | double

#### MapResolution — Resolution of generated map
5 (default) | positive real scalar

Resolution of the generated map, specified as the comma-separated pair consisting of 'MapResolution' and a positive real scalar in cells per meter.

Example: 'MapResolution',10

Data Types: single | double

## Output Arguments

#### map — Map with randomly scattered obstacles
binaryOccupancyMap object

A map with randomly scattered obstacles, returned as a binaryOccupancyMap object.

# Version History
**Introduced in R2020b**

## Extended Capabilities

#### C/C++ Code Generation
Generate C and C++ code using MATLAB® Coder™.

## See Also

`mapMaze` | `binaryOccupancyMap` | `validatorOccupancyMap`

# mapMaze

Generate random 2-D maze map

## Syntax

```
map = mapMaze
map = mapMaze(passageWidth)
map = mapMaze(passageWidth,wallThickness)
map = mapMaze( ___ ,Name,Value)
```

## Description

`map = mapMaze` generates a random 2-D maze map, `map`, as a `binaryOccupancyMap` object with a width and height of 50 meters and a resolution of 5 cells per meter. The maze map contains straight passages, turns, and T-junctions with a passage width of 4 grid cells and wall thickness of 1 grid cell.

`map = mapMaze(passageWidth)` generates a `binaryOccupancyMap` of a maze of the default size and resolution with a specified passage width, `passageWidth`, in number of grid cells.

`map = mapMaze(passageWidth,wallThickness)` specifies a wall thickness, `wallThickness`, in number of grid cells.

`map = mapMaze( ___ ,Name,Value)` specifies options using one or more name-value pair arguments in addition to any combination of input arguments from previous syntaxes. For example, `'MapSize',[50 30]` generates a random maze map with a width of 50 meters and height of 30 meters.

## Examples

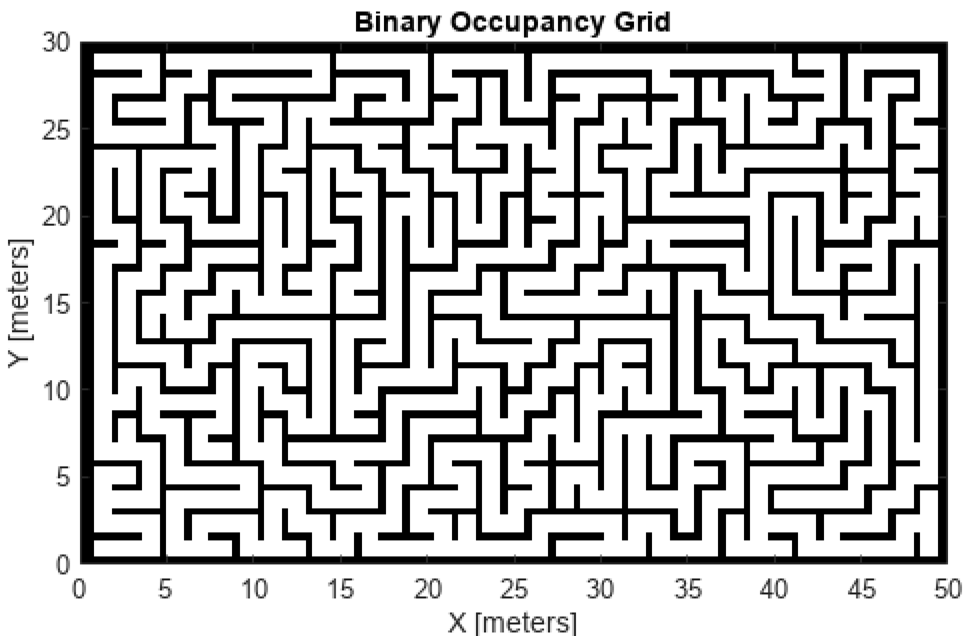
### Generate Random Maze Map

Generate a random 2-D maze map with a passage width of 5 grid cells and wall thickness of 2 grid cells. Specify the size of the map as 50 meters wide and 30 meters high with a resolution of 5 cells per meter.

```
map = mapMaze(5,2,'MapSize',[50 30],'MapResolution',5);
```

Visualize the generated obstacle map.

```
show(map)
```




## Input Arguments

**`passageWidth` — Width of maze passage**
`4` (default) | positive integer

Width of maze passage, specified as a positive integer in number of grid cells.

Data Types: `single` | `double`

**`wallThickness` — Thickness of maze wall**
`1` (default) | positive integer

Thickness of maze wall, specified as a positive integer in number of grid cells.

Data Types: `single` | `double`

### Name-Value Pair Arguments

Specify optional pairs of arguments as `Name1=Value1,...,NameN=ValueN`, where `Name` is the argument name and `Value` is the corresponding value. Name-value arguments must appear after other arguments, but the order of the pairs does not matter.

*Before R2021a, use commas to separate each name and value, and enclose* `Name` *in quotes.*

Example: `'MapSize',[50 40]` generates a randomly distributed obstacle map with a width of 50 meters and height of 40 meters.

**MapSize — Width and height of generated map**
[50 50] (default) | two-element vector of positive real finite numbers

Width and height of the generated map, specified as the comma-separated pair consisting of 'MapSize' and a two-element vector of positive real finite numbers of the form [*Width Height*]. Specify both values in meters.

Example: 'MapSize',[50 30]

Data Types: single | double

**MapResolution — Resolution of generated map**
5 (default) | positive real scalar

Resolution of the generated map, specified as the comma-separated pair consisting of 'MapResolution' and a positive real scalar in cells per meter.

Example: 'MapResolution',10

Data Types: single | double

## Output Arguments

**map — Random maze map**
binaryOccupancyMap object

Random maze map, returned as a binaryOccupancyMap object.

## Tips

- when the number of grid cells along map width could not accommodate given maze parameters, ceil(MapWidth*MapResolution) must be greater than or equal to (passageWidth +2*wallThickness).
- when the number of grid cells along map height could not accommodate given maze parameters, ceil(MapHeight*MapResolution) must be greater than or equal to (passageWidth +2*wallThickness).

# Version History

**Introduced in R2021a**

## See Also

mapClutter | binaryOccupancyMap | validatorOccupancyMap

# matchScans

Estimate pose between two laser scans

## Syntax

```
pose = matchScans(currScan,refScan)
pose = matchScans(currRanges,currAngles,refRanges,refAngles)
[pose,stats] = matchScans( ___ )
[ ___ ] = matchScans( ___ ,Name,Value)
```

## Description

`pose = matchScans(currScan,refScan)` finds the relative pose between a reference `lidarScan` and a current `lidarScan` object using the normal distributions transform (NDT).

`pose = matchScans(currRanges,currAngles,refRanges,refAngles)` finds the relative pose between two laser scans specified as ranges and angles.

`[pose,stats] = matchScans( ___ )` returns additional statistics about the scan match result using the previous input arguments.

`[ ___ ] = matchScans( ___ ,Name,Value)` specifies additional options specified by one or more `Name,Value` pair arguments.

## Examples

### Match Lidar Scans

Create a reference lidar scan using `lidarScan`. Specify ranges and angles as vectors.

```
refRanges = 5*ones(1,300);
refAngles = linspace(-pi/2,pi/2,300);
refScan = lidarScan(refRanges,refAngles);
```

Using the `transformScan` (Robotics System Toolbox) function, generate a second lidar scan at an `x,y` offset of `(0.5,0.2)`.

```
currScan = transformScan(refScan,[0.5 0.2 0]);
```

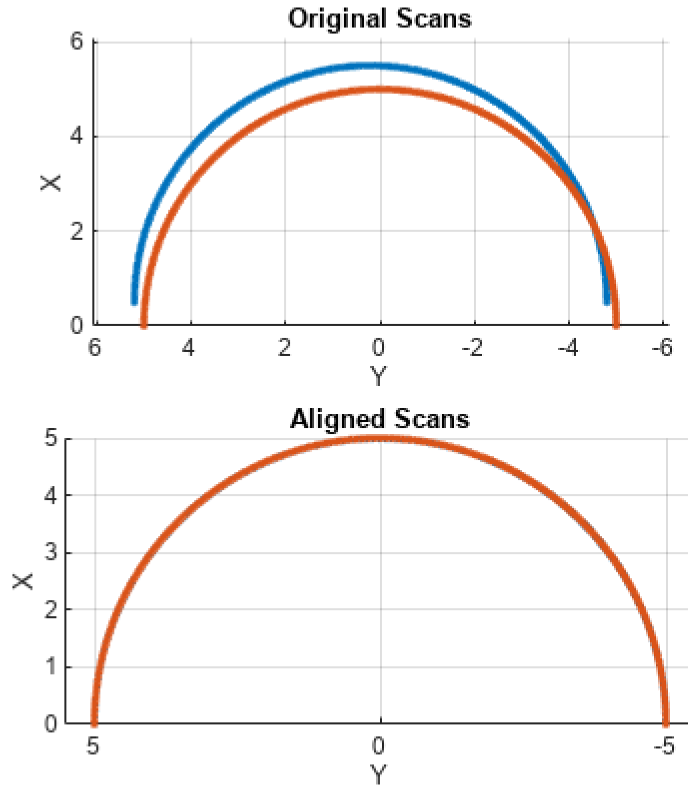
Match the reference scan and the second scan to estimate the pose difference between them.

```
pose = matchScans(currScan,refScan);
```

Use the `transformScan` function to align the scans by transforming the second scan into the frame of the first scan using the relative pose difference. Plot both the original scans and the aligned scans.

```
currScan2 = transformScan(currScan,pose);

subplot(2,1,1);
hold on
```

```
plot(currScan)
plot(refScan)
title('Original Scans')
hold off

subplot(2,1,2);
hold on
plot(currScan2)
plot(refScan)
title('Aligned Scans')
xlim([0 5])
hold off
```




### Match Laser Scans

This example uses the `'fminunc'` solver algorithm to perform scan matching. This solver algorithm requires an Optimization Toolbox™ license.

Specify a reference laser scan as ranges and angles.

```
refRanges = 5*ones(1,300);
refAngles = linspace(-pi/2,pi/2,300);
```

Using the `transformScan` (Robotics System Toolbox) function, generate a second laser scan at an `x,y` offset of `(0.5,0.2)`.

```
[currRanges,currAngles] = transformScan(refRanges,refAngles,[0.5 0.2 0]);
```

Match the reference scan and the second scan to estimate the pose difference between them.

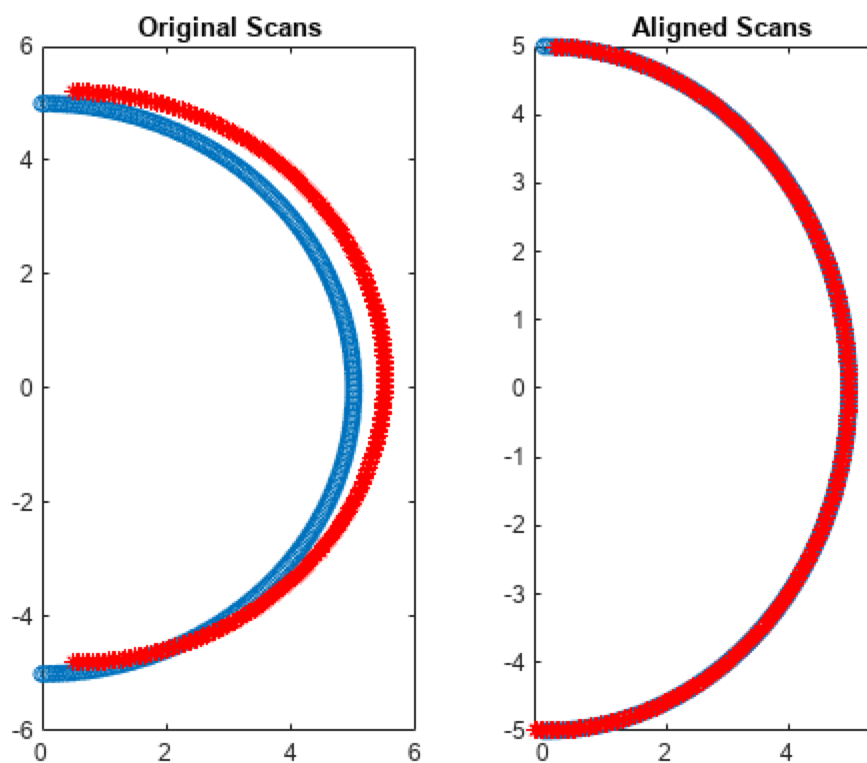
```
pose = matchScans(currRanges,currAngles,refRanges,refAngles,'SolverAlgorithm','fminunc');
```

Improve the estimate by giving an initial pose estimate.

```
pose = matchScans(currRanges,currAngles,refRanges,refAngles,...
                  'SolverAlgorithm','fminunc','InitialPose',[-0.4 -0.1 0]);
```

Use the `transformScan` function to align the scans by transforming the second scan into the frame of the first scan using the relative pose difference. Plot both the original scans and the aligned scans.

```
[currRanges2,currAngles2] = transformScan(currRanges,currAngles,pose);

[x1, y1] = pol2cart(refAngles,refRanges);
[x2, y2] = pol2cart(currAngles,currRanges);
[x3, y3] = pol2cart(currAngles2,currRanges2);

subplot(1,2,1)
plot(x1,y1,'o',x2,y2,'*r')
title('Original Scans')
subplot(1,2,2)
plot(x1,y1,'o',x3,y3,'*r')
title('Aligned Scans')
```



## Input Arguments

**`currScan` — Current lidar scan readings**
`lidarScan` object

Current lidar scan readings, specified as a `lidarScan` object.

Your lidar scan can contain `Inf` and `NaN` values, but the algorithm ignores them.

**`refScan` — Reference lidar scan readings**
`lidarScan` object

Reference lidar scan readings, specified as a `lidarScan` object.

Your lidar scan can contain `Inf` and `NaN` values, but the algorithm ignores them.

**`currRanges` — Current laser scan ranges**
vector in meters

Current laser scan ranges, specified as a vector. Ranges are given as distances to objects measured from the laser sensor.

Your laser scan ranges can contain `Inf` and `NaN` values, but the algorithm ignores them.

**`currAngles` — Current laser scan angles**
vector in radians

Current laser scan angles, specified as a vector in radians. Angles are given as the orientations of the corresponding range measurements.

**`refRanges` — Reference laser scan ranges**
vector in meters

Reference laser scan ranges, specified as a vector in meters. Ranges are given as distances to objects measured from the laser sensor.

Your laser scan ranges can contain `Inf` and `NaN` values, but the algorithm ignores them.

**`refAngles` — Reference laser scan angles**
vector in radians

Reference laser scan angles, specified as a vector in radians. Angles are given as the orientations of the corresponding range measurements.

### Name-Value Pair Arguments

Specify optional pairs of arguments as `Name1=Value1,...,NameN=ValueN`, where `Name` is the argument name and `Value` is the corresponding value. Name-value arguments must appear after other arguments, but the order of the pairs does not matter.

*Before R2021a, use commas to separate each name and value, and enclose* `Name` *in quotes.*

Example: `"InitialPose",[1 1 pi/2]`

**`SolverAlgorithm` — Optimization algorithm**
`"trust-region"` (default) | `"fminunc"`

Optimization algorithm, specified as either "trust-region" or "fminunc". Using "fminunc" requires an Optimization Toolbox™ license.

**InitialPose — Initial guess of current pose**
[0 0 0] (default) | [x y theta]

Initial guess of the current pose relative to the reference laser scan, specified as the comma-separated pair consisting of "InitialPose" and an [x y theta] vector. [x y] is the translation in meters and theta is the rotation in radians.

**CellSize — Length of cell side**
1 (default) | numeric scalar

Length of a cell side in meters, specified as the comma-separated pair consisting of "CellSize" and a numeric scalar. matchScans uses the cell size to discretize the space for the NDT algorithm.

Tuning the cell size is important for proper use of the NDT algorithm. The optimal cell size depends on the input scans and the environment of your robot. Larger cell sizes can lead to less accurate matching with poorly sampled areas. Smaller cell sizes require more memory and less variation between subsequent scans. Sensor noise influences the algorithm with smaller cell sizes as well. Choosing a proper cell size depends on the scale of your environment and the input data.

**MaxIterations — Maximum number of iterations**
400 (default) | scalar integer

Maximum number of iterations, specified as the comma-separated pair consisting of "MaxIterations" and a scalar integer. A larger number of iterations results in more accurate pose estimates, but at the expense of longer execution time.

**ScoreTolerance — Lower bounds on the change in NDT score**
1e-6 (default) | numeric scalar

Lower bound on the change in NDT score, specified as the comma-separated pair consisting of "ScoreTolerance" and a numeric scalar. The NDT score is stored in the Score field of the output stats structure. Between iterations, if the score changes by less than this tolerance, the algorithm converges to a solution. A smaller tolerance results in more accurate pose estimates, but requires a longer execution time.

## Output Arguments

**pose — Pose of current scan**
[x y theta]

Pose of current scan relative to the reference scan, returned as [x y theta], where [x y] is the translation in meters and theta is the rotation in radians.

**stats — Scan matching statistics**
structure

Scan matching statistics, returned as a structure with the following fields:

- Score — Numeric scalar representing the NDT score while performing scan matching. This score is an estimate of the likelihood that the transformed current scan matches the reference scan. Score is always nonnegative. Larger scores indicate a better match.

- `Hessian` — 3-by-3 matrix representing the Hessian of the NDT cost function at the given `pose` solution. The Hessian is used as an indicator of the uncertainty associated with the pose estimate.

## Version History

**Introduced in R2019b**

## References

[1] Biber, P., and W. Strasser. "The Normal Distributions Transform: A New Approach to Laser Scan Matching." *Intelligent Robots and Systems Proceedings*. 2003.

[2] Magnusson, Martin. "The Three-Dimensional Normal-Distributions Transform -- an Efficient Representation for Registration, Surface Analysis, and Loop Detection." PhD Dissertation. Örebro University, School of Science and Technology, 2009.

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

Code generation is supported for the default `SolverAlgorithm`, `"trust-region"`. You cannot use the `"fminunc"` algorithm in code generation.

## See Also

### Functions

`matchScansGrid` | `matchScansLine` | `transformScan` | `lidarScan`

### Classes

`occupancyMap` | `monteCarloLocalization`

### Topics

"Estimate Robot Pose with Scan Matching"

# matchScansGrid

Estimate pose between two lidar scans using grid-based search

## Syntax

```
pose = matchScansGrid(currScan,refScan)
[pose,stats] = matchScansGrid( ___ )
[ ___ ] = matchScansGrid( ___ ,Name,Value)
```

## Description

`pose = matchScansGrid(currScan,refScan)` finds the relative pose between a reference `lidarScan` and a current `lidarScan` object using a grid-based search. `matchScansGrid` converts lidar scan pairs into probabilistic grids and finds the pose between the two scans by correlating their grids. The function uses a branch-and-bound strategy to speed up computation over large discretized search windows.

`[pose,stats] = matchScansGrid( ___ )` returns additional statistics about the scan match result using the previous input arguments.

`[ ___ ] = matchScansGrid( ___ ,Name,Value)` specifies options using one or more `Name,Value` pair arguments. For example, `'InitialPose',[1 1 pi/2]` specifies an initial pose estimate for scan matching.

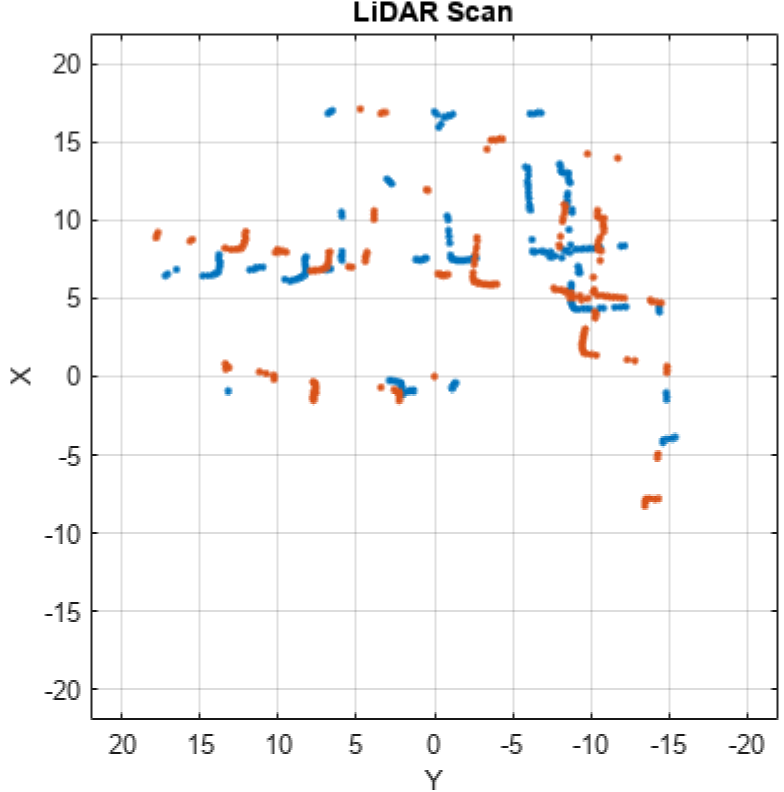
## Examples

### Match Scans Using Grid-Based Search

Perform scan matching using a grid-based search to estimate the pose between two laser scans. Generate a probabilistic grid from the scans and estimate the pose difference from those grids.

Load the laser scan data. These two scans are from an actual lidar sensor with changes in the robot pose and are stored as `lidarScan` objects.

```
load laserScans.mat scan scan2
plot(scan)
hold on
plot(scan2)
hold off
```

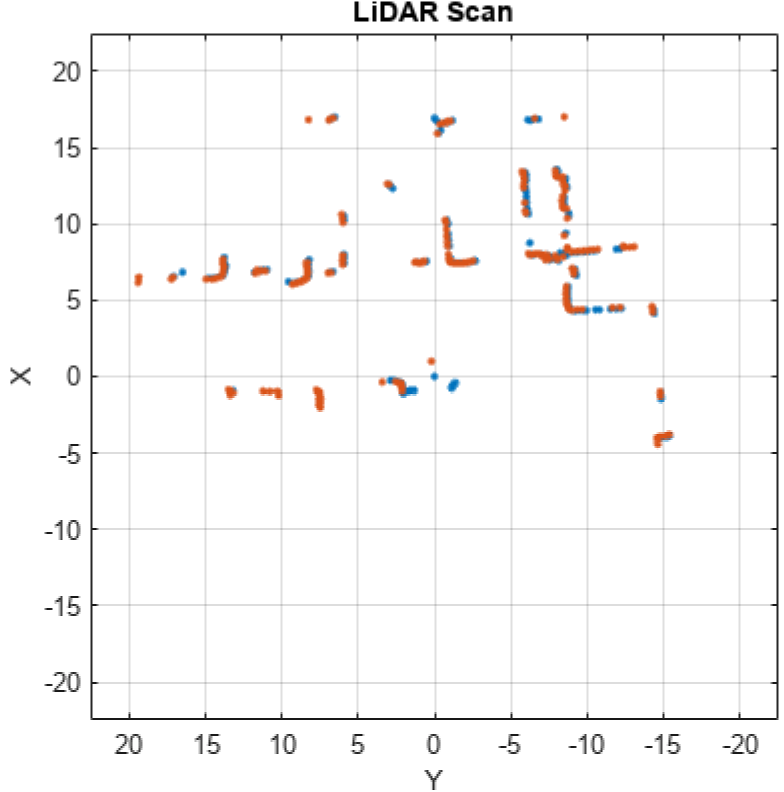



Use `matchScansGrid` to estimate the pose between the two scans.

```
relPose = matchScansGrid(scan2,scan);
```

Using the estimated pose, transform the current scan back to the reference scan. The scans overlap closely when you plot them together.

```
scan2Tformed = transformScan(scan2,relPose);

plot(scan)
hold on
plot(scan2Tformed)
hold off
```




## Input Arguments

**currScan — Current lidar scan readings**
lidarScan object

Current lidar scan readings, specified as a lidarScan object.

Your lidar scan can contain Inf and NaN values, but the algorithm ignores them.

**refScan — Reference lidar scan readings**
lidarScan object

Reference lidar scan readings, specified as a lidarScan object.

Your lidar scan can contain Inf and NaN values, but the algorithm ignores them.

### Name-Value Pair Arguments

Specify optional pairs of arguments as Name1=Value1,...,NameN=ValueN, where Name is the argument name and Value is the corresponding value. Name-value arguments must appear after other arguments, but the order of the pairs does not matter.

*Before R2021a, use commas to separate each name and value, and enclose* Name *in quotes.*

Example: 'InitialPose',[1 1 pi/2]

**`InitialPose` — Initial guess of current pose**
`[0 0 0]` (default) | `[x y theta]`

Initial guess of the current pose relative to the reference laser scan, specified as the comma-separated pair consisting of `'InitialPose'` and an `[x y theta]` vector. `[x y]` is the translation in meters and `theta` is the rotation in radians.

**`Resolution` — Grid cells per meter**
`20` (default) | positive integer

Grid cells per meter, specified as the comma-separated pair consisting of `'Resolution'` and a positive integer. The accuracy of the scan matching result is accurate up to the grid cell size.

**`MaxRange` — Maximum range of lidar sensor**
`8` (default) | positive scalar

Maximum range of lidar sensor, specified as the comma-separated pair consisting of `'MaxRange'` and a positive scalar.

**`TranslationSearchRange` — Search range for translation**
`[4 4]` (default) | `[x y]` vector

Search range for translation, specified as the comma-separated pair consisting of `'TranslationSearchRange'` and an `[x y]` vector. These values define the search window in meters around the initial translation estimate given in `InitialPose`. If the `InitialPose` is given as `[x0 y0]`, then the search window coordinates are `[x0-x x0+x]` and `[y0-y y0+y]`. This parameter is used only when `InitialPose` is specified.

**`RotationSearchRange` — Search range for rotation**
`pi/4` (default) | positive scalar

Search range for rotation, specified as the comma-separated pair consisting of `'RotationSearchRange'` and a positive scalar. This value defines the search window in radians around the initial rotation estimate given in `InitialPose`. If the `InitialPose` rotation is given as `th0`, then the search window is `[th0-a th0+a]`, where `a` is the rotation search range. This parameter is used only when `InitialPose` is specified.

## Output Arguments

**`pose` — Pose of current scan**
`[x y theta]` vector

Pose of current scan relative to the reference scan, returned as an `[x y theta]` vector, where `[x y]` is the translation in meters and `theta` is the rotation in radians.

**`stats` — Scan matching statistics**
structure

Scan matching statistics, returned as a structure with the following field:

- `Score` — Numeric scalar representing the score while performing scan matching. This score is an estimate of the likelihood that the transformed current scan matches the reference scan. `Score` is always nonnegative. Larger scores indicate a better match, but values vary depending on the lidar data used.

- `Covariance` — Estimated covariance representing the confidence of the computed relative pose, returned as a 3-by-3 matrix.

# Version History

**Introduced in R2019b**

## References

[1] Hess, Wolfgang, Damon Kohler, Holger Rapp, and Daniel Andor. "Real-Time Loop Closure in 2D LIDAR SLAM." *2016 IEEE International Conference on Robotics and Automation (ICRA)*. 2016.

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Functions

`matchScans` | `matchScansLine` | `lidarScan` | `transformScan`

### Classes

`lidarSLAM`

### Topics

"Implement Simultaneous Localization And Mapping (SLAM) with Lidar Scans"
"Implement Online Simultaneous Localization And Mapping (SLAM) with Lidar Scans"

# matchScansLine

Estimate pose between two laser scans using line features

## Syntax

```
relpose = matchScansLine(currScan,refScan,initialRelPose)
[relpose,stats] = matchScansLine( ___ )
[relpose,stats,debugInfo] = matchScansLine( ___ )
[ ___ ] = matchScansLine( ___ ,Name,Value)
```

## Description

`relpose = matchScansLine(currScan,refScan,initialRelPose)` estimates the relative pose between two scans based on matched line features identified in each scan. Specify an initial guess on the relative pose, `initialRelPose`.

`[relpose,stats] = matchScansLine( ___ )` returns additional information about the covariance and exit condition in `stats` as a structure using the previous inputs.

`[relpose,stats,debugInfo] = matchScansLine( ___ )` returns additional debugging info, `debugInfo`, from the line-based scan matching result.

`[ ___ ] = matchScansLine( ___ ,Name,Value)` specifies options using one or more `Name,Value` pair arguments.

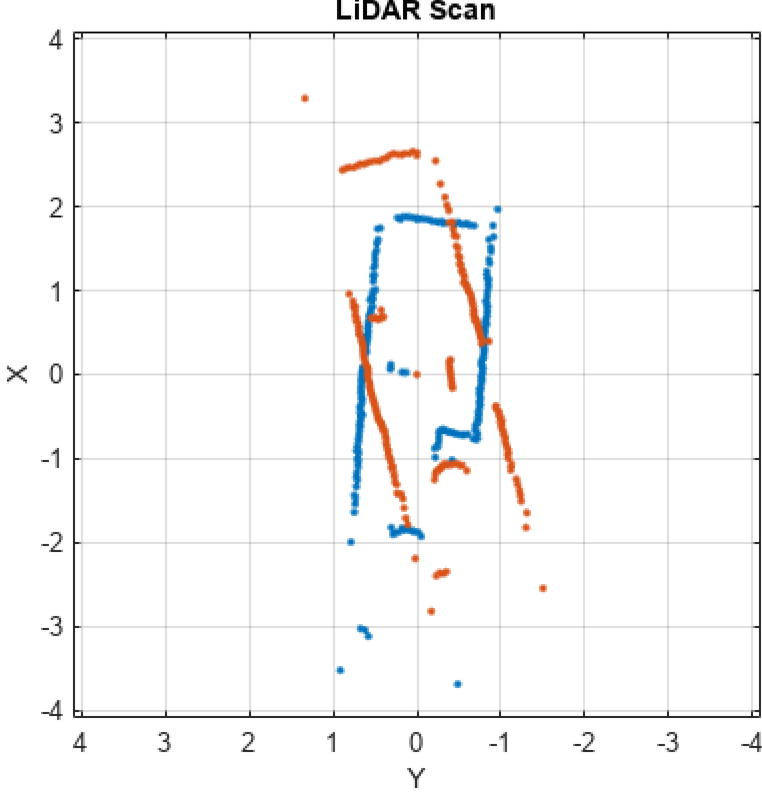
## Examples

### Estimate Pose of Scans with Line Features

This example shows how to use the `matchScansLine` function to estimate the relative pose between lidar scans given an initial estimate. The identified line features are visualized to show how the scan-matching algorithm associates features between scans.

Load a pair of lidar scans. The `.mat` file also contains an initial guess of the relative pose difference, `initGuess`, which could be based on odometry or other sensor data.

```
load tb3_scanPair.mat
plot(s1)
hold on
plot(s2)
hold off
```




Set parameters for line feature extraction and association. The noise of the lidar data determines the smoothness threshold, which defines when a line break occurs for a specific line feature. Increase this value for more noisy lidar data. The compatibility scale determines when features are considered matches. Increase this value for looser restrictions on line feature parameters.

```
smoothnessThresh = 0.2;
compatibilityScale = 0.002;
```

Call `matchScansLine` with the given initial guess and other parameters specified as name-value pairs. The function calculates line features for each scan, attempts to match them, and uses an overall estimate to get the difference in pose.

```
[relPose, stats, debugInfo] = matchScansLine(s2, s1, initGuess, ...
                                          'SmoothnessThreshold', smoothnessThresh, ...
                                          'CompatibilityScale', compatibilityScale);
```

After matching the scans, the `debugInfo` output gives you information about the detected line feature parameters, `[rho alpha]`, and the hypothesis of which features match between scans.

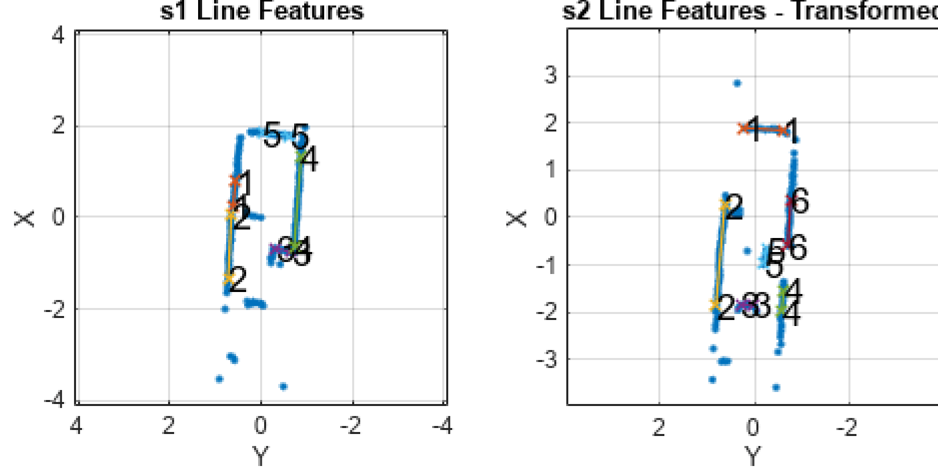
`debugInfo.MatchHypothesis` states that the first, second, and sixth line feature in `s1` match the fifth, second, and fourth features in `s2`.

```
debugInfo.MatchHypothesis
```

```
ans = 1×6

     5     2     0     0     0     4
```

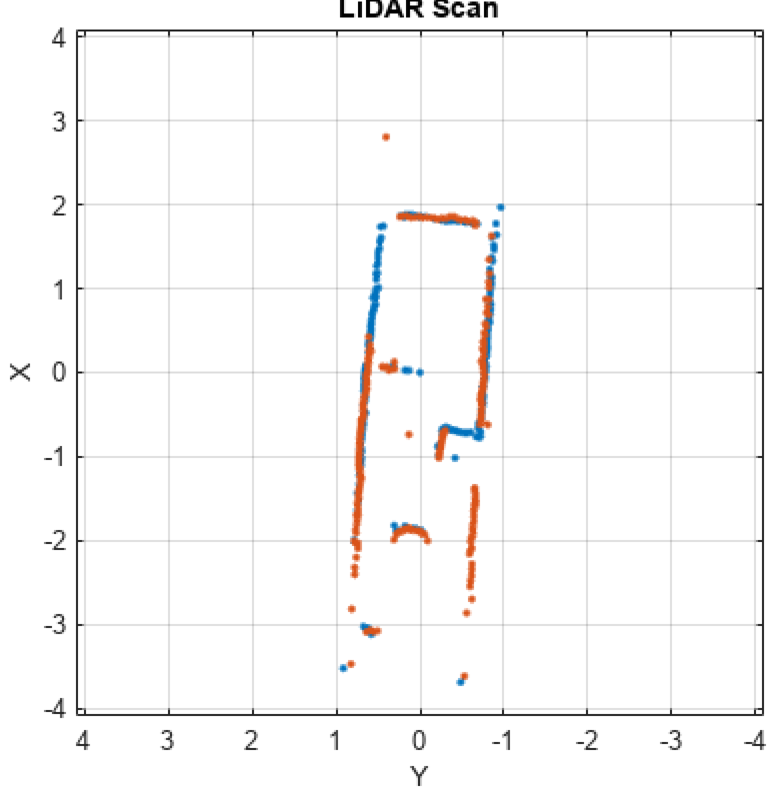
The provided helper function plots these two scans and the features extracted with labels. s2 is transformed to be in the same frame based on the initial guess for relative pose.

```
exampleHelperShowLineFeaturesInScan(s1, s2, debugInfo, initGuess);
```




Use the estimated relative pose from matchScansLine to transform s2. Then, plot both scans to show that the relative pose difference is accurate and the scans overlay to show the same environment.

```
s2t = transformScan(s2,relPose);
clf
plot(s1)
hold on
plot(s2t)
hold off
```




## Input Arguments

**`currScan` — Current lidar scan readings**
`lidarScan` object

Current lidar scan readings, specified as a `lidarScan`object.

Your lidar scan can contain `Inf` and `NaN` values, but the algorithm ignores them.

**`refScan` — Reference lidar scan readings**
`lidarScan` object

Reference lidar scan readings, specified as a `lidarScan` object.

Your lidar scan can contain `Inf` and `NaN` values, but the algorithm ignores them.

**`initialRelPose` — Initial guess of relative pose**
`[x y theta]`

Initial guess of the current pose relative to the reference laser scan frame, specified an `[x y theta]` vector. `[x y]` is the translation in meters and `theta` is the rotation in radians.

### Name-Value Pair Arguments

Specify optional pairs of arguments as `Name1=Value1,...,NameN=ValueN`, where `Name` is the argument name and `Value` is the corresponding value. Name-value arguments must appear after other arguments, but the order of the pairs does not matter.

*Before R2021a, use commas to separate each name and value, and enclose* `Name` *in quotes.*

Example: `"LineMergeThreshold",[0.10 0.2]`

**`SmoothnessThreshold` — Threshold to detect line break points in scan**
`0.1` (default) | scalar

Threshold to detect line break points in scan, specified as a scalar. Smoothness is defined by calling `diff(diff(scanData))` and assumes equally spaced scan angles. Scan points corresponding to smoothness values higher than this threshold are considered break points. For lidar scan data with a higher noise level, increase this threshold.

**`MinPointsPerLine` — Minimum number of scan points in each line feature**
`10` (default) | positive integer greater than 3

Minimum number of scan points in each line feature, specified as a positive integer greater than 3.

A line feature cannot be identified from a set of scan points if the number of points in that set is below this threshold. When the lidar scan data is noisy, setting this property too small may result in low-quality line features being identified and skew the matching result. On the other hand, some key line features may be missed if this number is set too large.

**`LineMergeThreshold` — Threshold on line parameters to merge line features**
`[0.05 0.1]` (default) | two-element vector `[rho alpha]`

Threshold on line parameters to merge line features, specified as a two-element vector `[rho alpha]`. A line is defined by two parameters:

- `rho` –– Distance from the origin to the line along a vector perpendicular to the line, specified in meters.
- `alpha` –– Angle between the `x`-axis and the `rho` vector, specified in radians.

If the difference between these parameters for two line features is below the given threshold, the line features are merged.

**`MinCornerPromenance` — Lower bound on prominence value to detect a corner**
`0.05` (default) | positive scalar

Lower bound on prominence value to detect a corner, specified as a positive scalar.

Prominence measures how much a local extrema stands out in the lidar data. Only values higher than this lower bound are considered a corner. Corners help identify line features, but are not part of the feature itself. For noisy lidar scan data, increase this lower bound.

**`CompatibilityScale` — Scale used to adjust the compatibility thresholds for feature association**
`0.0005` (default) | positive scalar

Scale used to adjust the compatibility thresholds for feature association, specified as a positive scalar. A lower scale means tighter compatibility threshold for associating features. If no features are found

in lidar data with obvious line features, increase this value. For invalid feature matches, reduce this value.

## Output Arguments

**relpose — Pose of current scan**
[x y theta]

Pose of current scan relative to the reference scan, returned as [x y theta], where [x y] is the translation in meters and theta is the rotation in radians.

**stats — Scan matching information**
structure

Scan matching information, returned as a structure with the following fields:

- Covariance –– 3-by-3 matrix representing the covariance of the relative pose estimation. The matScansLine function does not provide covariance between the (x,y) and the theta components of the relative pose. Therefore, the matrix follows the pattern: [Cxx, Cxy 0; Cyx Cyy 0; 0 0 Ctheta].
- ExitFlag –– Scalar value indicating the exit condition of the solver:
  - 0 –– No error.
  - 1 –– Insufficient number of line features (< 2) are found in one or both of the scans. Consider using different scans with more line features.
  - 2 –– Insufficient number of line feature matches are identified. This may indicate the initialRelPose is invalid or scans are too far apart.

**debugInfo — Debugging information for line-based scan matching result**
structure

Debugging information for line-based scan matching result, returned as a structure with the following fields:

- ReferenceFeatures –– Line features extracted from the reference scan as an *n*-by-2 matrix. Each line feature is represented as [rho alpha] for the parametric equation, *rho* = *x*•cos(*alpha*) + *y*•sin(*alpha*).
- ReferenceScanMask –– Mask indicating which points in the reference scan are used for each line feature as an *n*-by-*p* matrix. Each row corresponds to a row in ReferenceFeatures and contains zeros and ones for each point in refScan.
- CurrentFeatures –– Line features extracted from the current scan as an *n*-by-2 matrix. Each line feature is represented as [rho alpha] for the parametric equation, *rho* = *x*•cos(*alpha*) + *y*•sin(*alpha*).
- CurrentScanMask –– Mask indicating which points in the current scan are used for each line feature as an *n*-by-*p* matrix. Each row corresponds to a row in ReferenceFeatures and contains zeros and ones for each point in refScan.
- MatchHypothesis –– Best line feature matching hypothesis as an *n* element vector, where *n* is the number of line features in CurrentFeatures. Each element represents the corresponding feature in ReferenceFeaturesand gives the index of the matched feature in ReferenceFeatures is an index match the

- `MatchValue` –– Scalar value indicating a score for each `MatchHypothesis`. A lower value is considered a better match. If two elements of `MatchHypothesis` have the same index, the feature with a lower score is used.

# Version History

**Introduced in R2020a**

## References

[1] Neira, J., and J.d. Tardos. “Data Association in Stochastic Mapping Using the Joint Compatibility Test.” *IEEE Transactions on Robotics and Automation* 17, no. 6 (2001): 890–97. https://doi.org/10.1109/70.976019.

[2] Shen, Xiaotong, Emilio Frazzoli, Daniela Rus, and Marcelo H. Ang. “Fast Joint Compatibility Branch and Bound for Feature Cloud Matching.” *2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2016. https://doi.org/10.1109/iros.2016.7759281.

## See Also

`matchScans` | `matchScansGrid` | `lidarSLAM`

### Topics

“Estimate Robot Pose with Scan Matching”
“Implement Simultaneous Localization And Mapping (SLAM) with Lidar Scans”

# optimizePath

Optimize path while maintaining safe distance from obstacle

## Syntax

```
optPath = optimizePath(path)
optPath = optimizePath(path,map)
optPath = optimizePath(path,options)
optPath = optimizePath(path,map,options)
[optPath,kineticInfo] = optimizePath( ___ )
[optPath,kineticInfo,solutionInfo] = optimizePath( ___ )
```

## Description

`optPath = optimizePath(path)` optimizes the travel time and smoothness of the specified `path` for car-like robots in an empty map for the default parameters. The number of states in the `optPath` can be different than in the `path`.

`optPath = optimizePath(path,map)` optimizes the `path` in the specified `map` for the default parameters. The returned optimized path `optPath` tries to maintain a safety margin to obstacles in the map `map`.

`optPath = optimizePath(path,options)` optimizes the `path` in an empty map by parameters specified in `options`. Parameters related to trajectory, obstacle, and solver, along with the weights of those parameters can be specified in `options` as an `optimizePathOptions` object.

`optPath = optimizePath(path,map,options)` optimizes the `path` in the specified `map` for by parameters specified in `options`.

`[optPath,kineticInfo] = optimizePath( ___ )` also returns `kineticInfo` as a structure that contains the kinetic information of the optimized path.

`[optPath,kineticInfo,solutionInfo] = optimizePath( ___ )` also returns `solutionInfo` as a structure that contains the solution information of the optimized path.

## Examples

### Optimize Planned Path

#### Setup Environment

Load a map into the workspace.

```
map = load("exampleMaps.mat").complexMap;
```

Create a binary occupancy map.

```
map = binaryOccupancyMap(map);
```

Create a state validator object.

```
stateValidator = validatorOccupancyMap;
```

Assign the map to the state validator object.

```
stateValidator.Map = map;
```

Set the validation distance for the validator.

```
stateValidator.ValidationDistance = 0.01;
```

**Plan Path**

Initialize the `plannerHybridAStar` object with the state validator object. Specify the `MinTurningRadius` property of the planner as 2 meters.

```
planner = plannerHybridAStar(stateValidator,MinTurningRadius=2);
```

Define start and goal poses as [*x y theta*] vectors. *x* and *y* specify the position in meters, and *theta* specifies the orientation angle in radians.

```
start = [6 3 pi/2];
goal = [32 32 0];
```

Plan a path from the start pose to the goal pose.

```
path = plan(planner,start,goal);
inpath = path.States;
```

**Optimize Path**

Configure options for optimization.

```
options = optimizePathOptions
```

```
options = 
optimizePathOptions

   Trajectory Parameters
               MaxPathStates: 200
          ReferenceDeltaTime: 0.3000
            MinTurningRadius: 1
                 MaxVelocity: 0.4000
          MaxAngularVelocity: 0.3000
             MaxAcceleration: 0.5000
      MaxAngularAcceleration: 0.5000

   Obstacle Parameters
        ObstacleSafetyMargin: 0.5000
      ObstacleCutOffDistance: 2.5000
   ObstacleInclusionDistance: 0.7500

   Solver Parameters
                NumIteration: 4
          MaxSolverIteration: 15

   Weights
                  WeightTime: 10
            WeightSmoothness: 1000
      WeightMinTurningRadius: 10
```

```
             WeightVelocity: 100
      WeightAngularVelocity: 10
         WeightAcceleration: 10
  WeightAngularAcceleration: 10
            WeightObstacles: 50
```

Set the minimum turning radius value as same as in the planner.

```
options.MinTurningRadius = 2;
```

Specify the maximum number of poses allowed in the optimized path.

```
options.MaxPathStates = size(inpath,1) * 3;
```

Maintain a safe distance of `0.75` meters from the obstacles.

```
options.ObstacleSafetyMargin = 0.75;
```

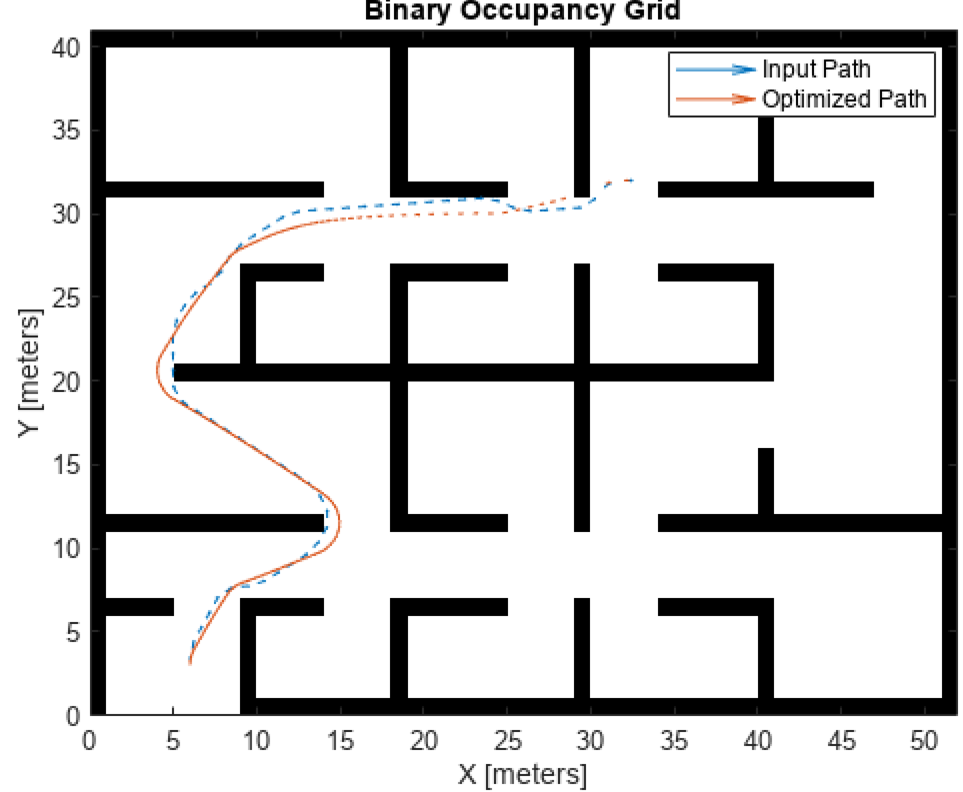
Optimize the path generated by the planner.

```
optpath = optimizePath(inpath,map,options);
```

**Visualize**

Visualize input path and optimized path in the map.

```
show(map)
hold on
quiver(inpath(:,1),inpath(:,2),cos(inpath(:,3)),sin(inpath(:,3)),0.1);
quiver(optpath(:,1),optpath(:,2),cos(optpath(:,3)),sin(optpath(:,3)),0.1);
legend("Input Path","Optimized Path")
```




## Input Arguments

**path — Path states**

real-valued *M*-by-2 matrix of the form [*x y*] | real-valued *M*-by-3 matrix of the form [*x y theta*]

Path states, specified as a real-valued *M*-by-2 matrix of the form [*x y*] or *M*-by-3 matrix of the form [*x y theta*]. *x* and *y* specify the position in meters. *theta* specifies the orientation in radians. *M* is the number of states in the path. The number of states in the path must be greater than or equal to 3.

Data Types: `single` | `double`

**map — Map representation**

`binaryOccupancyMap` object | `occupancyMap` object | `vehicleCostMap` object

Map representation, specified as a `binaryOccupancyMap`, `occupancyMap`, or `vehicleCostmap` object. This object represents the environment of the vehicle.

**options — Optimization options**

`optimizePathOptions` object

Optimization options, specified as `optimizePathOptions` object.

## Output Arguments

**optPath — Optimized path**

real-valued *N*-by-2 matrix of the form [*x y*] | real-valued *N*-by-3 matrix of the form [*x y theta*]

Path states, returned as a real-valued *N*-by-2 matrix of the form [*x y*] or *N*-by-3 matrix of the form [*x y theta*]. *x* and *y* specify the position in meters. *theta* specifies the orientation in radians. *N* is the number of states in the path. The number of states in the `optPath` can be different than in the `path`.

**`kineticInfo` — Kinetic Information**
structure

Kinetic Information, returned as a structure. The fields of the structure are:

**Fields of `kineticInfo`**

| Fields | Description |
|---|---|
| `TimeStamps` | Time corresponding to the pose in the optimized path. |
| `Velocity` | Velocity to travel between two consecutive poses. |
| `AngularVelocity` | Angular Velocity between two consecutive poses. |

Data Types: `struct`

**`solutionInfo` — Solution Information**
structure

Solution Information, returned as a structure. The fields of the structure are:

**Fields of `solutionInfo`**

| Fields | Description |
|---|---|
| `NumIterations` | Number of iterations performed. |
| `Cost` | Final cost of the path. |

Data Types: `struct`

# Version History

**Introduced in R2022a**

## References

[1] Rosmann, Christoph, Frank Hoffmann, and Torsten Bertram. “Kinodynamic Trajectory Optimization and Control for Car-like Robots.” In *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 5681–86. Vancouver, BC: IEEE, 2017. https://doi.org/10.1109/IROS.2017.8206458.

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

`optimizePathOptions`

# optimizePoseGraph

Optimize nodes in pose graph

## Syntax

```
updatedGraph = optimizePoseGraph(poseGraph)
updatedGraph = optimizePoseGraph(poseGraph,solver)
[updatedGraph,solutionInfo] = optimizePoseGraph( ___ )
[ ___ ] = optimizePoseGraph( ___ ,Name,Value)
```

## Description

`updatedGraph = optimizePoseGraph(poseGraph)` adjusts the poses based on their edge constraints defined in the specified graph to improve the overall graph. You optimize either a 2-D or 3-D pose graph. The returned pose graph has the same topology with updated nodes.

This pose graph optimization assumes all edge constraints and loop closures are valid. To consider trimming edges based on bad loop closures, see the `trimLoopClosures` function.

`updatedGraph = optimizePoseGraph(poseGraph,solver)` specifies the solver type for optimizing the pose graph.

`[updatedGraph,solutionInfo] = optimizePoseGraph( ___ )` returns additional statistics about the optimization process in `solutionInfo` using any of the previous syntaxes.

`[ ___ ] = optimizePoseGraph( ___ ,Name,Value)` specifies additional options using one or more `Name,Value` pairs. For example, `'MaxIterations',1000` increases the maximum number of iterations to 1000.

## Examples

### Optimize a 3-D Pose Graph

Optimize a pose graph based on the nodes and edge constraints. The pose graph used in this example is taken from the MIT Dataset and was generated using information extracted from a parking garage.

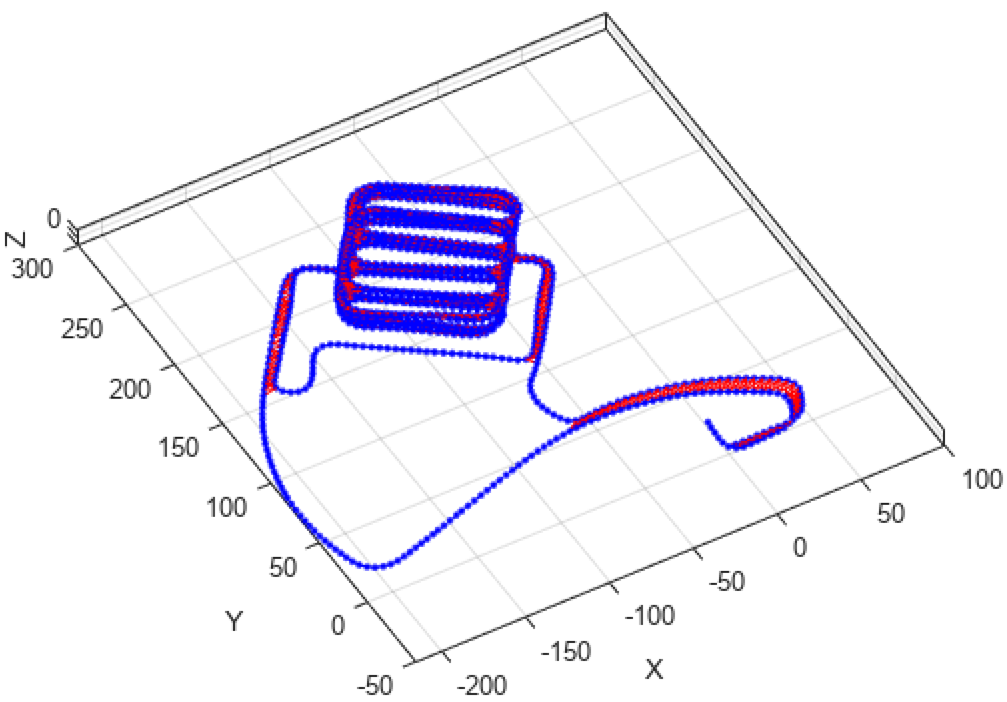
Load the pose graph from the MIT dataset. Inspect the `poseGraph3D` object to view the number of nodes and loop closures.

```
load parking-garage-posegraph.mat pg
disp(pg);
```

```
  poseGraph3D with properties:

               NumNodes: 1661
               NumEdges: 6275
    NumLoopClosureEdges: 4615
     LoopClosureEdgeIDs: [128 129 130 132 133 134 135 137 138 139 140 142 143 144 146 147 148 150
        LandmarkNodeIDs: [1x0 double]
```

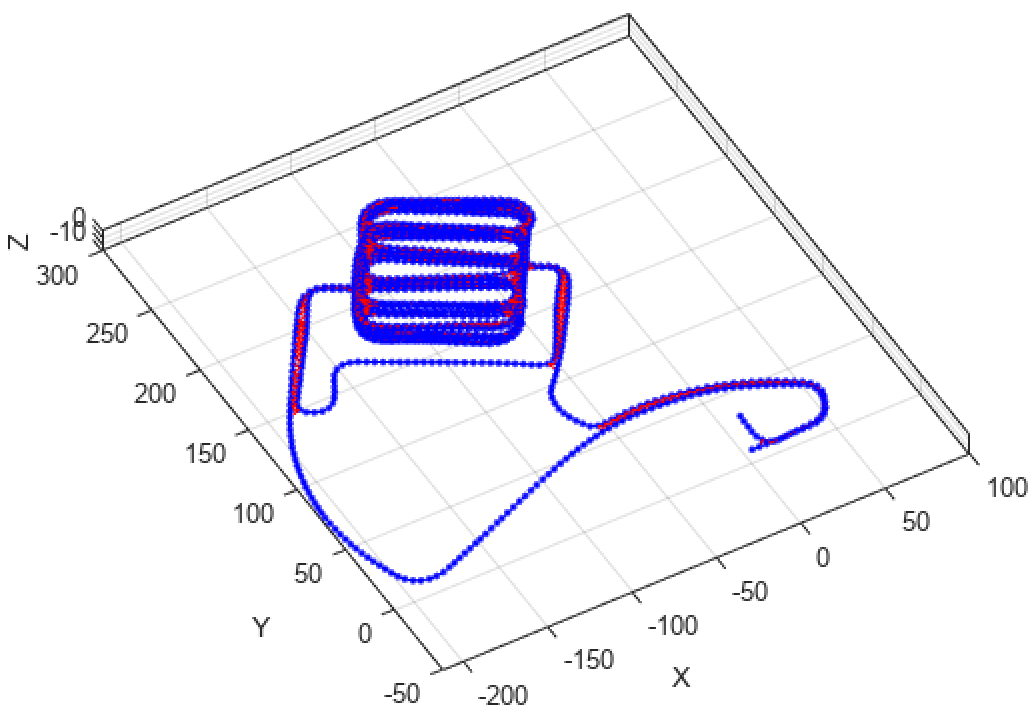
Plot the pose graph with IDs off. Red lines indicate loop closures identified in the dataset.

```
title('Original Pose Graph')
show(pg,'IDs','off');
view(-30,45)
```




Optimize the pose graph. Nodes are adjusted based on the edge constraints and loop closures. Plot the optimized pose graph to see the adjustment of the nodes with loop closures.

```
updatedPG = optimizePoseGraph(pg);
figure
title('Updated Pose Graph')
show(updatedPG,'IDs','off');
view(-30,45)
```




## Input Arguments

**poseGraph — 2-D or 3-D pose graph**
poseGraph object | poseGraph3D object | digraph object

2-D or 3-D pose graph, specified as a poseGraph, poseGraph3D, digraph object.

To use the digraph object, generate the pose graph using createPoseGraph from an imageviewset or pcviewset object. You must have Computer Vision Toolbox™ and the solver must be set to "builtin-trust-region". The 'LoopClosuresToIgnore' and 'FirstNodePose' name-value pairs are ignored if specified.

The edges of digraph object are described by simtform3d or rigidtform3d objects.

**solver — Pose graph solver**
"builtin-trust-region" (default) | "g2o-levenberg-marquardt"

Pose graph solver, specified as either "builtin-trust-region" or "g2o-levenberg-marquardt". To tune either solver, use the name-value pair arguments for that solver.

### Name-Value Pair Arguments

Specify optional pairs of arguments as Name1=Value1,...,NameN=ValueN, where Name is the argument name and Value is the corresponding value. Name-value arguments must appear after other arguments, but the order of the pairs does not matter.

*Before R2021a, use commas to separate each name and value, and enclose* `Name` *in quotes.*

Example: `'MaxTime', 300`

---

**Note** Depending on the `solver` input, the function supports different name-value pairs.

---

**If the solver input is set to "builtin-trust-region":**

**`MaxTime` — Maximum time allowed**
`500` (default) | positive numeric scalar

Maximum time allowed, specified as the comma-separated pair consisting of `'MaxTime'` and a positive numeric scalar in seconds. The optimizer exits after it exceeds this time.

**`GradientTolerance` — Lower bound on norm of gradient**
`0.5e-8` (default) | scalar

Lower bound on the norm of the gradient, specified as the comma-separated pair consisting of `'GradientTolerance'` and a scalar. The norm of the gradient is calculated based on the cost function of the optimization. If the norm falls below this value, the optimizer exits.

**`FunctionTolerance` — Lower bound on change in cost function**
`1e-8` (default) | scalar

Lower bound on the change in the cost function, specified as the comma-separated pair consisting of `'FunctionTolerance'` and a scalar. If the cost function change falls below this value between optimization steps, the optimizer exits.

**`StepTolerance` — Lower bound on step size**
`1e-12` (default) | scalar

Lower bound on the step size, specified as the comma-separated pair consisting of `'StepTolerance'` and a scalar. If the norm of the optimization step falls below this value, the optimizer exits.

**`InitialTrustRegionRadius` — Initial trust region radius**
`100` (default) | scalar

Initial trust region radius, specified as a scalar.

**`VerboseOutput` — Display intermediate iteration information**
`'off'` (default) | `'on'`

Display intermediate iteration information on the MATLAB command line, specified as the comma-separated pair consisting of `'VerboseOutput'` and either `'off'` or `'on'`.

**`LoopClosuresToIgnore` — IDs of loop closure edges in pose graph**
vector

IDs of loop closure edges in `poseGraph`, specified as the comma-separated pair consisting of `'LoopClosuresToIgnore'` and a vector. To get edge IDs from the pose graph, use `findEdgeID`.

**`FirstNodePose` — Pose of first node**
`[0 0 0]` or `[0 0 0 1 0 0 0]` (default) | `[x y theta]` | `[x y z qw qx qy qz]`

Pose of the first node in `poseGraph`, specified as the comma-separated pair consisting of `'FirstNodePose'` and a pose vector.

For `poseGraph` (2-D), the pose is an `[x y theta]` vector, which defines the relative *xy*-position and orientation angle, `theta`.

For `poseGraph3D`, the pose is an `[x y z qw qx qy qz]` vector, which defines the relative *xyz*-position and quaternion orientation, `[qw qx qy qz]`.

---

**Note** Many other sources for 3-D pose graphs, including `.g2o` formats, specify the quaternion orientation in a different order, for example, `[qx qy qz qw]`. Check the source of your pose graph data before adding nodes to your `poseGraph3D` object.

---

**If the solver input is set to "g2o-levenberg-marquardt":**

**`MaxIterations` — Maximum number of iterations**
`300` (default) | positive integer

Maximum number of iterations, specified as the comma-separated pair consisting of `'MaxIterations'` and a positive integer. The optimizer exits after it exceeds this number of iterations.

**`MaxTime` — Maximum time allowed**
`500` (default) | positive numeric scalar

Maximum time allowed, specified as the comma-separated pair consisting of `'MaxTime'` and a positive numeric scalar in seconds. The optimizer exits after it exceeds this time.

**`FunctionTolerance` — Lower bound on change in cost function**
`1e-8` (default) | scalar

Lower bound on the change in the cost function, specified as the comma-separated pair consisting of `'FunctionTolerance'` and a scalar. If the cost function change falls below this value between optimization steps, the optimizer exits.

**`VerboseOutput` — Display intermediate iteration information**
`'off'` (default) | `'on'`

Display intermediate iteration information on the MATLAB command line, specified as the comma-separated pair consisting of `'VerboseOutput'` and either `'off'` or `'on'`.

**`LoopClosuresToIgnore` — IDs of loop closure edges in pose graph**
vector

IDs of loop closure edges in `poseGraph`, specified as the comma-separated pair consisting of `'LoopClosuresToIgnore'` and a vector. To get edge IDs from the pose graph, use `findEdgeID`.

**`FirstNodePose` — Pose of first node**
`[0 0 0]` or `[0 0 0 1 0 0 0]` (default) | `[x y theta]` | `[x y z qw qx qy qz]`

Pose of the first node in `poseGraph`, specified as the comma-separated pair consisting of `'FirstNodePose'` and a pose vector.

For `poseGraph` (2-D), the pose is an `[x y theta]` vector, which defines the relative *xy*-position and orientation angle, `theta`.

For `poseGraph3D`, the pose is an `[x y z qw qx qy qz]` vector, which defines the relative *xyz*-position and quaternion orientation, `[qw qx qy qz]`.

**Note** Many other sources for 3-D pose graphs, including `.g2o` formats, specify the quaternion orientation in a different order, for example, `[qx qy qz qw]`. Check the source of your pose graph data before adding nodes to your `poseGraph3D` object.

## Output Arguments

### `updatedGraph` — Optimized 2-D or 3-D pose graph

`poseGraph` object | `poseGraph3D` object

Optimized 2-D or 3-D pose graph, returned as a `poseGraph` or `poseGraph3D` object.

### `solutionInfo` — Statistics of optimization process

structure

Statistics of optimization process, returned as a structure with these fields:

- `Iterations` — Number of iterations used in optimization.
- `ResidualError` — Value of cost function when optimizer exits.
- `Exit Flag` — Exit condition for optimizer:
  - `1` — Local minimum found.
  - `2` — Maximum number of iterations reached. See `MaxIterations` name-value pair argument.
  - `3` — Algorithm timed out during operation.
  - `4` — Minimum step size. The step size is below the `StepTolerance` name-value pair argument.
  - `5` — The change in error is below the minimum.
  - `8` — Trust region radius is below the minimum set in `InitialTrustRegionRadius`.

# Version History

**Introduced in R2019b**

## References

[1] Grisetti, G., R. Kummerle, C. Stachniss, and W. Burgard. "A Tutorial on Graph-Based SLAM." *IEEE Intelligent Transportation Systems Magazine*. Vol. 2, No. 4, 2010, pp. 31–43. doi:10.1109/mits.2010.939925.

[2] Carlone, Luca, Roberto Tron, Kostas Daniilidis, and Frank Dellaert. "Initialization Techniques for 3D SLAM: a Survey on Rotation Estimation and its Use in Pose Graph Optimization." *2015 IEEE International Conference on Robotics and Automation (ICRA)*. 2015, pp. 4597–4604.

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

- Use this syntax when constructing `poseGraph` or `poseGraph3D` objects for code generation:

  `poseGraph = poseGraph('MaxNumEdges',maxEdges,'MaxNumNodes',maxNodes)` specifies an upper bound on the number of edges and nodes allowed in the pose graph when generating code. This limit is only required when generating code.
- The `"g2o-levenberg-marquardt"` `solver` input argument is not supported for code generation.

## See Also

### Functions

`trimLoopClosures` | `addRelativePose` | `removeEdges` | `edgeNodePairs` | `edgeConstraints` | `findEdgeID` | `nodeEstimates`

### Objects

`poseGraph` | `poseGraph3D` | `lidarSLAM`

### Topics

"Implement Simultaneous Localization And Mapping (SLAM) with Lidar Scans"
"Implement Online Simultaneous Localization And Mapping (SLAM) with Lidar Scans"

# plotTransforms

Plot 3-D transforms from translations and rotations

## Syntax

```
ax = plotTransforms(translations,rotations)
ax = plotTransforms(transformations)
ax = plotTransforms( ___ ,Name,Value)
```

## Description

`ax = plotTransforms(translations,rotations)` draws transform frames in a 3-D figure window using the specified translations `translations`, and rotations, `rotations`. The *z*-axis always points upward.

`ax = plotTransforms(transformations)` draws transform frames for the specified SE(2) or SE(3) transformations, `transformations`.

`ax = plotTransforms( ___ ,Name,Value)` specifies additional options using name-value arguments. Specify multiple name-value arguments to set multiple options.

## Input Arguments

**`translations` — *xyz*-positions**
`[x y z]` vector | matrix of `[x y z]` vectors

*xyz*-positions specified as a vector or matrix of `[x y z]` vectors. Each row represents a new frame to plot with a corresponding orientation in `rotations`.

Example: `[1 1 1; 2 2 2]`

**`rotations` — Rotations of *xyz*-positions**
`quaternion` array | matrix of `[w x y z]` quaternion vectors | *N*-element array of `so2` or `so3` objects

Rotations of *xyz*-positions specified as a `quaternion` array, *N*-by-4 matrix of `[w x y z]` quaternion vectors, or an *N*-element array of `so2` or `so3` objects. *N* is the total number of rotations, and each element of the array, each row of the matrix or rotation transformation objects represent the rotation of the *xyz*-positions specified in `translations`.

If `rotations` is an *N*-element array of `so2` or `so3` objects, each element must be of the same type.

Example: `[1 1 1 0; 1 3 5 0]`

**`transformations` — Transformation**
`se2` object | `se3` object | *M*-element array of `se2` or `se3` objects

Transformations, specified as an `se2` object, an `se3` object, or an *M*-element array of `se2` or `se3` objects. *M* is the total number of transformations.

If you specify `transformations` as an array, each element must be of the same type.

### Name-Value Pair Arguments

Specify optional pairs of arguments as `Name1=Value1,...,NameN=ValueN`, where `Name` is the argument name and `Value` is the corresponding value. Name-value arguments must appear after other arguments, but the order of the pairs does not matter.

*Before R2021a, use commas to separate each name and value, and enclose* `Name` *in quotes.*

Example: `'FrameSize',5`

#### `FrameSize` — Size of frames and attached meshes
positive numeric scalar

Size of frame and attached meshes, specified as positive numeric scalar.

#### `FrameColor` — Color of frames
`"rgb"` (default) | RGB triplet | string scalar

Color of frames, specified as an RGB triplet or string scalar.

Example: `[0 0 1]` or `"green"`

#### `FrameAxisLabels` — *xyz* labels of coordinate frame
`"off"` (default) | `"on"`

*xyz* labels of the coordinate frame, specified as `"off"` to hide the labels or `"on"` to show the labels.

#### `FrameAxisLabels` — Frame axis labels
`""` (default) | `string` | *N*-element array of strings

Frame axis labels, specified as a string or *N*-element array of strings, where *N* is the total number of frames and each string corresponds to one frame at the same index of `transformations`, `translations`, or `rotations`.

#### `AxisLabels` — *xyz* labels of plotting axes
`"off"` (default) | `"on"`

*xyz* labels of the plotting axes, specified as `"off"` to hide the labels or `"on"`to show the labels.

#### `InertialZDirection` — Direction of positive *z*-axis of inertial frame
`"up"` (default) | `"down"`

Direction of the positive *z*-axis of inertial frame, specified as either `"up"` or `"down"`. In the plot, the positive *z*-axis always points up.

#### `MeshFilePath` — File path of mesh file attached to frames
character vector | string scalar

File path of mesh file attached to frames, specified as either a character vector or string scalar. The mesh is attached to each plotted frame at the specified position and orientation. Provided `.stl` are

- `"fixedwing.stl"`
- `"multirotor.stl"`
- `"groundvehicle.stl"`

Example: `'fixedwing.stl'`

**MeshColor — Color of attached mesh**
"red" (default) | RGB triplet | string scalar

Color of attached mesh, specified as an RGB triplet or string scalar.

Example: [0 0 1] or "green"

**View — Plot view**
"3D" (default) | "2D" | three-element vector

Plot view, specified as "3D", "2D", or a three-element vector of the form [*x*,*y*,*z*] that sets the view angle in Cartesian coordinates. The magnitude of *x*,*y*, and *z* are ignored.

**Parent — Axes used to plot transforms**
Axes object | UIAxes object

Axes used to plot the pose graph, specified as the comma-separated pair consisting of 'Parent' and either an Axes or UIAxes object. See axes or uiaxes.

## Output Arguments

**ax — Axes used to plot transforms**
Axes object | UIAxes object

Axes used to plot the pose graph, specified as the comma-separated pair consisting of 'Parent' and either an Axes or UIAxesobject. See axes or uiaxes.

# Version History

**Introduced in R2018b**

## See Also

**Functions**
quaternion | hom2cart | eul2quat | tform2quat | rotm2quat

**Objects**
se2 | se3 | so2 | so3

# poseGraphSolverOptions

Solver options for pose graph optimization

## Syntax

```
solverOptions = poseGraphSolverOptions(solverType)
```

## Description

`solverOptions = poseGraphSolverOptions(solverType)` returns the set of solver options with default values for the specified pose graph solver type.

## Examples

### Optimize and Trim Loop Closures For 2-D Pose Graphs

Optimize a pose graph based on the nodes and edge constraints. Trim loop closed based on their edge residual errors.

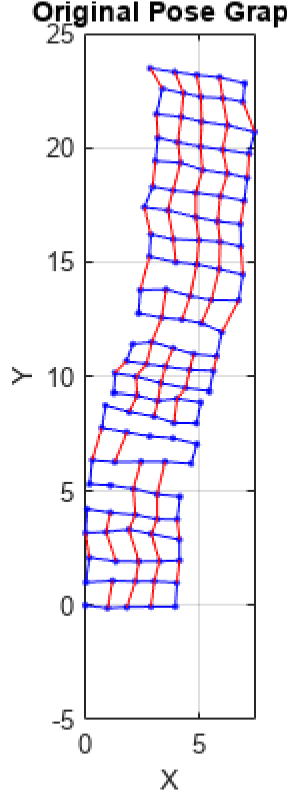
Load the data set that contains a 2-D pose graph. Inspect the `poseGraph` object to view the number of nodes and loop closures.

```
load grid-2d-posegraph.mat pg
disp(pg)
```

```
  poseGraph with properties:

               NumNodes: 120
               NumEdges: 193
    NumLoopClosureEdges: 74
     LoopClosureEdgeIDs: [120 121 122 123 124 125 126 127 128 129 130 131 132 133 134 135 136 137
        LandmarkNodeIDs: [1x0 double]
```

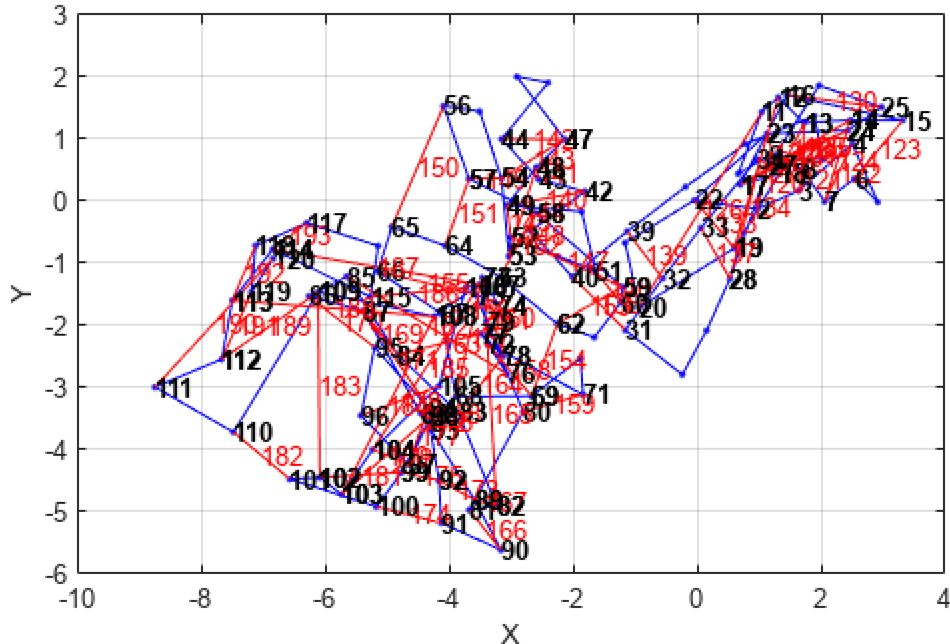
Plot the pose graph with IDs off. Red lines indicate loop closures identified in the dataset. The poses in the graph should follow a grid pattern, but show evidence of drift over time.

```
show(pg,'IDs','off');
title('Original Pose Graph')
```



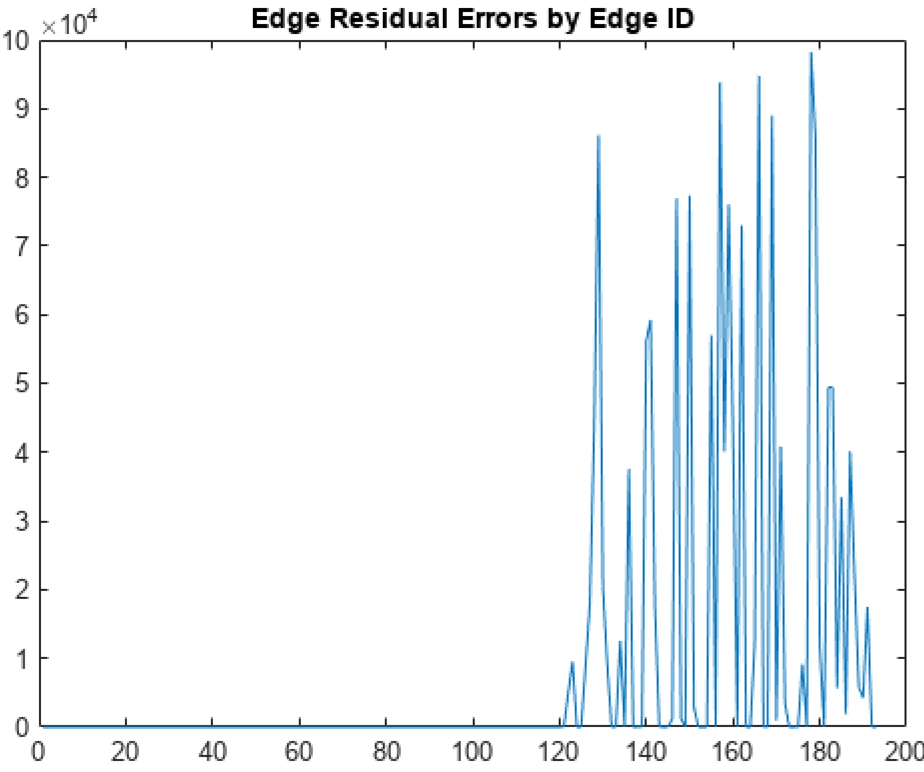

Optimize the pose graph using the `optimizePoseGraph` function. By default, this function uses the `"builtin-trust-region"` solver. Because the pose graph contains some bad loop closures, the resulting pose graph is actual not desirable.

```
pgOptim = optimizePoseGraph(pg);
figure;
show(pgOptim);
```




Look at the edge residual errors for the original pose graph. Large outlier error values at the end indicate bad loop closures.

```
resErrorVec = edgeResidualErrors(pg);
plot(resErrorVec);
title('Edge Residual Errors by Edge ID')
```




Certain loop closures should be trimmed from the pose graph based on their residual error. Use the `trimLoopClosures` function to trim these bad loop closures. Set the maximum and truncation threshold for the trimmer parameters. This threshold is set based on the measurement accuracy and should be tuned for your system.

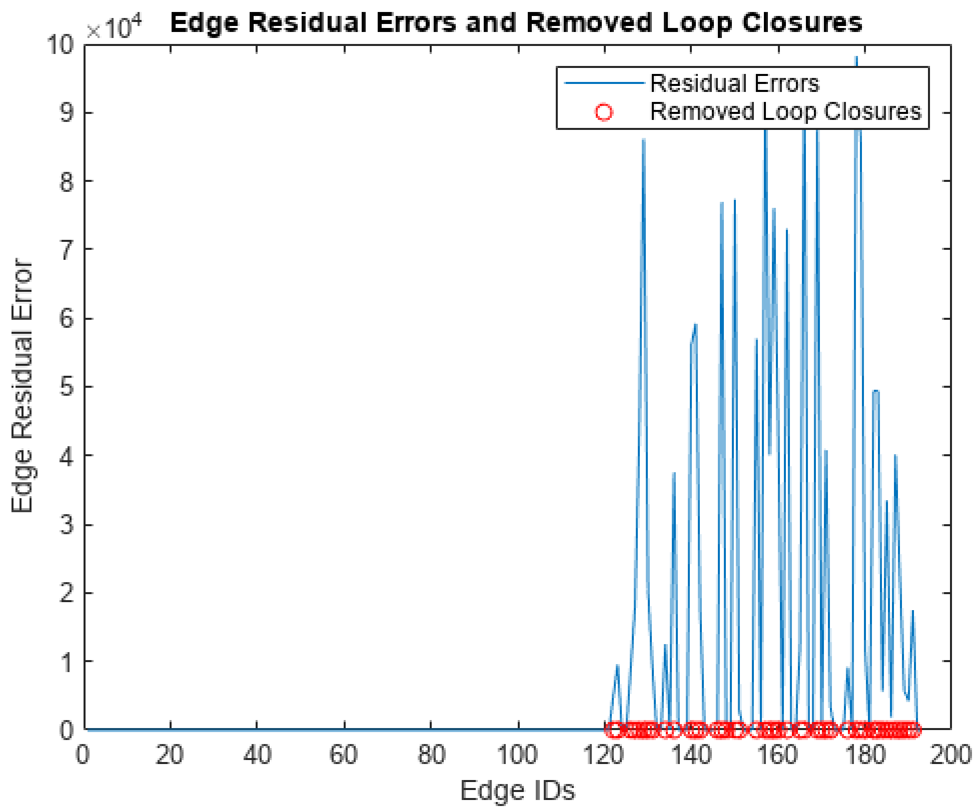
```
trimParams.MaxIterations = 100;
trimParams.TruncationThreshold = 25;

solverOptions = poseGraphSolverOptions;
```

Use the `trimLoopClosures` function with the trimmer parameters and solver options.

```
[pgNew, trimInfo, debugInfo] = trimLoopClosures(pg,trimParams,solverOptions);
```

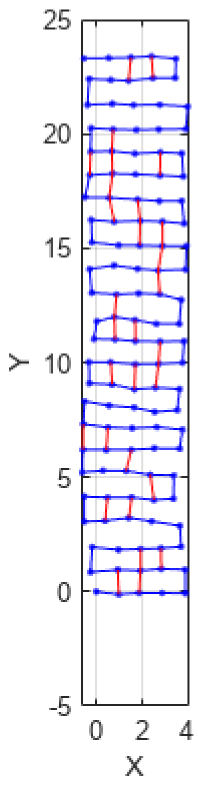
From the `trimInfo` output, plot the loop closures removed from the optimized pose graph. By plotting with the residual errors plot before, you can see the large error loop closures were removed.

```
removedLCs = trimInfo.LoopClosuresToRemove;

hold on
plot(removedLCs,zeros(length(removedLCs)),'or')
title('Edge Residual Errors and Removed Loop Closures')
legend('Residual Errors', 'Removed Loop Closures')
xlabel('Edge IDs')
ylabel('Edge Residual Error')
hold off
```




Show the new pose graph with the bad loop closures trimmed.

```
show(pgNew,"IDs","off");
```




## Input Arguments

**solverType — Pose graph solver type**
'builtin-trust-region' (default) | 'g2o-levenberg-marquardt'

Pose graph solver type, specified as 'builtin-trust-region' or 'g2o-levenberg-marquardt'.

The function generates a set of solver options with default values for the specified pose graph solver type:

```
pgSolverTrustRegion = poseGraphSolverOptions('builtin-trust-region')
```

```
pgSolverTrustRegion =

TrustRegion (builtin-trust-region-dogleg) options:

               MaxIterations: 300
                     MaxTime: 10
           FunctionTolerance: 1.0000e-08
           GradientTolerance: 5.0000e-09
               StepTolerance: 1.0000e-12
    InitialTrustRegionRadius: 100
               VerboseOutput: 'off'
```

```
pgSolverG2o = poseGraphSolverOptions('g2o-levenberg-marquardt')
```

```
pgSolverG2o =

G2oLevenbergMarquardt (g2o-levenberg-marquardt) options:

        MaxIterations: 300
              MaxTime: 10
    FunctionTolerance: 1.0000e-09
        VerboseOutput: 'off'
```

Data Types: `char` | `string`

## Output Arguments

**`solverOptions` — Pose graph solver options**
`poseGraphSolverOptions` parameters

Pose graph solver options, specified as a set of parameters generated by calling the `poseGraphSolverOptions` function. The function generates a set of solver options with default values for the specified pose graph solver type.

**If the `solverType` input is set to `"builtin-trust-region"`:**

| | Default | Description |
|---|---|---|
| `MaxIterations` | `300` | Maximum number of iterations, specified as a positive integer. The optimizer exits after it exceeds this number of iterations. |
| `MaxTime` | `500` | Maximum time allowed, specified as a positive numeric scalar in seconds. The optimizer exits after it exceeds this time. |
| `FunctionTolerance` | `1e-8` | Lower bound on the change in the cost function, specified as a scalar. If the cost function change falls below this value between optimization steps, the optimizer exits. |
| `GradientTolerance` | `0.5e-8` | Lower bound on the norm of the gradient, specified as a scalar. The norm of the gradient is calculated based on the cost function of the optimization. If the norm falls below this value, the optimizer exits. |
| `StepTolerance` | `1e-12` | Lower bound on the step size, specified as a scalar. If the norm of the optimization step falls below this value, the optimizer exits. |
| `InitialTrustRegionRadius` | `100` | Initial trust region radius, specified as a scalar. |
| `VerboseOutput` | `'off'` or `'on'` | Display intermediate iteration information on the MATLAB command line. |

**If the `solver` input is set to `"g2o-levenberg-marquardt"`:**

| | Default | Description |
|---|---|---|
| `MaxIterations` | `300` | Maximum number of iterations, specified as a positive integer. The optimizer exits after it exceeds this number of iterations. |
| `MaxTime` | `500` | Maximum time allowed, specified as a positive numeric scalar in seconds. The optimizer exits after it exceeds this time. |
| `FunctionTolerance` | `1e-8` | Lower bound on the change in the cost function, specified as a scalar. If the cost function change falls below this value between optimization steps, the optimizer exits. |
| `VerboseOutput` | `'off'` or `'on'` | Display intermediate iteration information on the MATLAB command line. |

# Version History

**Introduced in R2020b**

## See Also

**Functions**

`trimLoopClosures` | `edgeResidualErrors` | `edgeResidualErrors` | `removeEdges` | `edgeNodePairs` | `edgeConstraints`

**Objects**

`poseGraph` | `poseGraph3D` | `lidarSLAM`

# poseplot

3-D pose plot

## Syntax

```
poseplot
poseplot(quat)
poseplot(R)
poseplot( ___ ,position)
poseplot( ___ ,frame)
poseplot( ___ ,Name=Value)
poseplot(ax, ___ )
p = poseplot( ___ )
```

## Description

`poseplot` plots the pose (position and orientation) at the coordinate origin position with zero rotation. The default navigation frame is the north-east-down (NED) frame.

`poseplot(quat)` plots the pose with orientation specified by a quaternion `quat`. The position by default is `[0 0 0]`.

`poseplot(R)` plots the pose with orientation specified by a rotation matrix `R`. The position by default is `[0 0 0]`.

`poseplot( ___ ,position)` specifies the position of the pose plot.

`poseplot( ___ ,frame)` specifies the navigation frame of the pose plot.

`poseplot( ___ ,Name=Value)` specifies pose patch properties using one or more name-value arguments. For example, `poseplot(PatchFaceColor="r")` plots the pose with red face color. For a list of properties, see PosePatch Properties.

`poseplot(ax, ___ )` specifies the parent axes of the pose plot.

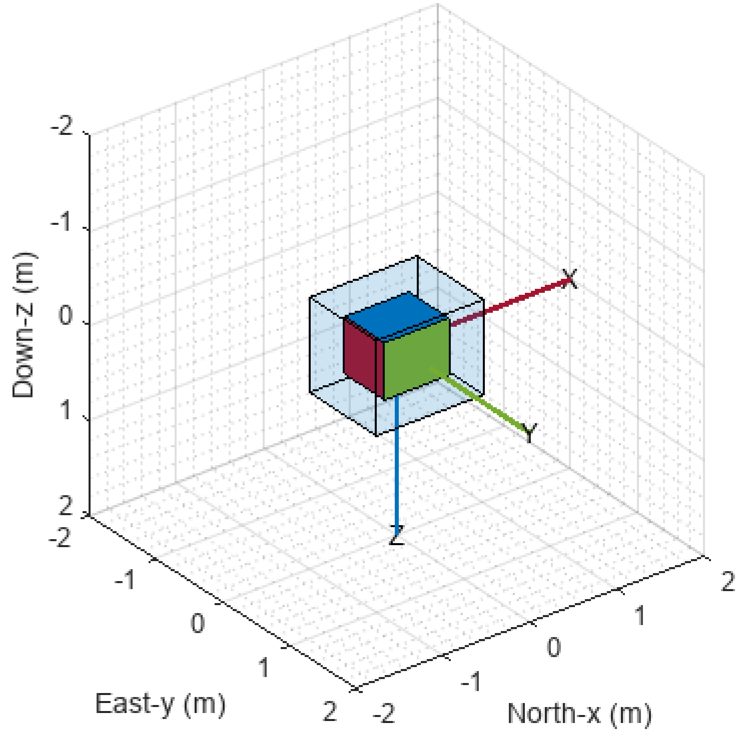
`p = poseplot( ___ )` returns the `PosePatch` object. Use `p` to modify properties of the pose patch after creation. For a list of properties, see PosePatch Properties.

## Examples

### Visualize Pose Using poseplot

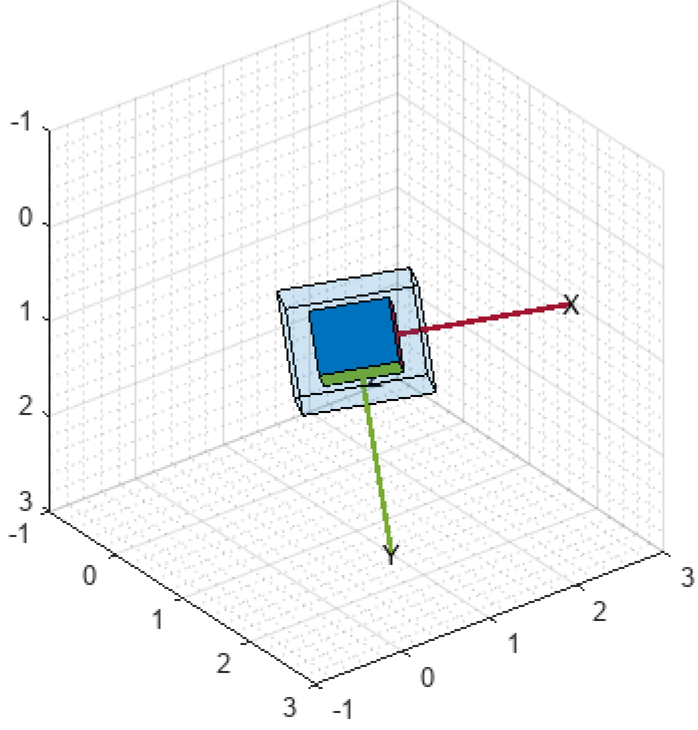
Plot the default pose using the `poseplot` function with default settings.

```
poseplot
xlabel("North-x (m)")
ylabel("East-y (m)")
zlabel("Down-z (m)");
```




Next, plot a pose with specified orientation and position.

```
q = quaternion([35 10 50],"eulerd","ZYX","frame");
position = [1 1 1];
poseplot(q,position)
```

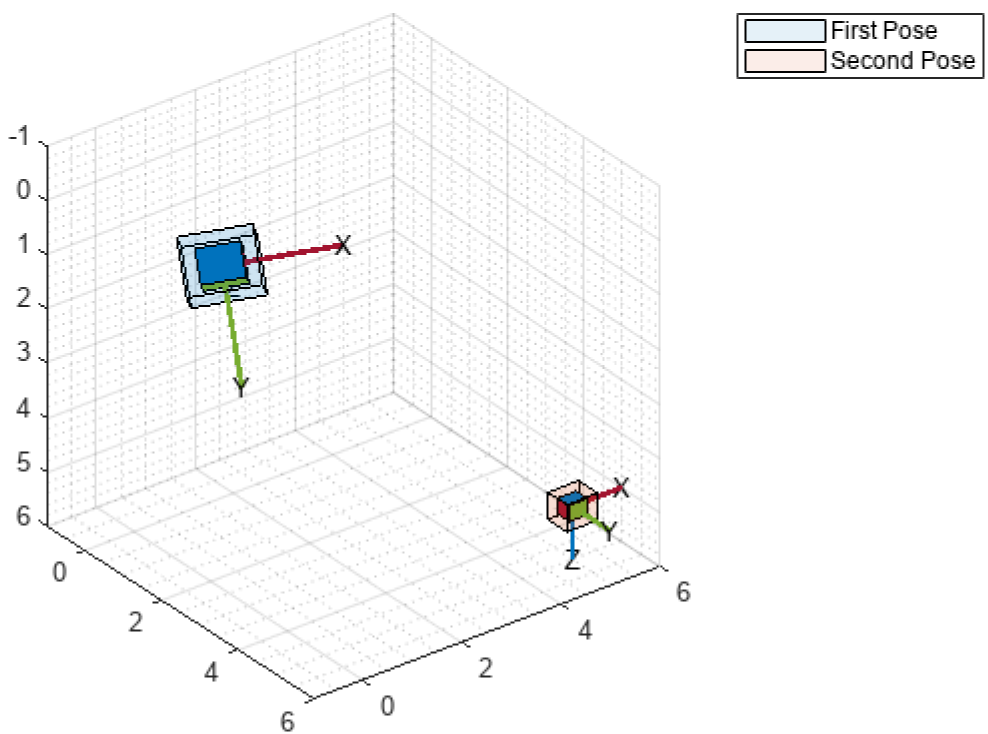



Then, plot a second pose on the figure and return the `PosePatch` object. Plot the second pose with a smaller size by using the `ScaleFactor` name-value argument.

```
hold on
p = poseplot(eye(3),[5 5 5],ScaleFactor=0.5)
```

```
p = 
  PosePatch with properties:

    Orientation: [3x3 double]
       Position: [5 5 5]

  Show all properties
```

```
legend("First Pose","Second Pose")
hold off
```




#### Animate Pose Using poseplot

Animate a series of poses using the `poseplot` function. First, define the initial and final positions.

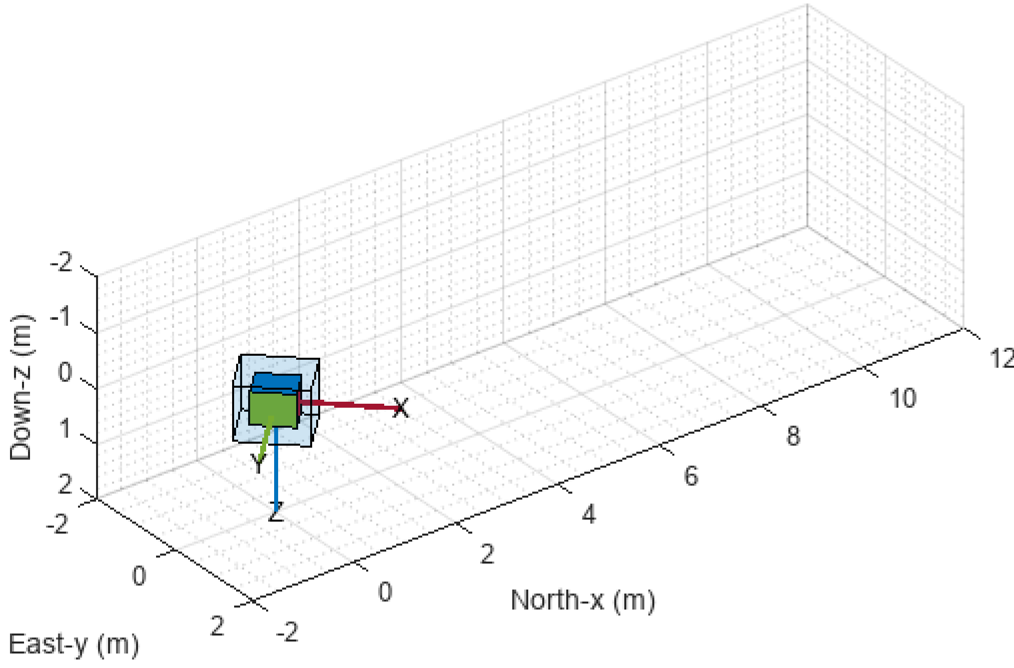
```
ps = [0 0 0];
pf = [10 0 0];
```

Then, define the initial and final orientations using the `quaternion` object.

```
qs = quaternion([45,0,0],'eulerd','ZYX','frame');
qf = quaternion([-45,0,0],'eulerd','ZYX','frame');
```

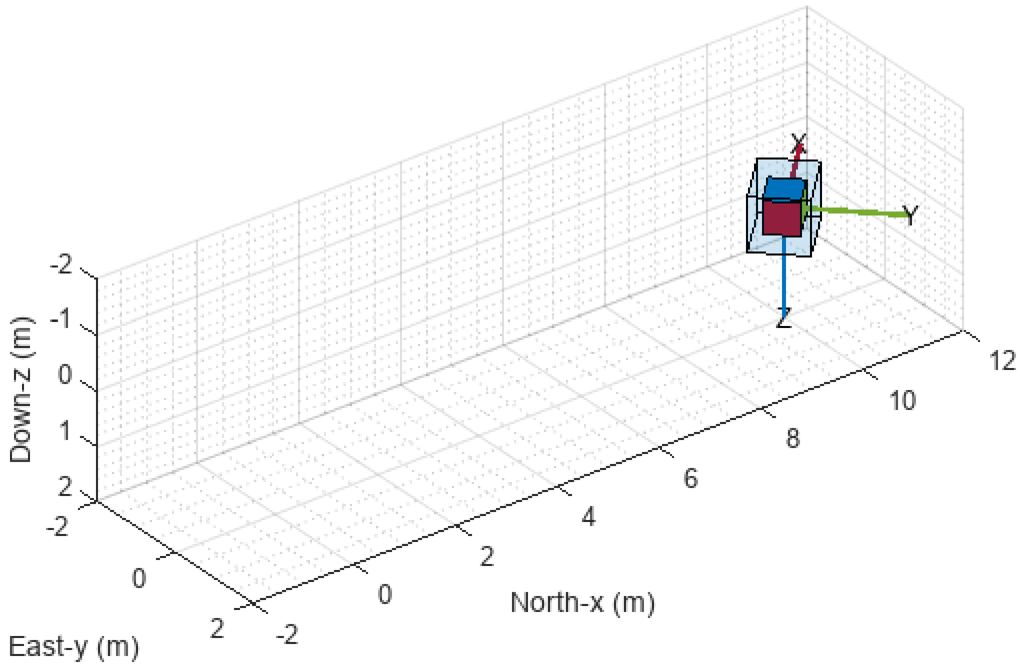
Show the starting pose.

```
patch = poseplot(qs,ps);
ylim([-2 2])
xlim([-2 12])
xlabel("North-x (m)")
ylabel("East-y (m)")
zlabel("Down-z (m)");
```




Change the position and orientation continuously using coefficients, and update the pose using the `set` object function.

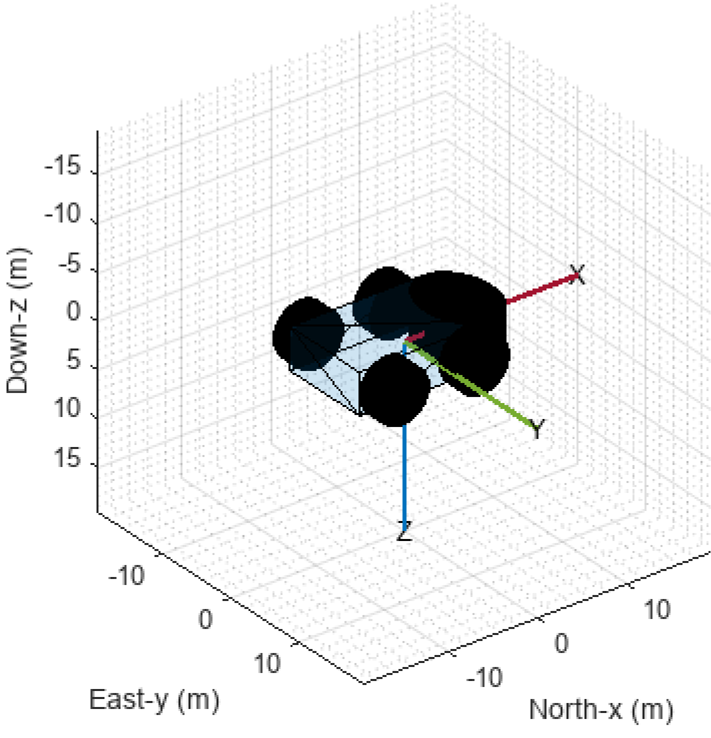
```
for coeff = 0:0.01:1
    q = slerp(qs,qf,coeff);
    position = ps + (pf - ps)*coeff;
    set(patch,Orientation=q,Position=position);
    drawnow
end
```




#### Show Poses with Meshes

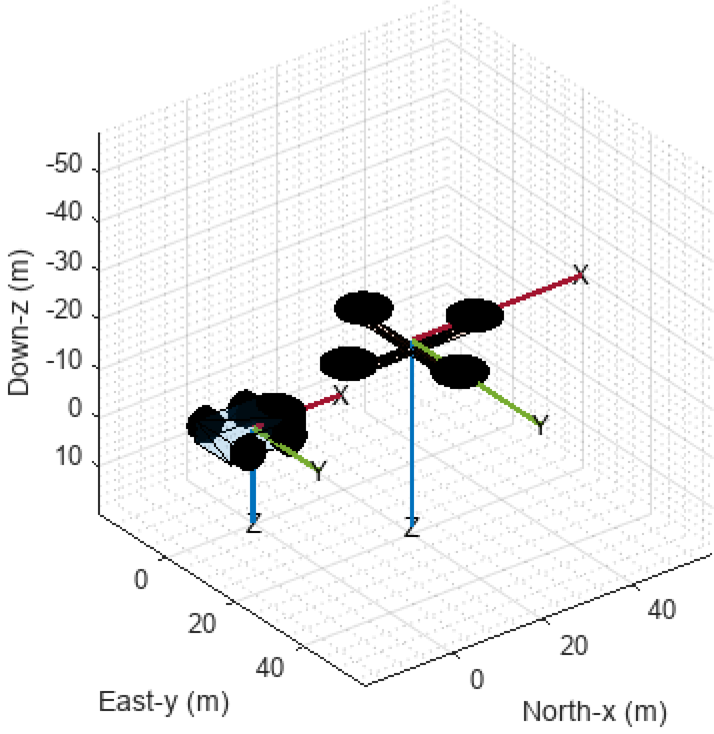
Plot orientations and positions in meshes using the `poseplot` function. First, plot a ground vehicle at the origin with zero rotation.

```
poseplot(ones("quaternion"),[0 0 0],MeshFileName="groundvehicle.stl",ScaleFactor=0.3);
xlabel("North-x (m)")
ylabel("East-y (m)")
zlabel("Down-z (m)")
```



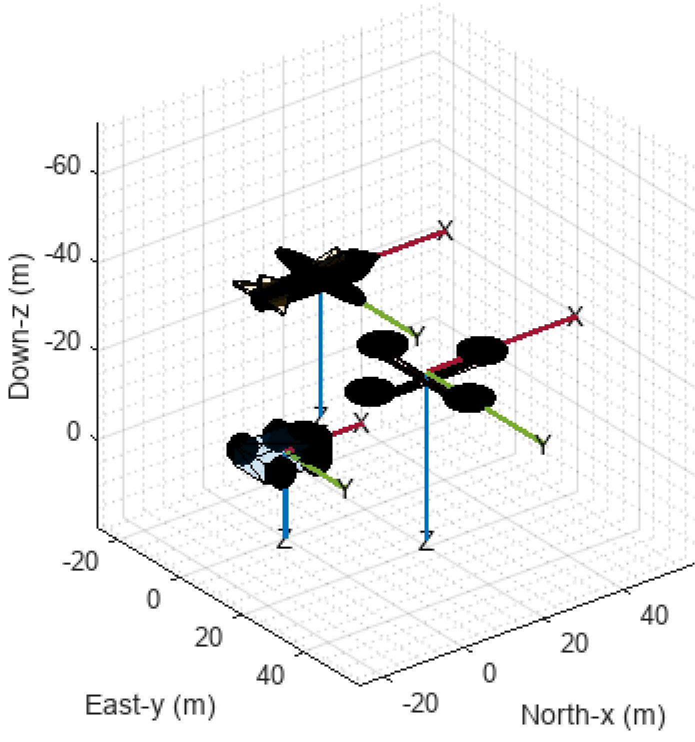

Second, plot a rotor at the position [20 20 -20] with zero rotation.

```
hold on
poseplot(ones("quaternion"),[20 20 -20],MeshFileName="multirotor.stl",ScaleFactor=0.2);
```




Lastly, plot a fixed-wing aircraft at the position `[5 5 -40]` with zero rotation.

```
poseplot(ones("quaternion"),[5 5 -40],MeshFileName="fixedwing.stl",ScaleFactor=0.4);
view([-37.8 28.4])
hold off
```




## Input Arguments

**`quat` — Quaternion**
`quaternion` object

Quaternion, specified as a `quaternion` object.

**`R` — Rotation matrix**
3-by-3 orthonormal matrix

Rotation matrix, specified as a 3-by-3 orthonormal matrix.

Example: `eye(3)`

**`position` — Position of pose plot**
three-element real-valued vector

Position of the pose plot, specified as a three-element real-valued vector.

Example: `[1 3 4]`

**`frame` — Navigation frame of pose plot**
`"NED"` (default) | `"ENU"`

Navigation frame of the pose plot, specified as `"NED"` for the north-east-down frame or `"ENU"` for the east-north-up frame.

When the parent axes status is `hold off`, specifying the NED navigation frame reverses the y- and z-axes in the figure by setting the `YDir` and `ZDir` properties of the parent axes.

**ax — Parent axes of pose plot**
`Axes` object

Parent axes of the pose plot, specified as an `Axes` object. If you do not specify the axes, the `poseplot` function uses the current axes.

### Name-Value Pair Arguments

Specify optional pairs of arguments as `Name1=Value1,...,NameN=ValueN`, where `Name` is the argument name and `Value` is the corresponding value. Name-value arguments must appear after other arguments, but the order of the pairs does not matter.

The `PosePatch` properties listed here are only a subset. For a complete list, see PosePatch Properties.

Example: `poseplot(PatchFaceAlpha=0.1)`

**`Orientation` — Orientation of pose plot**
`quaternion` object (default) | rotation matrix

Orientation of the pose plot, specified as a `quaternion` object or a rotation matrix.

**`Position` — Position of pose plot**
`[0 0 0]` (default) | three-element real-valued vector

Position of the pose plot, specified as a three-element real-valued vector.

**`MeshFileName` — Name of STL mesh file**
string scalar | character vector

Name of Standard Triangle Language (STL) mesh file, specified as a string scalar or a character vector containing the name of the mesh file. When you specify this argument, the `poseplot` function plots the mesh instead of the orientation box.

**`ScaleFactor` — Scale factor of pose plot**
`1` (default) | nonnegative scalar

Scale factor of the pose plot, specified as a nonnegative scalar. The scale factor controls the size of the orientation box. When you specify the `MeshFileName` argument, the scale factor also changes the scale of the mesh.

**`PatchFaceColor` — Patch face color**
`[0 0 0]` (default) | RGB triplet | hexadecimal color code | `"r"` | `"g"` | `"b"` | ...

Patch face color, specified as an RGB triplet, a hexadecimal color code, a color name, or a short name.

- An RGB triplet is a three-element row vector whose elements specify the intensities of the red, green, and blue components of the color. The intensities must be in the range `[0, 1]`; for example, `[0.4 0.6 0.7]`.
- A hexadecimal color code is a character vector or a string scalar that starts with a hash symbol (`#`) followed by three or six hexadecimal digits, which can range from `0` to `F`. The values are not case sensitive. Thus, the color codes `"#FF8800"`, `"#ff8800"`, `"#F80"`, and `"#f80"` are equivalent.

Here is a list of commonly used colors and their corresponding values.

| Color Name | Short Name | RGB Triplet | Hexadecimal Color Code | Appearance |
|---|---|---|---|---|
| "red" | "r" | [1 0 0] | "#FF0000" | |
| "green" | "g" | [0 1 0] | "#00FF00" | |
| "blue" | "b" | [0 0 1] | "#0000FF" | |
| "cyan" | "c" | [0 1 1] | "#00FFFF" | |
| "magenta" | "m" | [1 0 1] | "#FF00FF" | |
| "yellow" | "y" | [1 1 0] | "#FFFF00" | |
| "black" | "k" | [0 0 0] | "#000000" | |
| "white" | "w" | [1 1 1] | "#FFFFFF" | |

**PatchFaceAlpha — Patch face transparency**
0.1 (default) | scalar in range [0, 1]

Patch face transparency, specified as a scalar in range [0, 1]. A value of 1 is fully opaque and 0 is completely transparent.

### Output Arguments

**p — Pose patch object**
PosePatch object

Pose patch object, returned as a PosePatch object. You can use the returned object to query and modify properties of the plotted pose. For a list of properties, see PosePatch Properties.

## Version History

**Introduced in R2021b**

### See Also

PosePatch Properties

# PosePatch Properties

Pose plot appearance and behavior

## Description

PosePatch properties control the appearance and behavior of a PosePatch object. By changing property values, you can modify certain aspects of the pose plot. Use dot notation to query and set properties. To create a PosePatch object, use the poseplot function.

```
p = poseplot;
c = p.PatchFaceColor;
p.PatchFaceColor = "red";
```

### Properties

#### Position and Orientation

**Orientation — Orientation of pose plot**
quaternion object (default) | rotation matrix

Orientation of the pose plot, specified as a quaternion object or a rotation matrix.

**Position — Position of pose plot**
[0 0 0] (default) | three-element real-valued vector

Position of the pose plot, specified as a three-element real-valued vector.

#### Color and Styling

**ScaleFactor — Scale factor of pose plot**
1 (default) | nonnegative scalar

Scale factor of the pose plot, specified as a nonnegative scalar. The scale factor controls the size of the orientation box. When you specify the MeshFileName argument, the scale factor also changes the scale of the mesh.

**PatchFaceColor — Patch face color**
[0 0 0] (default) | RGB triplet | hexadecimal color code | "r" | "g" | "b" | ...

Patch face color, specified as an RGB triplet, a hexadecimal color code, a color name, or a short name.

- An RGB triplet is a three-element row vector whose elements specify the intensities of the red, green, and blue components of the color. The intensities must be in the range [0, 1]; for example, [0.4 0.6 0.7].
- A hexadecimal color code is a character vector or a string scalar that starts with a hash symbol (#) followed by three or six hexadecimal digits, which can range from 0 to F. The values are not case sensitive. Thus, the color codes "#FF8800", "#ff8800", "#F80", and "#f80" are equivalent.

Here is a list of commonly used colors and their corresponding values.

| Color Name | Short Name | RGB Triplet | Hexadecimal Color Code | Appearance |
| --- | --- | --- | --- | --- |
| "red" | "r" | [1 0 0] | "#FF0000" | |
| "green" | "g" | [0 1 0] | "#00FF00" | |
| "blue" | "b" | [0 0 1] | "#0000FF" | |
| "cyan" | "c" | [0 1 1] | "#00FFFF" | |
| "magenta" | "m" | [1 0 1] | "#FF00FF" | |
| "yellow" | "y" | [1 1 0] | "#FFFF00" | |
| "black" | "k" | [0 0 0] | "#000000" | |
| "white" | "w" | [1 1 1] | "#FFFFFF" | |

### MeshFileName — Name of STL mesh file

string scalar | character vector

Name of Standard Triangle Language (STL) mesh file, specified as a string scalar or a character vector containing the name of the mesh file. When you specify this argument, the `poseplot` function plots the mesh instead of the orientation box.

### PatchFaceAlpha — Patch face transparency

`0.1` (default) | scalar in range `[0, 1]`

Patch face transparency, specified as a scalar in range `[0, 1]`. A value of `1` is fully opaque and `0` is completely transparent.

#### Parent/Children

### Parent — Parent axes

`Axes` object

Parent axes, specified as an `Axes` object.

### Children — Children

empty `GraphicsPlaceholder` array | `DataTip` object array

Children, returned as an empty `GraphicsPlaceholder` array or a `DataTip` object array. Currently, this property is not used and is reserved for future use.

#### Interactivity

### Visible — Pose plot visibility

`"on"` (default) | `"off"` | on/off logical value

Pose plot visibility, specified as `"on"` or `"off"`, or as numeric or logical `1` (`true`) or `0` (`false`). A value of `"on"` is equivalent to `true`, and `"off"` is equivalent to `false`. Thus, you can use the value of this property as a logical value. The value is stored as an on/off logical value of type `matlab.lang.OnOffSwitchState`.

- `"on"` — Display the object.
- `"off"` — Hide the object without deleting it. You still can access the properties of an invisible object.

**HandleVisibility — Visibility of pose patch object handle**
"on" (default) | "off" | "callback"

Visibility of the pose patch object handle in the Children property of the parent, specified as one of these values:

- "on" — Object handle is always visible.
- "off" — Object handle is invisible at all times. This option is useful for preventing unintended changes by another function. Set HandleVisibility to "off" to temporarily hide the handle during the execution of that function. Hidden object handles are still valid.
- "callback" — Object handle is visible from within callbacks or functions invoked by callbacks, but not from within functions invoked from the command line. This option blocks access to the object at the command line, but permits callback functions to access it.

**Standard Chart Properties**

**DisplayName — Pose plot name to display in legend**
string scalar | character vector

Pose plot name to display in the legend, specified as a string scalar or character vector. The legend does not display until you call the legend command. If you do not specify the display name, then legend sets the label using the format "dataN", where N is the order of pose plots shown in the axes. You can also directly specify the legend. For example: legend("Pose1","Pose2").

**Type — Type of pose plot object**
'PosePatch' (default)

This property is read-only.

Type of pose plot object, returned as 'PosePatch'. Use this property to find all objects of a given type within a plotting hierarchy, for example, searching for the type using the findobj function.

**Annotation — Control for including or excluding object from legend**
Annotation object

This property is read-only.

Control for including or excluding the object from a legend, returned as an Annotation object. Set the underlying IconDisplayStyle property to one of these values:

- "on" — Include the object in the legend (default).
- "off" — Do not include the object in the legend.

For example, to exclude a graphics object, go, from the legend, set the IconDisplayStyle property to "off".

```
go.Annotation.LegendInformation.IconDisplayStyle = "off";
```

Alternatively, you can control the items in a legend using the legend function.

**SeriesIndex — Pose plot series index**
1 (default) | nonnegative integer

Pose plot series index, specified as a nonnegative integer. Use this property to reassign the marker colors of several PosePatch objects so that they match each other. By default, the SeriesIndex

property of a `PosePatch` object is a number that corresponds to the order of creation of the object, starting at `0`.

MATLAB uses the number to calculate indices for assigning colors when you call plotting functions if you do not specify the color directly. The indices refer to the rows of the arrays stored in the `ColorOrder` property of the axes.

# Version History

**Introduced in R2021b**

## See Also

`poseplot`

# pseudoranges

Pseudoranges between GNSS receiver and satellites

## Syntax

```
p = pseudoranges(recPos,satPos)
[p,pdot] = pseudoranges( ___ ,recVel,satVel)
[p,pdot] = pseudoranges( ___ ,Name,Value)
```

## Description

`p = pseudoranges(recPos,satPos)` returns the pseudoranges between the receiver at position `recPos` and the satellites at positions `satPos`.

`[p,pdot] = pseudoranges( ___ ,recVel,satVel)` returns the pseudorange rates `pdot` between the receiver and satellites. Use this syntax with the input arguments in the previous syntax.

`[p,pdot] = pseudoranges( ___ ,Name,Value)` specifies the measurement noise for the ranges and range rates using name-value arguments. For example, `[p,pdot] = pseudoranges(__,'RangeAccuracy',2)` sets the measurement noise in pseudoranges, specified as a scalar standard deviation in meters.

## Examples

### Get Satellite Pseudoranges for Receiver Position and Velocity

Use the `pseudoranges` function to get the pseudorange and pseudorange rate for given satellite and receiver positions and velocities. Get the satellite positions and velocities using the `gnssconstellation` function.

Specify a receiver position in geodetic coordinates (latitude, longitude, altitude) and receiver velocity in the local navigation frame.

```
recPos = [42 -71 50];
recVel = [1 2 3];
```

Get the satellite positions for the current time.

```
t = datetime('now');
[gpsSatPos,gpsSatVel] = gnssconstellation(t);
```

Get the pseudoranges and pseudorange rates between the receiver and satellites.

```
[p,pdot] = pseudoranges(recPos,gpsSatPos,recVel,gpsSatVel);
```

## Input Arguments

**recPos — Receiver position**

three-element vector of the form [*latitude longitude altitude*]

Receiver position in geodetic coordinates, specified as a three-element vector of the form [*latitude longitude altitude*].

Data Types: `single` | `double`

**`satPos` — Satellite positions**
*N*-by-3 matrix of scalars

Satellite positions in the Earth-centered Earth-fixed (ECEF) coordinate system in meters, specified as an *N*-by-3 matrix of scalars. *N* is the number of satellites in the constellation.

Data Types: `single` | `double`

**`recVel` — Receiver velocity**
three-element vector of the form [*vx vy vz*]

Receiver velocity in the local navigation frame using north-east-down (NED) coordinates, specified as a three-element vector of the form [*vx vy vz*].

Data Types: `single` | `double`

**`satVel` — Satellite velocities**
*N*-by-3 matrix of scalars

Satellite velocities in the Earth-centered Earth-fixed (ECEF) coordinate system in meters per second, specified as an *N*-by-3 matrix of scalars. *N* is the number of satellites in the constellation.

Data Types: `single` | `double`

### Name-Value Pair Arguments

Specify optional pairs of arguments as `Name1=Value1,...,NameN=ValueN`, where `Name` is the argument name and `Value` is the corresponding value. Name-value arguments must appear after other arguments, but the order of the pairs does not matter.

*Before R2021a, use commas to separate each name and value, and enclose* `Name` *in quotes.*

Example: `'RangeAccuracy',0.5` sets the measurement noise of the pseudoranges to 0.5 meters.

**`RangeAccuracy` — Measurement noise in pseudoranges**
`1` (default) | scalar

Measurement noise in pseudoranges, specified as a scalar standard deviation in meters.

Data Types: `single` | `double`

**`RangeRateAccuracy` — Measurement noise in pseudorange rates**
`0.02` (default) | scalar

Measurement noise in pseudorange rates, specified as a scalar standard deviation in meters per second.

Data Types: `single` | `double`

## Output Arguments

**p — Pseudoranges between satellites and receiver**
*n*-element vector

Pseudoranges between the satellites and receiver, returned as an *n*-element vector in meters.

Data Types: `single` | `double`

**`pdot` — Pseudorange rates between satellites and receiver**
`zeros(n,1)` (default) | *n*-element vector

Pseudorange rates between the satellites and receiver, returned as an *n*-element vector in meters per second. If you do not provide velocity inputs, this output is zero.

Data Types: `single` | `double`

# Version History

**Introduced in R2021a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Objects

`gnssSensor` | `gpsSensor` | `imuSensor`

### Functions

`skyplot` | `gnssconstellation` | `lookangles` | `receiverposition`

# quat2axang

Convert quaternion to axis-angle rotation

## Syntax

```
axang = quat2axang(quat)
```

## Description

`axang = quat2axang(quat)` converts a quaternion, `quat`, to the equivalent axis-angle rotation, `axang`.

## Examples

### Convert Quaternion to Axis-Angle Rotation

```
quat = [0.7071 0.7071 0 0];
axang = quat2axang(quat)
```

```
axang = 1×4

    1.0000         0         0    1.5708
```

## Input Arguments

**quat — Unit quaternion**
*n*-by-4 matrix | n-element vector of `quaternion` objects

Unit quaternion, specified as an *n*-by-4 matrix or n-element vector of `quaternion` objects containing *n* quaternions. If the input is a matrix, each row is a quaternion vector of the form $q = [w\ x\ y\ z]$, with *w* as the scalar number.

Example: `[0.7071 0.7071 0 0]`

## Output Arguments

**axang — Rotation given in axis-angle form**
*n*-by-4 matrix

Rotation given in axis-angle form, returned as an *n*-by-4 matrix of *n* axis-angle rotations. The first three elements of every row specify the rotation axis, and the last element defines the rotation angle (in radians).

Example: `[1 0 0 pi/2]`

## Version History

**Introduced in R2015a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`axang2quat` | `quaternion`

# quat2eul

Convert quaternion to Euler angles

## Syntax

```
eul = quat2eul(quat)
eul = quat2eul(quat,sequence)
[eul,eulAlt] = quat2eul( ___ )
```

## Description

`eul = quat2eul(quat)` converts a quaternion rotation, `quat`, to the corresponding Euler angles, `eul`. The default order for Euler angle rotations is `"ZYX"`.

`eul = quat2eul(quat,sequence)` converts a quaternion into Euler angles. The Euler angles are specified in the axis rotation sequence, `sequence`. The default order for Euler angle rotations is `"ZYX"`.

`[eul,eulAlt] = quat2eul( ___ )` also returns an alternate set of Euler angles that represents the same rotation `eulAlt`.

## Examples

### Convert Quaternion to Euler Angles

```
quat = [0.7071 0.7071 0 0];
eulZYX = quat2eul(quat)
```

```
eulZYX = 1×3

         0         0    1.5708
```

### Convert Quaternion to Euler Angles Using ZYZ Axis Order

```
quat = [0.7071 0.7071 0 0];
eulZYZ = quat2eul(quat,'ZYZ')
```

```
eulZYZ = 1×3

    1.5708   -1.5708   -1.5708
```

## Input Arguments

**quat — Unit quaternion**
*n*-by-4 matrix | n-element vector of `quaternion` objects

Unit quaternion, specified as an *n*-by-4 matrix or n-element vector of `quaternion` objects containing *n* quaternions. If the input is a matrix, each row is a quaternion vector of the form $q = [w\ x\ y\ z]$, with *w* as the scalar number.

Example: `[0.7071 0.7071 0 0]`

**`sequence` — Axis rotation sequence**
`"ZYX"` (default) | `"ZYZ"` | `"XYZ"`

Axis rotation sequence for the Euler angles, specified as one of these string scalars:

- `"ZYX"` (default) – The order of rotation angles is *z*-axis, *y*-axis, *x*-axis.
- `"ZYZ"` – The order of rotation angles is *z*-axis, *y*-axis, *z*-axis.
- `"XYZ"` – The order of rotation angles is *x*-axis, *y*-axis, *z*-axis.

Data Types: `string` | `char`

## Output Arguments

**`eul` — Euler rotation angles**
*n*-by-3 matrix

Euler rotation angles in radians, returned as an *n*-by-3 array of Euler rotation angles. Each row represents one Euler angle set.

Example: `[0 0 1.5708]`

**`eulAlt` — Alternate Euler rotation angle solution**
*n*-by-3 matrix

Alternate Euler rotation angle solution in radians, returned as an *n*-by-3 array of Euler rotation angles. Each row represents one Euler angle set.

Example: `[0 0 1.5708]`

# Version History

**Introduced in R2015a**

### R2020a: Alternate Euler angle output

`quat2eul` now optionally outputs an alternate set of Euler angles that also represent the same rotation as the original output Euler angles.

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

`eul2quat` | `quaternion`

# quat2rotm

Convert quaternion to rotation matrix

## Syntax

```
rotm = quat2rotm(quat)
```

## Description

`rotm = quat2rotm(quat)` converts a quaternion `quat` to an orthonormal rotation matrix, `rotm`. When using the rotation matrix, premultiply it with the coordinates to be rotated (as opposed to postmultiplying).

## Examples

### Convert Quaternion to Rotation Matrix

```
quat = [0.7071 0.7071 0 0];
rotm = quat2rotm(quat)
```

```
rotm = 3×3

    1.0000         0         0
         0   -0.0000   -1.0000
         0    1.0000   -0.0000
```

## Input Arguments

**`quat` — Unit quaternion**
*n*-by-4 matrix | n-element vector of `quaternion` objects

Unit quaternion, specified as an *n*-by-4 matrix or n-element vector of objects containing *n* quaternions. If the input is a matrix, each row is a quaternion vector of the form $q = [w\ x\ y\ z]$, with $w$ as the scalar number.

Example: `[0.7071 0.7071 0 0]`

## Output Arguments

**`rotm` — Rotation matrix**
3-by-3-by-*n* matrix

Rotation matrix, returned as a 3-by-3-by-*n* matrix containing *n* rotation matrices. Each rotation matrix has a size of 3-by-3 and is orthonormal. When using the rotation matrix, premultiply it with the coordinates to be rotated (as opposed to postmultiplying).

Example: `[0 0 1; 0 1 0; -1 0 0]`

## Version History

**Introduced in R2015a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`rotm2quat` | `quaternion` | `so2` | `so3`

# quat2tform

Convert quaternion to homogeneous transformation

## Syntax

```
tform = quat2tform(quat)
```

## Description

`tform = quat2tform(quat)` converts a quaternion, `quat`, to a homogeneous transformation matrix, `tform`. When using the transformation matrix, premultiply it with the coordinates to be transformed (as opposed to postmultiplying).

## Examples

### Convert Quaternion to Homogeneous Transformation

```
quat = [0.7071 0.7071 0 0];
tform = quat2tform(quat)
```

```
tform = 4×4

    1.0000         0         0         0
         0   -0.0000   -1.0000         0
         0    1.0000   -0.0000         0
         0         0         0    1.0000
```

## Input Arguments

### `quat` — Unit quaternion

*n*-by-4 matrix | n-element vector of `quaternion` objects

Unit quaternion, specified as an *n*-by-4 matrix or n-element vector of `quaternion` objects containing *n* quaternions. If the input is a matrix, each row is a quaternion vector of the form $q = [w\ x\ y\ z]$, with *w* as the scalar number.

Example: `[0.7071 0.7071 0 0]`

## Output Arguments

### `tform` — Homogeneous transformation

4-by-4-by-*n* matrix

Homogeneous transformation matrix, returned as a 4-by-4-by-*n* matrix of *n* homogeneous transformations. When using the rotation matrix, premultiply it with the coordinates to be rotated (as opposed to postmultiplying).

Example: `[0 0 1 0; 0 1 0 0; -1 0 0 0; 0 0 0 1]`

## Version History

**Introduced in R2015a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

`tform2quat` | `quaternion` | `se2` | `se3`

# read

Read data from GPS receiver

## Syntax

```
[tt,overrun] = read(gps)
[lla,groundSpeed,course,dops,gpsReceiverTime,timestamp,overrun] = read(gps)
```

## Description

`[tt,overrun] = read(gps)` returns the GPS readings in `timetable` format. This is a non blocking read which returns *N* data points in timetable format, where *N* is specified by `SamplesPerRead` property and `timetable` is specified using `OutputFormat` property of `gpsdev` object.

`[lla,groundSpeed,course,dops,gpsReceiverTime,timestamp,overrun] = read(gps)` returns matrices of measurements from the GPS. This is a non blocking read which returns *N* data points in matrix format, where *N* is specified by `SamplesPerRead` property and `matrix` is specified using `OutputFormat` property of the `gpsdev` object.

## Examples

### Read Data from GPS Receiver as Timetable

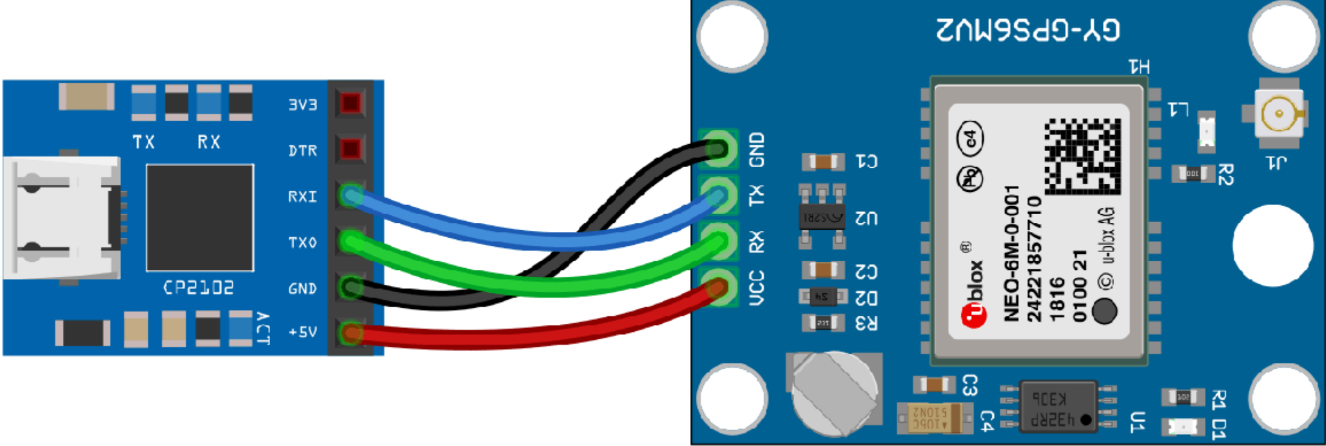
Read data from the GPS receiver connected to the host computer on a specific serial port.

#### Required Hardware

To run this example, you need:

- UBlox Neo-6M GPS module
- GPS antenna
- USB to UART module
- USB cable
- Connecting wires

### Hardware Connection




Connect the pins on the UBlox Neo-6M GPS module to the pins on your USB to UART module. The connections are:

- VCC - +5V
- RX - TXO
- TX - RXI
- GND - GND

Connect the GPS antenna to the GPS module. Connect the USB to UART module to the host computer with a USB cable. GPS Fix can be easily acquired in locations that have a clear view of the sky. Wait for the GPS module to acquire satelite signals (Fix).This can be verified by checking the Fix LED (D1) of your GPS module.

### Create GPS Object

Create a `gpsdev` object for the GPS receiver connected to a specific port. Specify the output format of the data as a timetable.

```
gps = gpsdev('COM4','OutputFormat',"timetable")
```

```
gps = 
  gpsdev with properties:

                         SerialPort: COM4
                           BaudRate: 9600 (bits/s)

                     SamplesPerRead: 1
                           ReadMode: "latest"
                        SamplesRead: 0
Show all properties all functions
```

### Read the GPS data

Read the GPS data and return them as a timetable.

```
[tt,overruns] = read(gps)
```

```
tt=1×5 timetable
              Time                            LLA                 GroundSpeed    Course        DOP
    ________________________    _________________________    ___________    ______    __________

    22-Mar-2021 15:31:15.190    17.47     78.343     449.6      0.25619       NaN       9.31    1.4
```

```
overruns = 0
```

Display number of samples read and the samples available in the host buffer.

```
gps.SamplesRead
```

```
ans = 1
```

```
gps.SamplesAvailable
```

```
ans = 0
```

Release the GPS object to configure the non tunable properties. The release function also clears the buffer and resets the `SamplesRead` and `SamplesAvailable` properties.

```
release(gps)
```

Specify the number of samples per read to 2. Read the GPS data.

```
gps.SamplesPerRead = 2;
read(gps)
```

```
ans=2×5 timetable
              Time                            LLA                 GroundSpeed    Course        DOP
    ________________________    _________________________    ___________    ______    __________

    22-Mar-2021 15:31:17.178    17.47     78.343       450     0.063791       NaN       9.32    1.4
    22-Mar-2021 15:31:17.178    17.47     78.343       450     0.063791       NaN       9.32    1.4
```

Display number of samples read and the samples available in the host buffer.

```
gps.SamplesRead
```

```
ans = 1
```

```
gps.SamplesAvailable
```

```
ans = 0
```

#### Clean Up

When the connection is no longer needed, clear the associated object.

```
delete(gps);
clear gps;
```

#### Read Data from GPS Receiver as Matrix

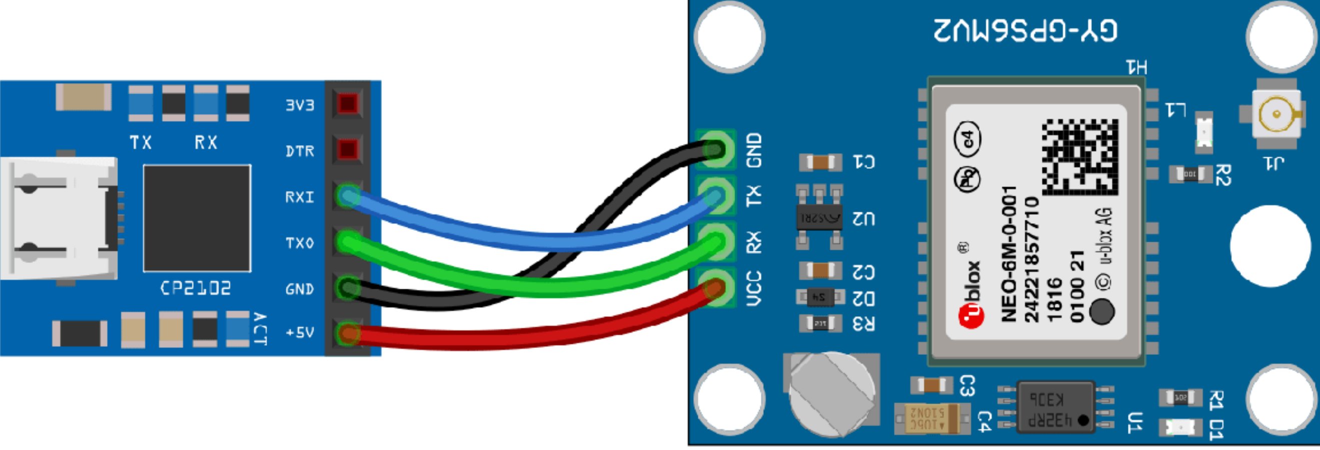
Read data from the GPS receiver connected to the host computer using `serialport` object.

**Required Hardware**

To run this example, you need:

- UBlox Neo-6M GPS module
- GPS antenna
- USB to UART module
- USB cable
- Connecting wires

**Hardware Connection**




Connect the pins on the UBlox Neo-6M GPS module to the pins on your USB to UART module. The connections are:

- VCC - +5V
- RX - TXO
- TX - RXI
- GND - GND

Connect the GPS antenna to the GPS module. Connect the USB to UART module to the host computer with a USB cable. GPS Fix can be easily acquired in locations that have a clear view of the sky. Wait for the GPS module to acquire satelite signals (Fix).This can be verified by checking the Fix LED (D1) of your GPS module.

**Create GPS Object**

Connect to the GPS receiver using `serialport` object. Specify the port name and the baud rate. Specify the output format of the data as matrix.

```
s = serialport('COM4',9600);
gps = gpsdev(s,'OutputFormat',"matrix")
```

```
gps = 
  gpsdev with properties:
```

```
                    SerialPort: COM4
                      BaudRate: 9600 (bits/s)

                SamplesPerRead: 1
                      ReadMode: "latest"
                   SamplesRead: 0
Show all properties all functions
```

#### Read the GPS data

Read the GPS data and return them as matrices.

```
[lla,speed,course,dops,gpsReceiverTime,timestamp,overruns] = read(gps)
```

```
lla = 1×3

   NaN   NaN   NaN


speed = NaN

course = NaN

dops = 1×3

   NaN   NaN   NaN


gpsReceiverTime = datetime
   NaT


timestamp = datetime
   22-Mar-2021 03:41:00.274


overruns = 1
```

Display number of samples read and the samples available in the host buffer.

```
gps.SamplesRead
```

```
ans = 1
```

```
gps.SamplesAvailable
```

```
ans = 0
```

Flush all GPS data accumulated in the buffers and reset the `SamplesRead` and `SamplesAvailable` properties.

```
flush(gps)
```

Display number of samples read and the samples available in the host buffer.

```
gps.SamplesRead
```

```
ans = 0
```

```
gps.SamplesAvailable
```

```
ans = 0
```

### Clean Up

When the connection is no longer needed, clear the associated object.

```
delete(gps);
clear gps;
clear s;
```

## Input Arguments

**gps — GPS sensor**
gpsdev object

The GPS sensor, specified as a `gpsdev` object.

## Output Arguments

**tt — GPS data**
timetable

GPS data, returned as a `timetable`. The `timetable` returned has the following fields:

- LLA (Latitude, Longitude, Altitude)
- Ground Speed
- Course over ground
- Dilution of Precisions(DOPs), VDOP,HDOP,PDOP
- GPS Receiver Time
- Time — System time when the data is read, in `datetime` or `duration` format

Data Types: `timetable`

**lla — Position in LLA coordinate system**
*N*-by-3 matrix

Position of the GPS receiver in the geodetic latitude, longitude, and altitude (LLA), returned as a real finite *N*-by-3 array. Latitude and longitude are in degrees with North and East being positive. Altitude is in meters.

Data Types: `double`

**groundSpeed — Speed in m/s**
*N*-by-1 vector

Speed over ground, returned as a real finite *N*-by-1 vector.

Data Types: `double`

**course — Course over ground**
*N*-by-1 vector

Course over ground relative to true north, returned as a real finite *N*-by-1 vector of values between 0 and 2pi radians.

Data Types: `double`

**dops — Dilution of precisions**
*N*-by-3 matrix

Dilution of precisions, returned as a real finite *N*-by-3 matrix of the form `[PDOP,HDOP,VDOP]`.

Data Types: `double`

**gpsReceiverTime — UTC time**
*N*-by-1 vector

UTC time, returned as a *N*-by-1 vector.

Data Types: `datetime`

**timestamp — Time at which GPS data is read**
*N*-by-1 vector

Time at which GPS data is read, returned as a real finite *N*-by-1 vector. This is the system time. If the `TimeFormat` is `datetime`, the timestamp will be `datetime`. If the `TimeFormat` is a `duration`, the timestamp will be `duration`

- `datetime` — Displays the date and time at which the data is read.
- `duration` — Displays the time elapsed in seconds after the first call of the `read` function or the last execution of the `release` function.

**Note** If the `SamplesPerRead` is greater than 1, an extrapolation is done on the time value. Hence it might not be precise.

Data Types: `datetime` | `duration`

**overrun — Overrun**
scalar

The number of samples lost between consecutive calls to `read`. The overrun is zero when `ReadMode` is set to `oldest`.

Data Types: `double`

## More About

### read Output

The `gpsdev` object expects GPRMC, GPGGA, and GPGSA sentences as outputs from the GPS receiver to get the required values. The `read` function errors out if these sentences are not available.

The `read` function outputs `NaN` and `NaT` in the following situations:

- If the GPS module does not receive valid data because there is no satellite lock or when GPS does not give a particular value.
- If there is a checksum failure, corresponding data points will be `NaN` for numeric outputs (`lla`, `speed`, `course`, `dops`) and `NaT` for `gpsRecieverTime`. `lla` is taken from GPGGA sentence,

speed,course, and gpsRecieverTime is taken GPRMC sentence and dops are taken from GPGSA sentence.

Because read function is non blocking, the following is expected:

- If no new data is available, the output of read is the previous data. For example, if the delay between subsequent reads is less than the UpdateRate of the GPS receiver.

Because GPS data is validated in the first read operation, it might take more time compared to the subsequent read operations.

# Version History

**Introduced in R2020b**

## See Also

**Objects**
gpsdev

**Functions**
flush | release | info | writeBytes

# readBinaryOccupancyGrid

Read binary occupancy grid

## Syntax

```
map = readBinaryOccupancyGrid(msg)
map = readBinaryOccupancyGrid(msg,thresh)
map = readBinaryOccupancyGrid(msg,thresh,val)
```

## Description

`map = readBinaryOccupancyGrid(msg)` returns a `binaryOccupancyMap` object by reading the data inside a ROS message, `msg`, which must be a `'nav_msgs/OccupancyGrid'` message. All message data values greater than or equal to the occupancy threshold are set to occupied, `1`, in the map. All other values, including unknown values (`-1`) are set to unoccupied, `0`, in the map.

**Note** The `msg` input is an `'nav_msgs/OccupancyGrid'` ROS message. For more info, see `OccupancyGrid`.

`map = readBinaryOccupancyGrid(msg,thresh)` specifies a threshold, `thresh`, for occupied values. All values greater than or equal to the threshold are set to occupied, `1`. All other values are set to unoccupied, `0`.

`map = readBinaryOccupancyGrid(msg,thresh,val)` specifies a value to set for unknown values (`-1` ). By default, all unknown values are set to unoccupied, `0`.

## Input Arguments

**`msg` — `'nav_msgs/OccupancyGrid'` ROS message**
`OccupancyGrid` object handle

`'nav_msgs/OccupancyGrid'` ROS message, specified as a `OccupancyGrid` object handle.

**`thresh` — Threshold for occupied values**
50 (default) | scalar

Threshold for occupied values, specified as a scalar. Any value greater than or equal to the threshold is set to occupied, `1`. All other values are set to unoccupied, `0`.

Data Types: `double`

**`val` — Value to replace unknown values**
0 (default) | 1

Value to replace unknown values, specified as either `0` or `1`. Unknown message values (`-1`) are set to the given value.

Data Types: `double` | `logical`

## Output Arguments

**map — Binary occupancy grid**
binaryOccupancyMap object handle

Binary occupancy grid, returned as a binaryOccupancyMap object handle. map is converted from a 'nav_msgs/OccupancyGrid' message on the ROS network. The object is a grid of binary values, where 1 indicates an occupied location and 0 indications an unoccupied location.

# Version History

**Introduced in R2015a**

## See Also

**Objects**
OccupancyGrid | occupancyMap | binaryOccupancyMap

**Functions**
rosReadOccupancyGrid | rosWriteBinaryOccupancyGrid | rosWriteOccupancyGrid

# readOccupancyGrid

Read occupancy grid message

## Syntax

```
map = readOccupancyGrid(msg)
```

## Description

`map = readOccupancyGrid(msg)` returns an `occupancyMap` object by reading the data inside a ROS message, `msg`, which must be a `'nav_msgs/OccupancyGrid'` message. All message data values are converted to probabilities from 0 to 1. The unknown values (-1) in the message are set as 0.5 in the map.

**Note** The `msg` input is an `'nav_msgs/OccupancyGrid'` ROS message. For more info, see `OccupancyGrid`.

## Input Arguments

**`msg` — `'nav_msgs/OccupancyGrid'` ROS message**
`OccupancyGrid` object handle

`'nav_msgs/OccupancyGrid'` ROS message, specified as an `OccupancyGrid` ROS message object handle.

## Output Arguments

**`map` — Occupancy map**
`occupancyMap` object handle

Occupancy map, returned as an `occupancyMap` object handle.

# Version History

**Introduced in R2016b**

## See Also

**Functions**
`rosReadBinaryOccupancyGrid` | `rosReadOccupancyMap3D` | `rosWriteBinaryOccupancyGrid` | `rosWriteOccupancyGrid`

# readOccupancyMap3D

Read 3-D map from Octomap ROS message

## Syntax

```
map = readOccupancyMap3D(msg)
```

## Description

`map = readOccupancyMap3D(msg)` reads the data inside a ROS `'octomap_msgs/Octomap'` message to return an `occupancyMap3D` object. All message data values are converted to probabilities from 0 to 1.

## Input Arguments

**msg — `Octomap` ROS message**
structure

`Octomap` ROS message, specified as a structure of message type `'octomap_msgs/Octomap'`. Get this message by subscribing to an `'octomap_msgs/Octomap'` topic using `rossubscriber` on a live ROS network or by creating your own message using `rosmessage`.

## Output Arguments

**map — 3-D occupancy map**
`occupancyMap3D` object handle

3-D occupancy map, returned as an `occupancyMap3D` object handle.

# Version History

**Introduced in R2021a**

## See Also

`occupancyMap3D` | `rosmessage` | `rossubscriber`

# receiverposition

Estimate GNSS receiver position and velocity

## Syntax

```
recPos = receiverposition(p,satPos)
[recPos,recVel] = receiverposition( ___ ,pdot,satVel)
[recPos,recVel,hdop,vdop] = receiverposition( ___ )
[recPos,recVel,hdop,vdop,info] = receiverposition( ___ )
```

## Description

`recPos = receiverposition(p,satPos)` returns the receiver position estimated from the pseudoranges and satellite positions.

`[recPos,recVel] = receiverposition( ___ ,pdot,satVel)` also returns the receiver velocity estimated from the pseudorange rates `pdot` and satellite velocities `satVel`.

`[recPos,recVel,hdop,vdop] = receiverposition( ___ )` also returns the horizontal dilution of precision `hdop` and vertical dilution of precision `vdop` associated with the position estimate.

`[recPos,recVel,hdop,vdop,info] = receiverposition( ___ )` returns information about the clock bias, clock drift, and time dilution of precision.

## Examples

### Estimate Receiver Position from Pseudoranges and Satellite Positions

Use the `receiverposition` function to estimate a GNSS receiver position. Get the satellte positiions and velocities using the `gnssconstellation` function. Generate pseudoranges from these positions using the `pseudoranges` function.

Specify a receiver position in geodetic coordinates (latitude, longitude, altitude) and a receiver velocity in the local navigation frame.

```
recPos = [42 -71 50];
recVel = [1 2 3];
```

Get the satellite positions for the current time.

```
t = datetime('now');
[gpsSatPos,gpsSatVel] = gnssconstellation(t);
```

Get the pseudoranges and pseudorange rates between the GNSS receiver and the satellites.

```
[p,pdot] = pseudoranges(recPos,gpsSatPos,recVel,gpsSatVel);
```

Use the pseudoranges to estimate the receiver position and velocity. The values close to your original receiver position and velocity used to generate the satellite position and pseudoranges.

```
[lla,gnssVel] = receiverposition(p,gpsSatPos,pdot,gpsSatVel)
```

```
lla = 1×3

   42.0000  -71.0000   50.2591

gnssVel = 1×3

    1.0035    2.0126    3.0031
```

## Input Arguments

**p — Pseudoranges between satellites and receiver**
*n*-element vector

Pseudoranges between the satellites and receiver, specified as an *n*-element vector in meters.

Data Types: single | double

**satPos — Satellite positions**
*N*-by-3 matrix of scalars

Satellite positions in the Earth-centered Earth-fixed (ECEF) coordinate system in meters, specified as an *N*-by-3 matrix of scalars. *N* is the number of satellites in the constellation.

Data Types: single | double

**pdot — Pseudorange rates between satellites and receiver**
*n*-element vector

Pseudorange rates between the satellites and receiver, specified as an *n*-element vector in meters per second.

Data Types: single | double

**satVel — Velocity readings in local navigation coordinate system (m/s)**
*N*-by-3 matrix of scalar

Velocity readings of the GNSS receiver in the local navigation coordinate system in meters per second, specified as an *N*-by-3 matrix of scalars. *N* is the number of satellites in the constellation.

Data Types: single | double

## Output Arguments

**recPos — Receiver position**
three-element vector of the form [lat lon alt]

Receiver position in geodetic coordinates, returned as a three-element vector of the form *[latitude longitude altitude]*

Data Types: single | double

**recVel — Receiver velocity**
three-element vector of the form [vx vy vz]

Receiver velocity in the local navigation frame using north-east-down (NED) coordinates, returned as a three-element vector of the form *[vx vy vz]*.

Data Types: `single` | `double`

**hdop — Horizontal dilution of precision**
scalar

Horizontal dilution of precision, returned as a scalar.

Data Types: `double`

**vdop — Vertical dilution of precision**
scalar

Vertical dilution of precision, returned as a scalar.

Data Types: `double`

**`info` — Information about clock bias, clock drift, and TDOP**
structure

Information about clock bias, clock drift, and time dilution of precision (TDOP), returned as a structure containing these fields:

- `ClockBias` — Estimated bias error in receiver clock, in seconds.
- `ClockDrift` — Estimated drift error in receiver clock, in seconds per second.
- `TDOP` — Time dilution of precision.

# Version History

**Introduced in R2021a**

## References

[1] Groves, Paul D. *Principles of GNSS, Inertial, and Multisensor Integrated Navigation Systems.* 2nd ed. GNSS Technology and Application Series. Boston: Artech House, 2013.

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
`gnssSensor` | `gpsSensor` | `imuSensor`

**Functions**
`skyplot` | `gnssconstellation` | `lookangles` | `pseudoranges`

# release

Release the GPS object

## Syntax

```
release(gps)
```

## Description

`release(gps)` release the system objects, allows configuration of non tunable properties, clear the buffers, and resets the values of `SamplesRead` and `SamplesAvailable` properties.

## Examples

### Read Data from GPS Receiver as Timetable

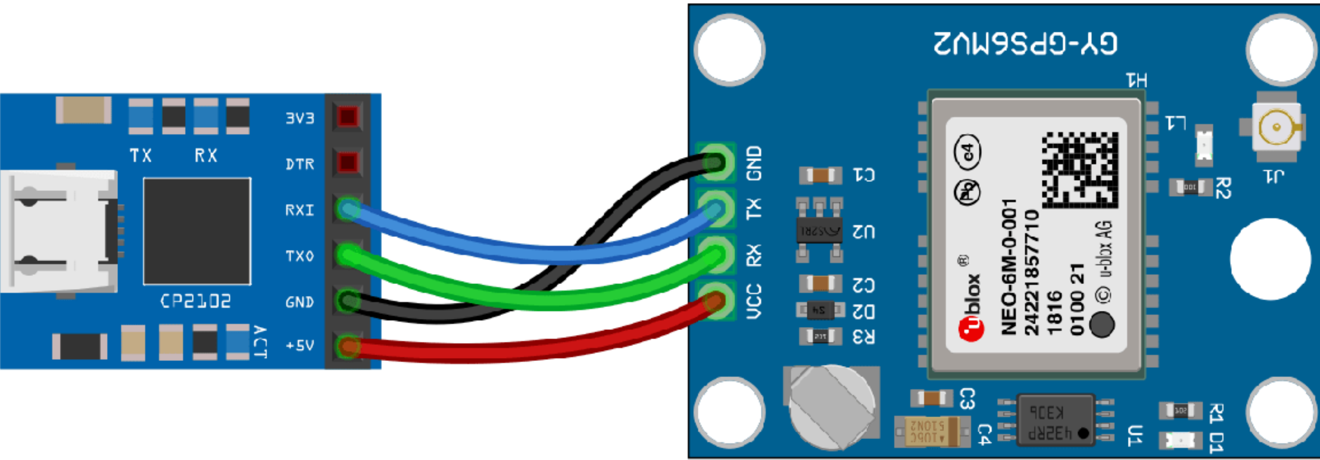
Read data from the GPS receiver connected to the host computer on a specific serial port.

#### Required Hardware

To run this example, you need:

- UBlox Neo-6M GPS module
- GPS antenna
- USB to UART module
- USB cable
- Connecting wires

#### Hardware Connection



Connect the pins on the UBlox Neo-6M GPS module to the pins on your USB to UART module. The connections are:

- VCC - +5V
- RX - TXO
- TX - RXI
- GND - GND

Connect the GPS antenna to the GPS module. Connect the USB to UART module to the host computer with a USB cable. GPS Fix can be easily acquired in locations that have a clear view of the sky. Wait for the GPS module to acquire satelite signals (Fix).This can be verified by checking the Fix LED (D1) of your GPS module.

**Create GPS Object**

Create a `gpsdev` object for the GPS receiver connected to a specific port. Specify the output format of the data as a timetable.

```
gps = gpsdev('COM4','OutputFormat',"timetable")
```

```
gps = 
  gpsdev with properties:

                         SerialPort: COM4
                           BaudRate: 9600 (bits/s)

                     SamplesPerRead: 1
                           ReadMode: "latest"
                        SamplesRead: 0
Show all properties all functions
```

**Read the GPS data**

Read the GPS data and return them as a timetable.

```
[tt,overruns] = read(gps)
```

```
tt=1×5 timetable
              Time                           LLA                GroundSpeed    Course        DOI
    ________________________    _________________________    ___________    ______    ________

    22-Mar-2021 15:31:15.190    17.47     78.343     449.6      0.25619       NaN      9.31     1.4
```

```
overruns = 0
```

Display number of samples read and the samples available in the host buffer.

```
gps.SamplesRead
```

```
ans = 1
```

```
gps.SamplesAvailable
```

```
ans = 0
```

Release the GPS object to configure the non tunable properties. The release function also clears the buffer and resets the `SamplesRead` and `SamplesAvailable` properties.

```
release(gps)
```

Specify the number of samples per read to 2. Read the GPS data.

```
gps.SamplesPerRead = 2;
read(gps)
```

```
ans=2×5 timetable
              Time                          LLA                GroundSpeed    Course        DOI
    ________________________    _________________________    ___________    ______    ___________

    22-Mar-2021 15:31:17.178    17.47    78.343       450     0.063791       NaN      9.32    1.4
    22-Mar-2021 15:31:17.178    17.47    78.343       450     0.063791       NaN      9.32    1.4
```

Display number of samples read and the samples available in the host buffer.

```
gps.SamplesRead
```

```
ans = 1
```

```
gps.SamplesAvailable
```

```
ans = 0
```

### Clean Up

When the connection is no longer needed, clear the associated object.

```
delete(gps);
clear gps;
```

## Input Arguments

**gps — GPS sensor**
`gpsdev` object

The GPS sensor, specified as a `gpsdev` object.

# Version History

**Introduced in R2020b**

## See Also

**Objects**
`gpsdev`

**Functions**
`flush` | `writeBytes` | `read` | `info`

# removeInvalidData

Remove invalid range and angle data

## Syntax

```
validScan = removeInvalidData(scan)
validScan = removeInvalidData(scan,Name,Value)
```

## Description

`validScan = removeInvalidData(scan)` returns a new `lidarScan` object with all `Inf` and `NaN` values from the input `scan` removed. The corresponding angle readings are also removed.

`validScan = removeInvalidData(scan,Name,Value)` provides additional options specified by one or more `Name,Value` pairs.

## Examples

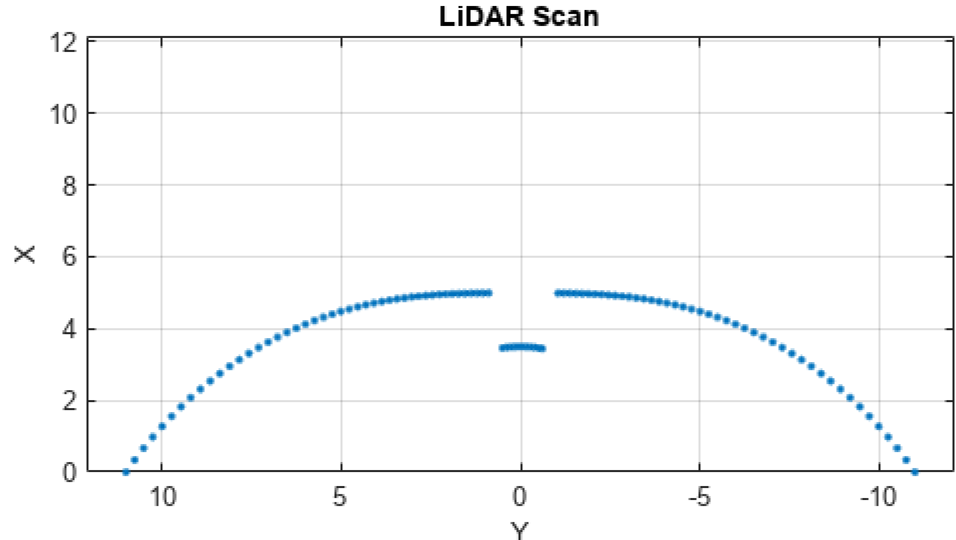
### Plot Lidar Scan and Remove Invalid Points

Specify lidar data as vectors of ranges and angles. These values include readings outside of the sensors range.

```
x = linspace(-2,2);
ranges = abs((1.5).*x.^2 + 5);
ranges(45:55) = 3.5;
angles = linspace(-pi/2,pi/2,numel(ranges));
```

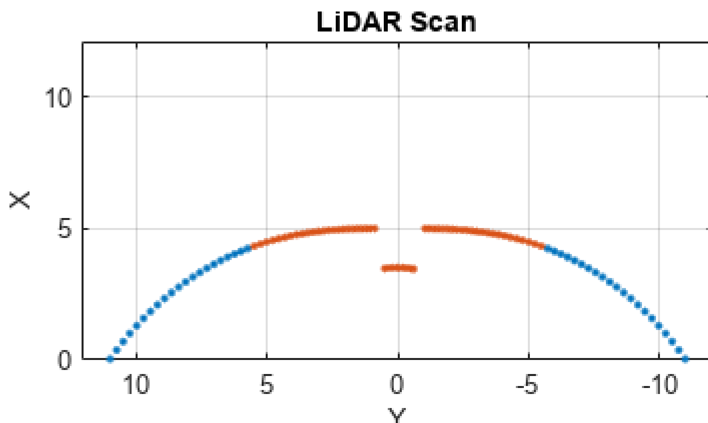
Create a lidar scan by specifying the ranges and angles. Plot all points of the lidar scan.

```
scan = lidarScan(ranges,angles);
plot(scan)
```




Remove invalid points based on a specified minimum and maximum range.

```
minRange = 0.1;
maxRange = 7;
scan2 = removeInvalidData(scan,'RangeLimits',[minRange maxRange]);
hold on
plot(scan2)
legend('All Points','Valid Points')
```




## Input Arguments

**scan — Lidar scan readings**
lidarScan object

Lidar scan readings, specified as a lidarScan object.

### Name-Value Pair Arguments

Specify optional pairs of arguments as Name1=Value1,...,NameN=ValueN, where Name is the argument name and Value is the corresponding value. Name-value arguments must appear after other arguments, but the order of the pairs does not matter.

*Before R2021a, use commas to separate each name and value, and enclose* Name *in quotes.*

Example: ["RangeLimits",[0.05 2]

**RangeLimits — Range reading limits**
two-element vector

Range reading limits, specified as a two-element vector, [minRange maxRange], in meters. All range readings and corresponding angles outside these range limits are removed

Data Types: single | double

**`AngleLimits` — Angle limits**
two-element vector

Angle limits, specified as a two-element vector, `[minAngle maxAngle]` in radians. All angles and corresponding range readings outside these angle limits are removed.

Angles are measured counter-clockwise around the positive *z*-axis.

Data Types: `single` | `double`

## Output Arguments

**`validScan` — Lidar scan readings**
`lidarScan` object

Lidar scan readings, specified as a `lidarScan` object. All invalid lidar scan readings are removed.

# Version History

**Introduced in R2019b**

## See Also

`lidarScan` | `transformScan` | `matchScans`

# rinexinfo

Get information about RINEX file

## Syntax

```
fileinfo = rinexinfo(filename)
```

## Description

`fileinfo = rinexinfo(filename)` gets information about the specified RINEX version 3 file `filename`, and returns it as a structure, `fileinfo`. The contents of `fileinfo` depend on the RINEX file type and the satellite system in the file.

## Examples

#### Query Navigation And Observation Messages From RINEX File

#### GPS Navigation Message Info

```
filename = "GODS00USA_R_20211750000_01D_GN.rnx";
info = rinexinfo(filename)
```

```
info = struct with fields:
             FileVersion: 3.0400
     FileSatelliteSystem: 'G'
                FileType: 'N'
                Comments: [3x1 string]
    LeapSecondParameters: [1x1 struct]
                     PGM: "JPS2RIN v.2.0.191"
                   RunBy: "JAVAD GNSS"
            CreationDate: 25-Jun-2021 00:06:25
                FileName: "GODS00USA_R_20211750000_01D_GN.rnx"
                FileSize: 109092
```

#### Galileo Navigation Message Info

```
filename = "GODS00USA_R_20211750000_01D_EN.rnx";
info = rinexinfo(filename)
```

```
info = struct with fields:
               FileVersion: 3.0400
       FileSatelliteSystem: 'E'
                  FileType: 'N'
                  Comments: [3x1 string]
    IonosphericCorrections: [1x1 struct]
      LeapSecondParameters: [1x1 struct]
                       PGM: "JPS2RIN v.2.0.191"
                     RunBy: "JAVAD GNSS"
              CreationDate: 25-Jun-2021 00:06:25
                  FileName: "GODS00USA_R_20211750000_01D_EN.rnx"
```

```
                  FileSize: 1063207
```

**GLONASS Navigation Message Info**

```
filename = "GODS00USA_R_20211750000_01D_RN.rnx";
info = rinexinfo(filename)
```

```
info = struct with fields:
              FileVersion: 3.0400
      FileSatelliteSystem: 'R'
                 FileType: 'N'
                 Comments: [3x1 string]
    LeapSecondParameters: [1x1 struct]
                      PGM: "JPS2RIN v.2.0.191"
                    RunBy: "JAVAD GNSS"
             CreationDate: 25-Jun-2021 00:06:25
                 FileName: "GODS00USA_R_20211750000_01D_RN.rnx"
                 FileSize: 141452
```

**BeiDou Navigation Message Info**

```
filename = "GODS00USA_R_20211750000_01D_CN.rnx";
info = rinexinfo(filename)
```

```
info = struct with fields:
              FileVersion: 3.0400
      FileSatelliteSystem: 'C'
                 FileType: 'N'
                 Comments: [3x1 string]
     LeapSecondParameters: [1x1 struct]
                      PGM: "JPS2RIN v.2.0.191"
                    RunBy: "JAVAD GNSS"
             CreationDate: 25-Jun-2021 00:06:26
    TimeSystemCorrections: [1x1 struct]
                 FileName: "GODS00USA_R_20211750000_01D_CN.rnx"
                 FileSize: 155431
```

**NavIC/IRNSS Navigation Message Info**

```
filename = "ARHT00ATA_R_20211750000_01D_IN.rnx";
info = rinexinfo(filename)
```

```
info = struct with fields:
              FileVersion: 3.0400
      FileSatelliteSystem: 'I'
                 FileType: 'N'
                 Comments: [3x1 string]
    LeapSecondParameters: [1x1 struct]
                      PGM: "JPS2RIN v.2.0.191"
                    RunBy: "JAVAD GNSS"
             CreationDate: 25-Jun-2021 00:03:18
                 FileName: "ARHT00ATA_R_20211750000_01D_IN.rnx"
                 FileSize: 74322
```

### QZSS Navigation Message Info

```
filename = "ARHT00ATA_R_20211750000_01D_JN.rnx";
info = rinexinfo(filename)
```

```
info = struct with fields:
            FileVersion: 3.0400
    FileSatelliteSystem: 'J'
               FileType: 'N'
               Comments: [3x1 string]
   LeapSecondParameters: [1x1 struct]
                    PGM: "JPS2RIN v.2.0.191"
                  RunBy: "JAVAD GNSS"
           CreationDate: 25-Jun-2021 00:03:18
               FileName: "ARHT00ATA_R_20211750000_01D_JN.rnx"
               FileSize: 22970
```

### SBAS Navigation Message Info

```
filename = "GOP600CZE_R_20211750000_01D_SN.rnx";
info = rinexinfo(filename)
```

```
info = struct with fields:
            FileVersion: 3.0400
    FileSatelliteSystem: 'S'
               FileType: 'N'
               Comments: "SBAS NAVIGATION DATA FROM STATION GOP6 (RIGTC, GO PECNY)    "
                    PGM: "sbf2rin-13.4.5"
                  RunBy: "RIGTC, GO PECNY"
           CreationDate: 25-Jun-2021 00:26:37
               FileName: "GOP600CZE_R_20211750000_01D_SN.rnx"
               FileSize: 1083132
```

### Mixed Observation Info

```
filename = "GODS00USA_R_20211750000_01H_30S_MO.rnx";
info = rinexinfo(filename)
```

```
info = struct with fields:
                FileVersion: 3.0400
        FileSatelliteSystem: 'M'
                   FileType: 'O'
           ObservationTypes: [4x1 struct]
              NumSatellites: 44
              AntennaNumber: "02083"
                AntennaType: "JAVRINGANT_DM   SCIS"
            AntennaDeltaHEN: [0.0083 0 0]
             ApproxPosition: [1.1308e+06 -4.8313e+06 3.9941e+06]
    GLONASSFrequencyNumbers: [1x1 struct]
                   Interval: 30
       LeapSecondParameters: [1x1 struct]
                 MarkerName: "GODS"
               MarkerNumber: "40451M128"
                   Observer: "GGN"
                     Agency: "NASA GODDARD SPACE FLIGHT CENTER"
                        PGM: "JPS2RIN v.2.0.191"
                      RunBy: "JAVAD GNSS"
```

```
      CreationDate: 24-Jun-2021 01:05:22
 TotalObservations: [44x1 struct]
    ReceiverNumber: "02704"
      ReceiverType: "JAVAD TRE_3 DELTA"
   ReceiverVersion: "4.0.02"
        PhaseShift: [22x1 struct]
      FirstObsTime: 23-Jun-2021 23:59:42
       LastObsTime: 24-Jun-2021 00:59:12
          FileName: "GODS00USA_R_20211750000_01H_30S_MO.rnx"
          FileSize: 1240462
```

## Input Arguments

**`filename` — Name of RINEX version 3 file**
string scalar | character vector

Name of the RINEX version 3 file to read data from, specified as a string scalar or character vector.

Example: `"GODS00USA_R_20211750000_01D_GN.rnx"`

Data Types: `string` | `char`

## Output Arguments

**`fileinfo` — RINEX file contents**
structure

RINEX file contents, returned as a structure. The structure has different fields depending on the type of RINEX file and the header entries in the file. See the “Output for Navigation Message Files” on page 1-224 and “Output for Observation Message Files” on page 1-227 sections for more information about the output structure.

## More About

### Output for Navigation Message Files

If the specified RINEX file is a navigation message file, the `fileinfo` output is a structure with these fields:

| Field | Type | Description |
|---|---|---|
| `FileName` | `string` | Name of file |
| `FileSize` | `double` | File size in bytes |
| `SatelliteSystem` | `string` | `"GPS"`, `"Galileo"`, `"GLONASS"`, `"BeiDou"`, `"NavIC"`, `"QZSS"`, `"SBAS"`, or `"Mixed"` |
| `Version` | `double` | Format Version |
| `FileType` | `char` | File type, specified as either `'N'` for navigation message files and `'O'` for observation data files. |
| `PGM` | `string` | Name of the program that created the file |
| `RunBy` | `string` | Name of the agency that created the file |

| Field | Type | Description |
|---|---|---|
| CreationDate | string | Date and time of file creation |
| Comments (Optional) | string | Comment lines from file header |
| IonosphericCorrections (Optional) | structure array | An array of structures with a number of elements equal to the number of IONOSPHERIC CORR header lines in the file. Each structure has the CorrectionType, Parameters, TimeMark, and SVID fields.<br><br>TimeMark and SVID are optional for all satellite systems except BeiDou.<br><br>Correction type:<br>• GAL — Galileo ai0 to ai2<br>• GPSA — GPS alpha0 to alpha3<br>• GPSB — GPS beta0 to beta3<br>• QZSA — QZS alpha0 to alpha3<br>• QZSB — QZS beta0 to beta3<br>• BDSA — BDS alpha0 to alpha3<br>• BDSB — BDS beta0 to beta3<br>• IRNA — NavIC/IRNSS alpha0 to alpha3<br>• IRNB — NavIC/IRNSS beta0 to beta3<br><br>Parameters:<br>• GAL — ai0, ai1, ai2, Blank<br>• GPS — alpha0 to alpha3 or beta0 to beta3<br>• QZS — alpha0 to alpha3 or beta0 to beta3<br>• BDS — alpha0 to alpha3 or beta0 to beta3<br>• IRN — alpha0 to alpha3 or beta0 to beta3<br>• Time mark, Transmission Time (seconds of week) converted to hours of day and then to A—X. A is 00h—01h, B is 01h—02h, ..., X is 23—24h satellite system time.<br>• SV ID, identify which satellite provided the ionospheric parameters |

| Field | Type | Description |
|---|---|---|
| TimeSystemCorrections | structure | An array of structures with a number of elements equal to the number of TIME SYSTEM CORR header lines in the file. Each structure has the CorrectionType, Parameters, ReferenceTime, ReferenceWeekNumber, SVID, and UTCID fields.<br><br>Correction type:<br>• GPUT = GPS - UTC (a0, a1)<br>• GLUT = GLO - UTC (a0 = -TauC, a1 = zero)<br>• GAUT = GAL - UTC ( a0, a1)<br>• BDUT = BDS - UTC (a0 = A0UTC, a1 = A1UTC )<br>• QZUT = QZS - UTC (a0, a1)<br>• IRUT = IRN - UTC (a0 = A0UTC, a1 = A1UTC )<br>• SBUT = SBAS - UTC (a0, a1)<br>• GLGP = GLO - GPS (a0 = -TauGPS, a1 = zero)<br>• GAGP = GAL - GPS (a0 = A0G, a1 = A1G for GAL INAV/FNAV; a0 = –A0GGTO, a1 = –A1 GGTO for GPS CNAV)<br>• QZGP = QZS - GPS (a0, a1)<br>• IRGP = IRN - GPS (a0 = A0, a1 = A1 )<br><br>Parameters:<br>• a0, a1 coefficients of linear polynomial Δt = a0 + a1 · (t - tref) for fractional part (excluding leap seconds) of time system difference (a0; sec, a1; sec/sec)<br>• Reference time (T) for polynomial (Seconds into GPS/GAL/BDS/QZS/IRN/SBAS week)<br>• Reference week number (W)<br>• GPS/GAL/QZS/IRN/SBAS week aligned to GPS, continuous number from 6-Jan-1980<br>• GLONASS T and W zero.<br>• BDS week, continuous from: 1-Jan-2006<br>• SV ID, System identifier and PRN/slot number ‘snn’ of the GNSS satellite broadcasting the time system difference or SBAS satellite broadcasting the MT12. Use EGNOS, WAAS, or MSAS for SBAS time differences from MT17.<br>• UTC Identifier<br>• 0 if unknown<br>• 1 = UTC(NIST)<br>• 2 = UTC(USNO)<br>• 3 = UTC(SU)<br>• 4 = UTC(BIPM) |

| Field | Type | Description |
|---|---|---|
| | | • 5 = UTC(Europe Lab)<br>• 6 = UTC(CRL)<br>• 7 = UTC(NTSC) (BDS)<br>• >7 = not assigned yet. |
| LeapSecondParameters (Optional) | structure | Leap second parameters in a structure with fields LeapSeconds, DeltaTimeLeapSeconds, WeekNumber, DayNumber, and TimeSystemID .<br>• LeapSeconds — Current number of leap seconds.<br>• DeltaTimeLeapSeconds — Future or past leap seconds. For example, it is future leap seconds if the week and day numbers are in the future.<br>• WeekNumber — For GPS, GAL, QZS, and IRN, number of weeks since January 6, 1980. For BDS, it is number of weeks since January 1, 2006.<br>• DayNumber — The day number is the GPS or BeiDou day before the leap second. For GPS, this number is in the range [1, 7]. For Beidou, this number is in the range [0, 6].<br>• TimeSystemID — Only "GPS" and "BDT" are valid values. If blank the field defaults to "GPS". |

Note that optional fields are not present in the structure unless specified in the RINEX file.

### Output for Observation Message Files

If the specified RINEX file is an observation message file, the output is a structure with these fields:

| Field | Type | Entry |
|---|---|---|
| FileName | string | Name of file |
| FileSize | double | File size in bytes |
| SatelliteSystem | string | "GPS", "Galileo", "GLONASS", "BeiDou", "NavIC", "QZSS", "SBAS", or "Mixed" |
| Version | double | Format Version |
| FileType | char | File type, specified as either 'N' for navigation message files and 'O' for observation data files. |
| PGM | string | Name of the program that created the file |
| RunBy | string | Name of the agency that created the file |
| CreationDate | string | Date and time of file creation |
| Comments (Optional) | string | Comment lines from file header |
| MarkerName | string | Name of antenna marker |
| MarkerNumber (Optional) | string | Number of antenna marker |

| Field | Type | Entry |
|---|---|---|
| MarkerType (Optional for GEODETIC and NON_GEODETIC marker types) | string | Type of marker |
| Observer | string | Name of observer |
| Agency | string | Name of agency |
| ReceiverNumber | string | Receiver number |
| ReceiverType | string | Receiver type |
| ReceiverVersion | string | Receiver version |
| AntennaNumber | string | Antenna number |
| AntennaType | string | Antenna type |
| ApproxPosition | double | Approximate marker position in meters. |
| AntennaDeltaHEN | double | Height of the antenna reference point (ARP) above marker, and horizontal eccentricity of ARP relative to marker (East/North) in meters. |
| AntennaDeltaXYZ | double | Position of antenna reference point for antenna on vehicle in meters. |
| AntennaPhaseCenter (Optional) | structure array | A structure array with number of elements equal to the number of ANTENNA: PHASECENTER header lines in the file. Each structure has SatelliteSystem, ObservationCode, and PhaseCenterfields. Where:<br><br>SatelliteSystem — The specified satellite system.<br><br>ObservationCode — The observation code. See the “Observation Type Descriptors” on page 1-231 section for more information.<br><br>PhaseCenter — The average phase center position with respect to the antenna reference point, in meters, North/East/Up for fixed station, *XYZ*body-fixed system for a vehicle. |
| AntennaBSightXYZ | double | Direction of the vertical antenna axis toward the GNSS satellites. If the antenna is on a vehicle, the direction is a unit vector in a body-fixed coordinate system. If the antenna is a tilted antenna on fixed station, the direction is a unit vector in East-North-Up (ENU) left-handed system. |
| AntennaZeroDirXYZ (Optional) | double | Zero direction of the antenna. If the antenna is on a vehicle, the zero direction is unit vector is in a body-fixed coordinate system. If the tilted antenna is on a fixed station, the zero direction is a unit vector in East-North-Up (ENU) left-handed system. |

| Field | Type | Entry |
|---|---|---|
| CenterOfMassXYZ | double | Current center of mass of the vehicle in a body-fixed coordinate system, in meters. |
| ObservationTypes | structure array | A structure array with number of elements equal to the number of satellite systems in the file. Each structure has SatelliteSystem and Descriptors fields. Where:<br><br>SatelliteSystem — String specifying the satellite system.<br><br>Descriptors — String array of 3-element observation descriptors. The first element is the Type, the second is the Band, and the third is the Attribute. See the "Observation Type Descriptors" on page 1-231 section for more information. |
| SignalStrengthUnit (Optional) | string | Unit of the carrier to noise ratio observables SNN (if present) DBHZ: S/N given in dbHz. |
| Interval (Optional) | double | Observation interval in seconds. |
| FirstObsTime (Optional, unless RINEX file is a mixed GNSS file) | datetime | Time of first observation record. Time systems are:<br><br>• GPS — GPS time system<br>• GLO — UTC time system<br>• GAL — Galileo time system<br>• QZS — QZSS time system<br>• BDT — BDS time system<br>• IRN — NavIC/IRNSS time system |
| HasReceiverClockOffset (Optional, unless, the epoch lines of the data section reports clock offsets) | logical | Epoch, code, and phase are corrected by applying the real-time-derived receiver clock offset. |
| DCBS (Optional) | structure array | An array with number of elements equal to number of satellite systems in the file. Each structure has SatelliteSystem, Program, and Source fields. Where:<br><br>SatelliteSystem — String specifying satellite system<br><br>Program — String specifying the program used to apply differential code bias corrections (DCBS)<br><br>Source — String URL of source of corrections |

| Field | Type | Entry |
|---|---|---|
| PCVS (Optional) | structure array | An array with number of elements equal to number of satellite systems in the file. Each structure has SatelliteSystem, Program, and Source fields. Where:<br><br>SatelliteSystem — String specifying satellite system<br><br>Program — String specifying the program used to apply phase center variation corrections (PCVS)<br><br>Source — String URL of source of corrections |
| ScaleFactor | structure array | An array with number of elements equal to number of “SYS / SCALE FACTOR” header lines in the file. Each structure has SatelliteSystem, Factor, and ObservationTypes fields. Where:<br><br>SatelliteSystem — String specifying satellite system<br><br>Factor — is a factor to divide stored observations with before use<br><br>ObservationTypes — is a list of observation types |
| PhaseShift (Optional) | structure array | An array with number of elements equal to number of “SYS / PHASE SHIFT” header lines in the file. Each structure has SatelliteSystem, ObservationType, Correction, SatelliteIDs fields. Where:<br><br>SatelliteSystem — String specifying the satellite system.<br><br>ObservationType — String specifying carrier phase observation code.<br><br>Correction — Value of correction applied (cycles).<br><br>SatelliteIDs — String array of satellites where correction is applied. |
| GLONASSFrequencyNumbers (Optional unless using files with GLONASS satellites) | structure | A structure with fields Slot and FrequencyNumber. Where:<br><br>Slot — String array of satellite numbers (system code (R), slot)<br><br>FrequencyNumber — Vector of integer doubles. |
| GLONASSCodePhaseBias | structure | A structure with fields ObservationTypes and Bias. Where:<br><br>ObservationTypes — String array of observation types. Valid values are “C1C”, “C1P”, “C2C”, or “C2P”.<br><br>Bias — Vector of code phase bias corrections in meters. |

| Field | Type | Entry |
| --- | --- | --- |
| LeapSecondParameters (Optional) | structure | Leap second parameters in a structure with fields LeapSeconds, DeltaTimeLeapSeconds, WeekNumber, DayNumber, and TimeSystemID .<br>• LeapSeconds — Current number of leap seconds.<br>• DeltaTimeLeapSeconds — Future or past leap seconds. For example, it is future leap seconds if the week and day numbers are in the future.<br>• WeekNumber — For GPS, GAL, QZS, and IRN, number of weeks since January 6, 1980. For BDS, it is number of weeks since January 1, 2006.<br>• DayNumber — The day number is the GPS or BeiDou day before the leap second. For GPS, this number is in the range [1, 7]. For Beidou, this number is in the range [0, 6].<br>• TimeSystemID — Only "GPS" and "BDT" are valid values. If blank the field defaults to "GPS". |
| NumSatellites (Optional) | double | Number of satellites, for which observations are stored in the file. |
| TotalObservations (Optional) | structure array | An array of structure with the number of elements equal to the number of PRN / # OF OBS header lines in the file. Each structure has a SatelliteID and NumObservations field. |

Note that optional fields are not present in the structure unless specified in the RINEX file.

**Observation Type Descriptors**

Observation type descriptors is a string comprised of three parts. The first part is the observation type, the second is the frequency band, and the third is the attribute which indicates the tracking mode or channel.

The observation type can be one of five types.

**Type**

- C — Code or pseudorange, is the distance, in meters, between the receiver antenna and the satellite antenna including delays and other biases.
- L — Phase is the carrier phase range from the antenna to the satellite, measured in whole cycles.
- D — Doppler shift indicating the approach of satellites, where a positive value indicates an approaching satellite.
- S — Raw signal strength (carrier to noise ratio) as an integer in the range [1, 9].
- X — Receiver channel numbers.

You can identify the frequency band code number given a frequency band and a satellite system.

**Frequency Band vs Satellite System**

| Frequency Band Code Number | GPS | QZSS | SBAS | BDS | GLO | GAL | NavIC/ IRNSS |
|---|---|---|---|---|---|---|---|
| 1 | L1 | L1 | L1 | L1 | G1 | E1 | — |
| 2 | L2 | L2 | — | B1 | G2 | — | — |
| 3 | — | — | — | — | G3 | — | — |
| 4 | — | — | — | — | G1a | — | — |
| 5 | L5 | L5 | L5 | B2a | — | E5a | L5 |
| 6 | — | L6 | — | B3 or B3A | G2a | E6 | — |
| 7 | — | — | — | B2 or B2b | — | E5b | — |
| 8 | — | — | — | B2a and B2b | — | E5a and E5b | — |
| 9 | — | — | — | — | — | — | S |

You can identify the attribute letter given a channel or code and a satellite system.

**Attribute vs Satellite System**

| Attribute Letter | GPS | QZSS | SBAS | BDS | GLO | GAL | NavIC/ IRNSS |
|---|---|---|---|---|---|---|---|
| A | — | — | — | — | A channel | A channel | A channel |
| B | — | — | — | — | A channel | A channel | A channel |
| C | C code-based | C code-based | C code-based | — | C code-based | C channel | C channel |
| D | Semi-codeless | Semi-codeless | — | Data channel | — | — | — |
| E | — | E channel | — | — | — | — | — |
| I | I channel | I channel | — | I channel | — | I channel | — |
| L | L channel (L2C GPS)<br><br>P channel | L channel<br><br>P channel | — | — | — | — | — |
| M | M-based code | — | — | — | — | — | — |
| N | Codeless | — | — | — | — | — | — |
| P | P code-based | — | — | Pilot channel | P code-based | — | — |
| Q | Q channel | Q channel | — | Q channel | — | Q channel | — |
| S | D channel<br><br>M channel (L2C GPS) | D channel<br><br>M channel | — | — | — | — | — |
| W | Based on Z-tracking | — | — | — | — | — | — |
| X | I and Q channels<br><br>M and L channels<br><br>D and P channels | I and Q channels<br><br>M and L channels<br><br>D and P channels | — | I and Q channels<br><br>D and P channels | — | B and C channels<br><br>I and Q channels | B and C channels |
| Y | Y code-based | — | — | — | — | — | — |
| Z | — | I and Q channels<br><br>D and E channels | — | D and P channels | — | A, B, and C channels | — |

These are examples of codes:

- C1M — L1 pseudorange derived from the M channel for a GPS satellite.

- L5X — E5a carrier phase derived from the B and C channels for a Galileo satellite.
- S3I — G3 signal strength derived from the I channels for a GLONASS satellite.

# Version History

**Introduced in R2022a**

## References

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[2] International GNSS Service (for Daily 30-Second Galileo Broadcast Ephemeris Data, NASA Crustal Dynamics Data Information System (CDDIS), Greenbelt, MD, USA, Jun. 24, 2021; accessed June 25, 2021). https://dx.doi.org/10.5067/GNSS/gnss_daily_l_001.

[3] International GNSS Service (for Daily 30-Second GLONASS Broadcast Ephemeris Data, NASA Crustal Dynamics Data Information System (CDDIS), Greenbelt, MD, USA, Jun. 24, 2021; accessed August 19, 2021). https://dx.doi.org/10.5067/GNSS/gnss_daily_g_001.

[4] International GNSS Service (for Daily 30-Second BeiDou Broadcast Ephemeris Data, NASA Crustal Dynamics Data Information System (CDDIS), Greenbelt, MD, USA, Jun. 24, 2021; accessed August 19, 2021). https://dx.doi.org/10.5067/GNSS/gnss_daily_f_001.

[5] International GNSS Service (for Daily 30-Second NavIC/IRNSS Broadcast Ephemeris Data, NASA Crustal Dynamics Data Information System (CDDIS), Greenbelt, MD, USA, Jun. 24, 2021; accessed August 19, 2021). https://dx.doi.org/10.5067/GNSS/gnss_daily_i_001.

[6] International GNSS Service (for Daily 30-Second QZSS Broadcast Ephemeris Data, NASA Crustal Dynamics Data Information System (CDDIS), Greenbelt, MD, USA, Jun. 24, 2021; accessed August 19, 2021). https://dx.doi.org/10.5067/GNSS/gnss_daily_q_001.

[7] International GNSS Service (for Daily 30-Second SBAS Broadcast Ephemeris Data, NASA Crustal Dynamics Data Information System (CDDIS), Greenbelt, MD, USA, Jun. 24, 2021; accessed August 19, 2021). https://dx.doi.org/10.5067/GNSS/gnss_daily_h_001.

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[9] Romero, Ignacio, ed. *RINEX The Receiver Independent Exchange Format Version 3.05*. Darmstadt, Germany: IGS/RTCM ESA/ESOC/Navigation Support Office. December, 2020. Accessed on: Dec. 22, 2021. https://files.igs.org/pub/data/format/rinex305.pdf .

## See Also

**Functions**

`rinexread` | `gnssconstellation` | `pseudoranges`

# rinexread

Read data from RINEX file

## Syntax

```
data = rinexread(filename)
```

## Description

`data = rinexread(filename)` reads data from the RINEX version 3 file `filename` and returns a structure, `data`. The content of `data` depends on the RINEX file type and the satellite system in the file.

## Examples

### Read Navigation and Observation Data from RINEX File

Read navigation data from a RINEX file that contains GPS navigation message data.

```
filename = "GODS00USA_R_20211750000_01D_GN.rnx";
data = rinexread(filename)
```

```
data = struct with fields:
    GPS: [178x32 timetable]
```

View the GPS data read from the RINEX file.

```
data.GPS(1:4,:)
```

```
ans=4×32 timetable
            Time             SatelliteID    SVClockBias    SVClockDrift    SVClockDriftRate    IOD
    ____________________    ___________    ___________    ____________    ________________    ___

    24-Jun-2021 01:59:44        27         -0.00015208    -6.1391e-12            0            15
    24-Jun-2021 01:59:44        32          1.7294e-05    -1.5916e-12            0             4
    24-Jun-2021 02:00:00         5         -4.5857e-05    -1.1369e-12            0            85
    24-Jun-2021 02:00:00         8         -2.6249e-05    -1.4779e-12            0           118
```

Read navigation data from a RINEX file that contains Galileo navigation message data.

```
filename = "GODS00USA_R_20211750000_01D_EN.rnx";
data = rinexread(filename)
```

```
data = struct with fields:
    Galileo: [1798x32 timetable]
```

View the Galileo data read from the RINEX file.

```
data.Galileo(1:4,:)
```

```
ans=4×32 timetable
            Time            SatelliteID    SVClockBias    SVClockDrift    SVClockDriftRate    IOD
    ____________________    ___________    ___________    ____________    ________________    ___

    23-Jun-2021 23:50:00        12          0.0051451     -1.8929e-11            0             6
    23-Jun-2021 23:50:00        12          0.0051451     -1.8929e-11            0             6
    23-Jun-2021 23:50:00        18         -0.0016176     -1.4765e-11            0             6
    23-Jun-2021 23:50:00        18         -0.0016176     -1.4765e-11            0             6
```

Read navigation data from a RINEX file that contains GLONASS navigation message data.

```
filename = "GODS00USA_R_20211750000_01D_RN.rnx";
data = rinexread(filename)
```

```
data = struct with fields:
    GLONASS: [435x20 timetable]
```

View the GLONASS data read from the RINEX file.

```
data.GLONASS(1:4,:)
```

```
ans=4×20 timetable
            Time            SatelliteID    SVClockBias    SVFrequencyBias    MessageFrameTime
    ____________________    ___________    ___________    _______________    ________________

    24-Jun-2021 00:15:00         1          8.1313e-05           0              3.4563e+05
    24-Jun-2021 00:15:00         6          0.00020024           0              3.4563e+05
    24-Jun-2021 00:15:00         7         -4.2243e-05           0              3.4563e+05
    24-Jun-2021 00:15:00         8         -5.9644e-05           0              3.4563e+05
```

Read navigation data from a RINEX file that contains BeiDou navigation message data.

```
filename = "GODS00USA_R_20211750000_01D_CN.rnx";
data = rinexread(filename)
```

```
data = struct with fields:
    BeiDou: [262x32 timetable]
```

View the BeiDou data read from the RINEX file.

```
data.BeiDou(1:4,:)
```

```
ans=4×32 timetable
       Time        SatelliteID    SVClockBias    SVClockDrift    SVClockDriftRate    AODE     Cr
    ___________    ___________    ___________    ____________    ________________    ____    ___

    24-Jun-2021        19          0.00088369      1.405e-11            0             1      -12
    24-Jun-2021        22         -0.00094916     1.0036e-12            0             1      -1.5
    24-Jun-2021        23         -0.00094575    -1.3407e-11            0             1       65
    24-Jun-2021        29          0.00041021     5.2065e-12            0             1      -37
```

Read navigation data from a RINEX file that contains NavIC/IRNSS navigation message data.

```
filename = "ARHT00ATA_R_20211750000_01D_IN.rnx";
data = rinexread(filename)
```

```
data = struct with fields:
    NavIC: [121x32 timetable]
```

View the NavIC data read from the RINEX file.

```
data.NavIC(1:4,:)
```

```
ans=4×32 timetable
            Time            SatelliteID    SVClockBias    SVClockDrift    SVClockDriftRate    IOD
    ____________________    ___________    ___________    ____________    ________________    ___

    24-Jun-2021 00:05:36         5         0.00066972       2.874e-10            0             16
    24-Jun-2021 00:20:48         5         0.00066998      2.8831e-10            0             16
    24-Jun-2021 00:36:00         5         0.00067025      2.9002e-10            0             16
    24-Jun-2021 00:50:24         5          0.0006705      2.9024e-10            0             16
```

Read navigation data from a RINEX file that contains QZSS navigation message data.

```
filename = "ARHT00ATA_R_20211750000_01D_JN.rnx";
data = rinexread(filename)
```

```
data = struct with fields:
    QZSS: [38x32 timetable]
```

View the GPS data read from the RINEX file.

```
data.QZSS(1:4,:)
```

```
ans=4×32 timetable
            Time            SatelliteID    SVClockBias    SVClockDrift    SVClockDriftRate    IOD
    ____________________    ___________    ___________    ____________    ________________    ___

    24-Jun-2021 03:00:00         2         -3.9348e-07    -2.2737e-13            0            169
    24-Jun-2021 03:00:00         7         -3.4459e-08              0            0            169
    24-Jun-2021 04:00:00         2         -3.9442e-07    -2.2737e-13            0            173
    24-Jun-2021 04:00:00         7         -3.3993e-08              0            0            173
```

Read navigation data from a RINEX file that contains SBAS navigation message data.

```
filename = "GOP600CZE_R_20211750000_01D_SN.rnx";
data = rinexread(filename)
```

```
data = struct with fields:
    SBAS: [3342x16 timetable]
```

View the SBAS data read from the RINEX file.

```
data.SBAS(1:4,:)
```

```
ans=4×16 timetable
            Time            SatelliteID    SVClockBias    SVFrequencyBias    TransmissionTime
    ____________________    ___________    ___________    _______________    ________________

    23-Jun-2021 23:57:36        48                  0             0             3.4548e+05
```

```
    23-Jun-2021 23:59:44        48                   0           0                 3.456e+05
    24-Jun-2021 00:00:16        36                   0           0                3.4562e+05
    24-Jun-2021 00:00:00        44         -4.0373e-07           0                3.4563e+05
```

**Mixed Observation Data**

Read mixed observation data from a RINEX file that contains GPS, GLONASS, Galileo, and BeiDou observation message data.

```
filename = "GODS00USA_R_20211750000_01H_30S_MO.rnx";
data = rinexread(filename)
```

```
data = struct with fields:
        GPS: [1245x45 timetable]
    GLONASS: [1102x38 timetable]
    Galileo: [859x38 timetable]
     BeiDou: [1303x45 timetable]
```

View the GPS, GLONASS, Galileo, and BeiDou data read from the RINEX file.

```
data.GPS(1:4,:)
```

```
ans=4×45 timetable
       Time        SatelliteID    EpochFlag    ReceiverClockOffset       C1C        C1C_SSI    
    ___________    ___________    _________    ___________________    __________    _______    _

    24-Jun-2021         5             0            -0.00047787         2.266e+07      NaN      1
    24-Jun-2021        10             0            -0.00047787        2.4266e+07      NaN      1
    24-Jun-2021        13             0            -0.00047787        2.1788e+07      NaN       
    24-Jun-2021        15             0            -0.00047787             2e+07      NaN       
```

```
data.GLONASS(1:4,:)
```

```
ans=4×38 timetable
       Time        SatelliteID    EpochFlag    ReceiverClockOffset       C1C        C1C_SSI    
    ___________    ___________    _________    ___________________    __________    _______    _

    24-Jun-2021         1             0            -0.00047787        2.3169e+07      NaN      1
    24-Jun-2021         6             0            -0.00047787        2.3301e+07      NaN      1
    24-Jun-2021         7             0            -0.00047787        2.0036e+07      NaN      1
    24-Jun-2021         8             0            -0.00047787        2.0118e+07      NaN      1
```

```
data.Galileo(1:4,:)
```

```
ans=4×38 timetable
       Time        SatelliteID    EpochFlag    ReceiverClockOffset       C1X        C1X_SSI    
    ___________    ___________    _________    ___________________    __________    _______    _

    24-Jun-2021         4             0            -0.00047787        2.4922e+07      NaN      1
    24-Jun-2021        11             0            -0.00047787         2.375e+07      NaN      1
    24-Jun-2021        12             0            -0.00047787        2.1663e+07      NaN      1
    24-Jun-2021        18             0            -0.00047787        2.2857e+07      NaN      1
```

```
data.BeiDou(1:4,:)
```

```
ans=4×45 timetable
        Time        SatelliteID    EpochFlag    ReceiverClockOffset       C2I        C2I_SSI     _
    ___________     ___________    _________    ___________________    __________    _______    __

    24-Jun-2021         19             0            -0.00047787        2.2728e+07      NaN      1
    24-Jun-2021         20             0            -0.00047787        2.2033e+07      NaN      1
    24-Jun-2021         23             0            -0.00047787        2.6024e+07      NaN      1
    24-Jun-2021         29             0            -0.00047787         2.243e+07      NaN      1
```

## Input Arguments

**`filename` — Name of RINEX version 3 file**
string scalar | character vector

Name of the RINEX version 3 file to read data from, specified as a string scalar or character vector.

Example: `"GODS00USA_R_20211750000_01D_GN.rnx"`

Data Types: `string` | `char`

## Output Arguments

**`data` — Satellite system data from RINEX version 3 file**
structure

Satellite system data from the RINEX version 3 file, returned as a structure. The structure has a `timetable` containing different fields depending on the type of RINEX file and the header entries in the file. For more details on the fields in each navigation and observation files type, see the corresponding “More About” on page 1-239 section:

- “GPS Navigation Message” on page 1-239
- “Galileo Navigation Message” on page 1-241
- “GLONASS Navigation Message” on page 1-243
- “BeiDou Navigation Message” on page 1-244
- “NavIC/IRNSS Navigation Message” on page 1-245
- “QZSS Navigation Message” on page 1-247
- “SBAS Navigation Message” on page 1-248
- “Mixed Observation Data” on page 1-249

Data Types: `struct`

## More About

### GPS Navigation Message

| Field | Data Type | Description |
| --- | --- | --- |
| `Time` | `datetime` | GPS clock time |
| `SatelliteID` | `double` | Satellite system (G) number (PRN) |
| `SVClockBias` | `double` | SV clock bias in seconds |

| Field | Data Type | Description |
|---|---|---|
| SVClockDrift | double | SV clock drift in seconds per second |
| SVClockDriftRate | double | SV clock drift rate in seconds per second squared |
| IODE | double | Issue number of the satellite ephemeris data set, *Issue of Data, Ephemeris* (IODE) |
| Crs | double | Amplitude of the sine harmonic correction term to the orbit radius, in meters |
| Delta_n | double | Mean motion difference from the computed value at reference time, in radians per second. |
| M0 | double | Mean anomaly at the reference time, in radians |
| Cuc | double | Amplitude of the cosine harmonic correction term to the argument of latitude, in radians |
| Eccentricity | double | Eccentricity |
| Cus | double | Amplitude of the sine harmonic correction term to the argument of latitude, in radians |
| sqrtA | double | Square root of the semimajor axis (sqrt(m)) |
| Toe | double | Time of ephemeris (seconds of respective satellite week) |
| Cic | double | Amplitude of the cosine harmonic correction term to the angle of inclination, in radians |
| OMEGA0 | double | Longitude of ascending node of orbit plane at weekly epoch, in radians. |
| Cis | double | Amplitude of the sine harmonic correction term to the angle of inclination, in radians. |
| i0 | double | Inclination angle at reference time, in radians |
| Crc | double | Amplitude of the cosine harmonic correction term to the orbit radius, in meters |
| omega | double | Argument of perigee, in radians |
| OMEGA_DOT | double | Reference rate of right ascension, in radians per second |
| IDOT | double | Rate of inclination angle, in radians per second |
| L2ChannelCodes | double | Codes on L2 channel |
| GPSWeek | double | GPS week number, with time of ephemeris. This is a continuous number, not mod(1024) |
| L2PDataFlag | double | L2P data flag |
| SVAccuracy | double | SV accuracy in meters |
| SVHealth | double | SV health indicated by bits 17-22 (See GPS ICD Section 20.3.3.3.1.4) |
| TGD | double | Timing group delay in seconds |
| IODC | double | Issue number of the satellite clock data set, *Issue of Data, Clock* (IODC). (See GPS ICD Section 20.3.3.3.1.5) |

| Field | Data Type | Description |
| --- | --- | --- |
| TransmissionTime | double | Transmission time of the message |
| FitInterval | double | Fit interval in hours. Bit 17 w 10 sf 2 + IODC and Table 20-XII of the GPS ICD. |
| BRDCOrbit7Spare3 | double | Spare entry. May be used in a future version. |
| BRDCOrbit7Spare4 | double | Spare entry. May be used in a future version. |

**Galileo Navigation Message**

| Field | Data Type | Description |
| --- | --- | --- |
| Time | datetime | Galileo (GAL) clock time |
| SatelliteID | double | Satellite system (E) number |
| SVClockBias | double | SV clock bias in seconds |
| SVClockDrift | double | SV clock drift in seconds per second |
| SVClockDriftRate | double | SV clock drift rate in seconds per second squared |
| IODnav | double | Issue of data of the navigation batch |
| Crs | double | Amplitude of the sine harmonic correction term to the orbit radius, in meters |
| Delta_n | double | Mean motion difference from the computed value at reference time, in radians per second. |
| M0 | double | Mean anomaly at the reference time, in radians |
| Cuc | double | Amplitude of the cosine harmonic correction term to the argument of latitude, in radians |
| Eccentricity | double | Eccentricity |
| Cus | double | Amplitude of the sine harmonic correction term to the argument of latitude, in radians |
| sqrtA | double | Square root of the semimajor axis (sqrt(m)) |
| Toe | double | Time of ephemeris (seconds of respective satellite week) |
| Cic | double | Amplitude of the cosine harmonic correction term to the angle of inclination, in radians |
| OMEGA0 | double | Longitude of ascending node of orbit plane at weekly epoch, in radians. |
| Cis | double | Amplitude of the sine harmonic correction term to the angle of inclination, in radians. |
| i0 | double | Inclination angle at reference time, in radians |
| Crc | double | Amplitude of the cosine harmonic correction term to the orbit radius, in meters |
| omega | double | Argument of perigee, in radians |

| Field | Data Type | Description |
|---|---|---|
| OMEGA_DOT | double | Reference rate of right ascension, in radians per second |
| IDOT | double | Rate of inclination angle, in radians per second |
| DataSources | double | Data sources<br>• Bit 0 set: I/NAV E1-B<br>• Bit 1 set: F/NAV E5a-I<br>• Bit 2 set: I/NAV E5b-I<br>• Bits 0 and 2 : Both can be set if the navigation messages were merged, however, bits 0-2 cannot all be set, as the I/NAV and F/NAV messages contain different information.<br>• Bit 3 reserved for Galileo internal use<br>• Bit 4 reserved for Galileo internal use<br>• Bit 8 set: af0-af2, Toc, SISA are for E5a,E1<br>• Bit 9 set: af0-af2, Toc, SISA are for E5b,E1<br>• Bits 8-9 : exclusive (only one bit can be set) |
| GALWeek | double | GAL week number, with Toe. Continuous number, not mod(1024). |
| BRDCOrbit5Spare4 | double | Spare entry. May be used in a future version. |
| SISAccuracy | double | Signal in space accuracy in meters (-1.0 – no accuracy prediction available (NAPA) or unknown) |
| SVHealth | double | SV health (See Galileo ICD Section 5.1.9.3)<br>• Bit 0: E1B DVS<br>• Bits 1-2: E1B HS<br>• Bit 3: E5a DVS<br>• Bits 4-5 :E5a HS<br>• Bit 6: E5b DVS<br>• Bits 7-8: E5b HS |
| BGDE5aE1 | double | BGD E5a/E1 in seconds |
| BGDE5bE1 | double | BGD E5b/E1 in seconds |
| TransmissionTime | double | Transmission time of the message |
| BRDCOrbit7Spare2 | double | Spare entry. May be used in a future version. |
| BRDCOrbit7Spare3 | double | Spare entry. May be used in a future version. |
| BRDCOrbit7Spare4 | double | Spare entry. May be used in a future version. |

**GLONASS Navigation Message**

| Field | Data Type | Description |
|---|---|---|
| Time | datetime | UTC clock time |
| SatelliteID | double | Satellite system (R) number |
| SVClockBias | double | SV clock bias in seconds |
| SVFrequencyBias | double | SV relative frequency bias in hertz |
| MessageFrameTime | double | Message frame time in seconds of the UTC week |
| PositionX | double | Satellite position X in kilometers |
| VelocityX | double | Satellite velocity X dot in kilometers per second |
| AccelerationX | double | Satellite acceleration X in kilometers per second squared |
| Health | double | Satellite health (0 = healthy, 1 = unhealthy) |
| PositionY | double | Satellite position Y in kilometers |
| VelocityY | double | Satellite velocity Y dot in kilometers per second |
| AccelerationY | double | Satellite acceleration Y in kilometers per second squared |
| FrequencyNumber | double | Frequency number (ICD 5.1) |
| PositionZ | double | Satellite position Z in kilometers |
| VelocityZ | double | Satellite velocity Z dot in kilometers per second |
| AccelerationZ | double | Satellite acceleration Z in kilometers per second squared |
| AgeOperationInfo | double | Age of operation information in days |
| StatusFlags | double | Status flags, 9-bit binary number:<br>• M ; bit 7-8, GLO type indicator (00=GLO, 01=GLO-M/K)<br>• P4 ; bit 6, GLO-M/K only, 1=data updated, 0=data not updated<br>• P3 ; bit 5, num of satellites in current frame almanac (0 = 4 sats, 1 = 5 sats)<br>• P2 ; bit 4, indicate even (0) or odd (1) of time interval<br>• P1 ; bit 2-3, update and validity interval (00 = 0 min, 01 = 30 min, 10=45 min, 11=60 min)<br>• P ; bit 0-1, GLO-M/K only, time offset parameters tc, tGPS source (00 =ground, 01 = tc ground, tGPS onboard, 10 = tc on-board, tGPS ground, 11 = on-board) |
| GroupDelay | double | L1/L2 group delay difference in seconds |
| URAI | double | Raw accuracy index |

| Field | Data Type | Description |
| --- | --- | --- |
| HealthFlags | double | Health flags, 3-bit binary number<br>• l(3) ; bit 2, GLO-M/K only, health bit of string 3<br>• AC ; bit 1, 1 = almanac health reported in ephemerides record, 0 = not reported<br>• C ; bit 0, almanac health bit (1 = healthy, 0 = not healthy) |

**BeiDou Navigation Message**

| Field | Data Type | Description |
| --- | --- | --- |
| Time | datetime | BeiDou (BDT) time. This is a combination of entries from the record (Time of clock year, month, day, hour, minute, second). |
| SatelliteID | double | Satellite system (C) number |
| SVClockBias | double | SV clock bias in seconds |
| SVClockDrift | double | SV clock drift in seconds per second |
| SVClockDriftRate | double | SV clock drift rate in seconds per second squared |
| AODE | double | Age of satellite ephemeris data, *Age of Data, Ephemeris* (AODE). See BeiDou ICD Table Section 5.2.4.11 Table 5-8) and field range is: 0-31. |
| Crs | double | Amplitude of the sine harmonic correction term to the orbit radius, in meters |
| Delta_n | double | Mean motion difference from the computed value at reference time, in radians per second. |
| M0 | double | Mean anomaly at the reference time, in radians |
| Cuc | double | Amplitude of the cosine harmonic correction term to the argument of latitude, in radians |
| Eccentricity | double | Eccentricity |
| Cus | double | Amplitude of the sine harmonic correction term to the argument of latitude, in radians |
| sqrtA | double | Square root of the semimajor axis (`sqrt(m)`) |
| Toe | double | Time of ephemeris (seconds of respective satellite week) |
| Cic | double | Amplitude of the cosine harmonic correction term to the angle of inclination, in radians |
| OMEGA0 | double | Longitude of ascending node of orbit plane at weekly epoch, in radians. |
| Cis | double | Amplitude of the sine harmonic correction term to the angle of inclination, in radians. |
| i0 | double | Inclination angle at reference time, in radians |

| Field | Data Type | Description |
|---|---|---|
| Crc | double | Amplitude of the cosine harmonic correction term to the orbit radius, in meters |
| omega | double | Argument of perigee, in radians |
| OMEGA_DOT | double | Reference rate of right ascension, in radians per second |
| IDOT | double | Rate of inclination angle, in radians per second |
| BRDCOrbit5Spare2 | double | Spare entry. May be used in a future version. |
| BDTWeek | double | BDT week number |
| BRDCOrbit5Spare4 | double | Spare entry. May be used in a future version. |
| SVAccuracy | double | SV accuracy in meters (See BDS ICD Section 5.2.4) |
| SatH1 | double | SatH1 |
| TGD1 | double | TGD1 B1/B3 in seconds |
| TGD2 | double | TGD2 B2/B3 in seconds |
| TransmissionTime | double | Transmission time of the message |
| AODC | double | Age of satellite clock data, *Age of Data, Clock* (AODC). See BeiDou ICD Table Section 5.2.4.9 Table 5-6) and field range is: 0-31. |
| BRDCOrbit7Spare3 | double | Spare entry. May be used in a future version. |
| BRDCOrbit7Spare4 | double | Spare entry. May be used in a future version. |

**NavIC/IRNSS Navigation Message**

| Field | Data Type | Description |
|---|---|---|
| Time | datetime | NavIC/IRNSS clock time (same as GPS time) |
| SatelliteID | double | Satellite system (I) number (PRN) |
| SVClockBias | double | SV clock bias in seconds |
| SVClockDrift | double | SV clock drift in seconds per second |
| SVClockDriftRate | double | SV clock drift rate in seconds per second squared |
| IODEC | double | Issue number of the satellite ephemeris and clock data sets, *Issue of Data, Ephemeris and Clock* (IODEC) |
| Crs | double | Amplitude of the sine harmonic correction term to the orbit radius, in meters |
| Delta_n | double | Mean motion difference from the computed value at reference time, in radians per second. |
| M0 | double | Mean anomaly at the reference time, in radians |

| Field | Data Type | Description |
|---|---|---|
| Cuc | double | Amplitude of the cosine harmonic correction term to the argument of latitude, in radians |
| Eccentricity | double | Eccentricity |
| Cus | double | Amplitude of the sine harmonic correction term to the argument of latitude, in radians |
| sqrtA | double | Square root of the semimajor axis (sqrt(m)) |
| Toe | double | Time of ephemeris (seconds of respective satellite week) |
| Cic | double | Amplitude of the cosine harmonic correction term to the angle of inclination, in radians |
| OMEGA0 | double | Longitude of ascending node of orbit plane at weekly epoch, in radians. |
| Cis | double | Amplitude of the sine harmonic correction term to the angle of inclination, in radians. |
| i0 | double | Inclination angle at reference time, in radians |
| Crc | double | Amplitude of the cosine harmonic correction term to the orbit radius, in meters |
| omega | double | Argument of perigee, in radians |
| OMEGA_DOT | double | Reference rate of right ascension, in radians per second |
| IDOT | double | Rate of inclination angle, in radians per second |
| BRDCOrbit5Spare2 | double | Spare entry. May be used in a future version. |
| IRNWeek | double | IRN week number, with Toe. Continuous number, not mod(1024), counted from 1980 (same as GPS) |
| BRDCOrbit5Spare4 | double | Spare entry. May be used in a future version. |
| UserRangeAccuracy | double | User range accuracy in meters. See NavIC/IRNSS ICD Section 6.2.1.4 |
| HealthFlags | double | Health (Sub frame 1, bits 155(most significant) and 156(least significant)), where 0 = L5 and S healthy, 1 = L5 healthy and S unhealthy, 2= L5 unhealthy and S healthy, 3= both L5 and S unhealthy |
| TGD | double | Timing group delay in seconds |
| BRDCOrbit6Spare4 | double | Spare entry. May be used in a future version. |
| TransmissionTime | double | Transmission time of the message |
| BRDCOrbit7Spare2 | double | Spare entry. May be used in a future version. |
| BRDCOrbit7Spare3 | double | Spare entry. May be used in a future version. |

| Field | Data Type | Description |
|---|---|---|
| BRDCOrbit7Spare4 | double | Spare entry. May be used in a future version. |

**QZSS Navigation Message**

| Field | Data Type | Description |
|---|---|---|
| Time | datetime | QZSS clock time |
| SatelliteID | double | Satellite system (J) Satellite PRN-192 |
| SVClockBias | double | SV clock bias in seconds |
| SVClockDrift | double | SV clock drift in seconds per second |
| SVClockDriftRate | double | SV clock drift rate in seconds per second squared |
| IODE | double | Issue number of the satellite ephemeris data set, *Issue of Data, Ephemeris* (IODE) |
| Crs | double | Amplitude of the sine harmonic correction term to the orbit radius, in meters |
| Delta_n | double | Mean motion difference from the computed value at reference time, in radians per second. |
| M0 | double | Mean anomaly at the reference time, in radians |
| Cuc | double | Amplitude of the cosine harmonic correction term to the argument of latitude, in radians |
| Eccentricity | double | Eccentricity |
| Cus | double | Amplitude of the sine harmonic correction term to the argument of latitude, in radians |
| sqrtA | double | Square root of the semimajor axis (`sqrt(m)`) |
| Toe | double | Time of ephemeris (seconds of respective satellite week) |
| Cic | double | Amplitude of the cosine harmonic correction term to the angle of inclination, in radians |
| OMEGA0 | double | Longitude of ascending node of orbit plane at weekly epoch, in radians. |
| Cis | double | Amplitude of the sine harmonic correction term to the angle of inclination, in radians. |
| i0 | double | Inclination angle at reference time, in radians |
| Crc | double | Amplitude of the cosine harmonic correction term to the orbit radius, in meters |
| omega | double | Argument of perigee, in radians |
| OMEGA_DOT | double | Reference rate of right ascension, in radians per second |
| IDOT | double | Rate of inclination angle, in radians per second |
| L2ChannelCodes | double | Codes on L2 channel (fixed to 2, see IS-QZSS-PNT 4.1.2.7) |
| GPSWeek | double | GPS week number, with Toe. Continuous number, not mod(1024). |

| Field | Data Type | Description |
|---|---|---|
| L2PDataFlag | double | L2 P data flag set to 1 since QZSS does not track L2P |
| SVAccuracy | double | SV accuracy (m) (See IS-QZSS-PNT Section 5.4.3.1) |
| SVHealth | double | SV health (bits 17-22 w 3 sf 1) (See IS-QZSS-PNT 5.4.1) |
| TGD | double | Timing group delay (s) (The QZSS ICD specifies a do not use bit pattern “10000000”, this condition is represented by a blank field.) |
| IODC | double | Issue number of the satellite clock data set, *Issue of Data, Clock* (IODC) |
| TransmissionTime | double | Transmission time of the message |
| FitIntervalFlag | double | Fit interval flag (0/1) (See IS-QZSS-PNT, 4.1.2.4(3) 0 – two hours), 1 – more than 2 hours. |
| BRDCOrbit7Spare3 | double | Spare entry. May be used in a future version. |
| BRDCOrbit7Spare4 | double | Spare entry. May be used in a future version. |

**SBAS Navigation Message**

| Field | Data Type | Description |
|---|---|---|
| Time | datetime | SBAS clock time |
| SatelliteID | double | Satellite system (S) number |
| SVClockBias | double | SV clock bias in seconds |
| SVFrequencyBias | double | SV relative frequency bias in hertz |
| TransmissionTime | double | Transmission time of the message |
| PositionX | double | Satellite position X in kilometers |
| VelocityX | double | Satellite velocity X dot in kilometers per second |
| AccelerationX | double | Satellite acceleration X in kilometers per second squared |
| Health | double | Health: SBAS: See RINEX 3.05 Standard section 5.4.4 for: health, health availability and User Range Accuracy. |
| PositionY | double | Satellite position Y in kilometers |
| VelocityY | double | Satellite velocity Y dot in kilometers per second |
| AccelerationY | double | Satellite acceleration Y in kilometers per second squared |
| AccuracyCode | double | Accuracy code (URA, m) |
| PositionZ | double | Satellite position Z in kilometers |
| VelocityZ | double | Satellite velocity Z dot in kilometers per second |
| AccelerationZ | double | Satellite acceleration Z in kilometers per second squared |

| Field | Data Type | Description |
|---|---|---|
| IODN | double | Issue number of the satellite navigation data set, *Issue of Data, Navigation* (IODN). See reference RTCA DO-229, 8 first bits after Message Type if MT9 |

**Mixed Observation Data**

Mixed observation data may have multiple timetables in the output structure. Unlike the navigation messages, the most of the fields of the mixed observation files change depending on the observation types in the observation data. However, all observation data contains the same first fields.

**Main Observation Data Fields**

| Field | Data Type | Description |
|---|---|---|
| Time | datetime | Satellite clock time. |
| SatelliteID | double | Satellite system number. |
| EpochFlag | nonnegative integer | Epoch flag indicating the status of the satellite system.<br>• 0 — OK.<br>• 1 — Power failure between previous epoch and current epoch.<br>• >1 — Special event. See RINEX Version 3.05 File Section 5.3.2 for more information. |
| ReceiverClockOffset | double | Receiver clock offset in seconds |

The rest of the headers are observation codes comprised of three digits that represent type, band, and attribute. See "Observation Type Descriptors" on page 1-249 for more information about the possible types, bands, and attributes.

Each descriptor code has corresponding field for signal strength indicator (SSI) and, if the observation type is phase (L), a field for loss-of-lock indicator (LLI). For example, type L, band 1, and attribute X has the field L1X and has two additional fields, L1X_SSI and L1X_LLI.

The SSI fields are ratios specified as an integer in the range [1, 9]. A ratio of 1 is considered unreliable, above 5 is considered good, and 9 is the maximum possible signal strength.

The LLI fields are three-bit codes that are specified as an integer in the range [0, 7]. A value of 0 indicates no loss of lock or unknown. The least significant bit indicates a lost lock between the previous and current observations, the second bit indicates half-cycle ambiguity or slip is possible, and the most significant bit indicates binary offset carrier (BOC) tracking of a multiplexed BOC (MBOC) modulated signal.

**Observation Type Descriptors**

Observation type descriptors is a string comprised of three parts. The first part is the observation type, the second is the frequency band, and the third is the attribute which indicates the tracking mode or channel.

The observation type can be one of five types.

#### Type

- C — Code or pseudorange, is the distance, in meters, between the receiver antenna and the satellite antenna including delays and other biases.
- L — Phase is the carrier phase range from the antenna to the satellite, measured in whole cycles.
- D — Doppler shift indicating the approach of satellites, where a positive value indicates an approaching satellite.
- S — Raw signal strength (carrier to noise ratio) as an integer in the range [1, 9].
- X — Receiver channel numbers.

You can identify the frequency band code number given a frequency band and a satellite system.

**Frequency Band vs Satellite System**

| Frequency Band Code Number | GPS | QZSS | SBAS | BDS | GLO | GAL | NavIC/ IRNSS |
|---|---|---|---|---|---|---|---|
| 1 | L1 | L1 | L1 | L1 | G1 | E1 | — |
| 2 | L2 | L2 | — | B1 | G2 | — | — |
| 3 | — | — | — | — | G3 | — | — |
| 4 | — | — | — | — | G1a | — | — |
| 5 | L5 | L5 | L5 | B2a | — | E5a | L5 |
| 6 | — | L6 | — | B3 or B3A | G2a | E6 | — |
| 7 | — | — | — | B2 or B2b | — | E5b | — |
| 8 | — | — | — | B2a and B2b | — | E5a and E5b | — |
| 9 | — | — | — | — | — | — | S |

You can identify the attribute letter given a channel or code and a satellite system.

**Attribute vs Satellite System**

| Attribute Letter | GPS | QZSS | SBAS | BDS | GLO | GAL | NavIC/ IRNSS |
|---|---|---|---|---|---|---|---|
| A | — | — | — | — | A channel | A channel | A channel |
| B | — | — | — | — | A channel | A channel | A channel |
| C | C code-based | C code-based | C code-based | — | C code-based | C channel | C channel |
| D | Semi-codeless | Semi-codeless | — | Data channel | — | — | — |
| E | — | E channel | — | — | — | — | — |
| I | I channel | I channel | — | I channel | — | I channel | — |
| L | L channel (L2C GPS)<br><br>P channel | L channel<br><br>P channel | — | — | — | — | — |
| M | M-based code | — | — | — | — | — | — |
| N | Codeless | — | — | — | — | — | — |
| P | P code-based | — | — | Pilot channel | P code-based | — | — |
| Q | Q channel | Q channel | — | Q channel | — | Q channel | — |
| S | D channel<br><br>M channel (L2C GPS) | D channel<br><br>M channel | — | — | — | — | — |
| W | Based on Z-tracking | — | — | — | — | — | — |
| X | I and Q channels<br><br>M and L channels<br><br>D and P channels | I and Q channels<br><br>M and L channels<br><br>D and P channels | — | I and Q channels<br><br>D and P channels | — | B and C channels<br><br>I and Q channels | B and C channels |
| Y | Y code-based | — | — | — | — | — | — |
| Z | — | I and Q channels<br><br>D and E channels | — | D and P channels | — | A, B, and C channels | — |

These are examples of codes:

- C1M — L1 pseudorange derived from the M channel for a GPS satellite.

- L5X — E5a carrier phase derived from the B and C channels for a Galileo satellite.
- S3I — G3 signal strength derived from the I channels for a GLONASS satellite.

# Version History

**Introduced in R2022a**

## References

[1] International GNSS Service (for Daily 30-Second GPS Broadcast Ephemeris Data, NASA Crustal Dynamics Data Information System (CDDIS), Greenbelt, MD, USA, Jun. 24, 2021; accessed June 25, 2021). https://dx.doi.org/10.5067/GNSS/gnss_daily_n_001.

[2] International GNSS Service (for Daily 30-Second Galileo Broadcast Ephemeris Data, NASA Crustal Dynamics Data Information System (CDDIS), Greenbelt, MD, USA, Jun. 24, 2021; accessed June 25, 2021). https://dx.doi.org/10.5067/GNSS/gnss_daily_l_001.

[3] International GNSS Service (for Daily 30-Second GLONASS Broadcast Ephemeris Data, NASA Crustal Dynamics Data Information System (CDDIS), Greenbelt, MD, USA, Jun. 24, 2021; accessed August 19, 2021). https://dx.doi.org/10.5067/GNSS/gnss_daily_g_001.

[4] International GNSS Service (for Daily 30-Second BeiDou Broadcast Ephemeris Data, NASA Crustal Dynamics Data Information System (CDDIS), Greenbelt, MD, USA, Jun. 24, 2021; accessed August 19, 2021). https://dx.doi.org/10.5067/GNSS/gnss_daily_f_001.

[5] International GNSS Service (for Daily 30-Second NavIC/IRNSS Broadcast Ephemeris Data, NASA Crustal Dynamics Data Information System (CDDIS), Greenbelt, MD, USA, Jun. 24, 2021; accessed August 19, 2021). https://dx.doi.org/10.5067/GNSS/gnss_daily_i_001.

[6] International GNSS Service (for Daily 30-Second QZSS Broadcast Ephemeris Data, NASA Crustal Dynamics Data Information System (CDDIS), Greenbelt, MD, USA, Jun. 24, 2021; accessed August 19, 2021). https://dx.doi.org/10.5067/GNSS/gnss_daily_q_001.

[7] International GNSS Service (for Daily 30-Second SBAS Broadcast Ephemeris Data, NASA Crustal Dynamics Data Information System (CDDIS), Greenbelt, MD, USA, Jun. 24, 2021; accessed August 19, 2021). https://dx.doi.org/10.5067/GNSS/gnss_daily_h_001.

[8] International GNSS Service (for Hourly 30-Second Observation Data, NASA Crustal Dynamics Data Information System (CDDIS), Greenbelt, MD, USA, Jun. 24, 2021; accessed August 19, 2021). https://dx.doi.org/10.5067/GNSS/gnss_hourly_o_001.

[9] Romero, Ignacio, ed. *RINEX The Receiver Independent Exchange Format Version 3.05*. Darmstadt, Germany: IGS/RTCM ESA/ESOC/Navigation Support Office. December, 2020. Accessed on: Dec. 22, 2021. https://files.igs.org/pub/data/format/rinex305.pdf .

## See Also

**Functions**

`rinexinfo` | `gnssconstellation` | `pseudoranges`

**Topics**

"Ground Vehicle Pose Estimation for Tightly Coupled IMU and GNSS"

# rotm2axang

Convert rotation matrix to axis-angle rotation

## Syntax

```
axang = rotm2axang(rotm)
```

## Description

`axang = rotm2axang(rotm)` converts a rotation given as an orthonormal rotation matrix, `rotm`, to the corresponding axis-angle representation, `axang`. The input rotation matrix must be in the premultiply form for rotations.

## Examples

### Convert Rotation Matrix to Axis-Angle Rotation

```
rotm = [1 0 0 ; 0 -1 0; 0 0 -1];
axang = rotm2axang(rotm)
```

```
axang = 1×4

    1.0000         0         0    3.1416
```

## Input Arguments

**`rotm` — Rotation matrix**
3-by-3-by-*n* matrix

Rotation matrix, specified as a 3-by-3-by-*n* matrix containing *n* rotation matrices. Each rotation matrix has a size of 3-by-3 and must be orthonormal. The input rotation matrix must be in the premultiply form for rotations.

**Note** Rotation matrices that are slightly non-orthonormal can give complex outputs. Consider validating your matrix before inputting to the function.

Example: `[0 0 1; 0 1 0; -1 0 0]`

## Output Arguments

**axang — Rotation given in axis-angle form**
*n*-by-4 matrix

Rotation given in axis-angle form, returned as an *n*-by-4 matrix of *n* axis-angle rotations. The first three elements of every row specify the rotation axis, and the last element defines the rotation angle (in radians).

Example: `[1 0 0 pi/2]`

# Version History

**Introduced in R2015a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`axang2rotm` | `so3`

# rotm2eul

Convert rotation matrix to Euler angles

## Syntax

```
eul = rotm2eul(rotm)
eul = rotm2eul(rotm,sequence)
[eul,eulAlt] = rotm2eul( ___ )
```

## Description

`eul = rotm2eul(rotm)` converts a rotation matrix, `rotm`, to the corresponding Euler angles, `eul`. The input rotation matrix must be in the premultiply form for rotations. The default order for Euler angle rotations is `"ZYX"`.

`eul = rotm2eul(rotm,sequence)` converts a rotation matrix to Euler angles. The Euler angles are specified in the axis rotation sequence, `sequence`. The default order for Euler angle rotations is `"ZYX"`.

`[eul,eulAlt] = rotm2eul( ___ )` also returns an alternate set of Euler angles that represents the same rotation `eulAlt`.

## Examples

### Convert Rotation Matrix to Euler Angles

```
rotm = [0 0 1; 0 1 0; -1 0 0];
eulZYX = rotm2eul(rotm)
```

```
eulZYX = 1×3

         0    1.5708         0
```

### Convert Rotation Matrix to Euler Angles Using ZYZ Axis Order

```
rotm = [0 0 1; 0 1 0; -1 0 0];
eulZYZ = rotm2eul(rotm,'ZYZ')
```

```
eulZYZ = 1×3

   -3.1416   -1.5708   -3.1416
```

## Input Arguments

### `rotm` — Rotation matrix

3-by-3-by-*n* matrix

Rotation matrix, specified as a 3-by-3-by-*n* matrix containing *n* rotation matrices. Each rotation matrix has a size of 3-by-3 and is orthonormal. The input rotation matrix must be in the premultiply form for rotations.

---

**Note** Rotation matrices that are slightly non-orthonormal can give complex outputs. Consider validating your matrix before inputting to the function.

---

Example: `[0 0 1; 0 1 0; -1 0 0]`

### `sequence` — Axis-rotation sequence

`"ZYX"` (default) | `"ZYZ"` | `"ZXY"` | `"ZXZ"` | `"YXY"` | `"YZX"` | `"YXZ"` | `"YZY"` | `"XYX"` | `"XYZ"` | `"XZX"` | `"XZY"`

Axis-rotation sequence for the Euler angles, specified as one of these string scalars:

- `"ZYX"` (default)
- `"ZYZ"`
- `"ZXY"`
- `"ZXZ"`
- `"YXY"`
- `"YZX"`
- `"YXZ"`
- `"YZY"`
- `"XYX"`
- `"XYZ"`
- `"XZX"`
- `"XZY"`

Each character indicates the corresponding axis. For example, if the sequence is `"ZYX"`, then the three specified Euler angles are interpreted in order as a rotation around the *z*-axis, a rotation around the *y*-axis, and a rotation around the *x*-axis. When applying this rotation to a point, it will apply the axis rotations in the order *x*, then *y*, then *z*.

Data Types: `string` | `char`

## Output Arguments

### `eul` — Euler rotation angles

*n*-by-3 matrix

Euler rotation angles in radians, returned as an *n*-by-3 array of Euler rotation angles. Each row represents one Euler angle set.

Example: `[0 0 1.5708]`

**`eulAlt` — Alternate Euler rotation angle solution**
*n*-by-3 matrix

Alternate Euler rotation angle solution in radians, returned as an *n*-by-3 array of Euler rotation angles. Each row represents one Euler angle set.

Example: `[0 0 1.5708]`

# Version History

**Introduced in R2015a**

### R2020a: Alternate Euler angle output

`rotm2eul` now optionally outputs an alternate set of Euler angles `eulAlt` that also represent the same rotation as the original output Euler angles `eul`. So if you use `eul` or `eulAlt` to rotate a point, the resulting point is the same.

### R2023a: Additional Euler sequence support

`rotm2eul` supports additional Euler sequences for the `sequences` argument. These are all the supported Euler sequences:

- `"ZYX"`
- `"ZYZ"`
- `"ZXY"`
- `"ZXZ"`
- `"YXY"`
- `"YZX"`
- `"YXZ"`
- `"YZY"`
- `"XYX"`
- `"XYZ"`
- `"XZX"`
- `"XZY"`

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`eul2rotm` | `so2` | `so3`

# rotm2quat

Convert rotation matrix to quaternion

## Syntax

```
quat = rotm2quat(rotm)
```

## Description

`quat = rotm2quat(rotm)` converts a rotation matrix, `rotm`, to the corresponding unit quaternion representation, `quat`. The input rotation matrix must be in the premultiply form for rotations.

## Examples

### Convert Rotation Matrix to Quaternion

```
rotm = [0 0 1; 0 1 0; -1 0 0];
quat = rotm2quat(rotm)
```

```
quat = 1×4

    0.7071         0    0.7071         0
```

## Input Arguments

**`rotm` — Rotation matrix**
3-by-3-by-*n* matrix

Rotation matrix, specified as a 3-by-3-by-*n* matrix containing *n* rotation matrices. Each rotation matrix has a size of 3-by-3 and is orthonormal. The input rotation matrix must be in the premultiply form for rotations.

**Note** Rotation matrices that are slightly non-orthonormal can give complex outputs. Consider validating your matrix before inputting to the function.

Example: `[0 0 1; 0 1 0; -1 0 0]`

## Output Arguments

**`quat` — Unit quaternion**
*n*-by-4 matrix

Unit quaternion, returned as an *n*-by-4 matrix containing *n* quaternions. Each quaternion, one per row, is of the form $q = [w\ x\ y\ z]$, with *w* as the scalar number.

Example: `[0.7071 0.7071 0 0]`

## Version History

**Introduced in R2015a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`quat2rotm` | `so3` | `quaternion`

# rotm2tform

Convert rotation matrix to homogeneous transformation

## Syntax

```
tform = rotm2tform(rotm)
```

## Description

`tform = rotm2tform(rotm)` converts the rotation matrix `rotm` into a homogeneous transformation matrix `tform`. The input rotation matrix must be in the premultiply form for rotations. When using the transformation matrix, premultiply it by the coordinates to be transformed (as opposed to postmultiplying).

## Examples

### Convert Rotation Matrix to Homogeneous Transformation

```
rotm = [1 0 0 ; 0 -1 0; 0 0 -1];
tform = rotm2tform(rotm)
```

```
tform = 4×4

     1     0     0     0
     0    -1     0     0
     0     0    -1     0
     0     0     0     1
```

## Input Arguments

### `rotm` — Rotation matrix

2-by-2-by-*n* array | 3-by-3-by-*n* array

Rotation matrix, specified as a 2-by-2-by-*n* or a 3-by-3-by-*n* array containing *n* rotation matrices. Each rotation matrix is either 2-by-2 or 3-by-3 and is orthonormal. The input rotation matrix must be in the premultiplied form for rotations.

**Note** Rotation matrices that are not orthonormal can be normalized with the `normalize` function.

2-D rotation matrices are of this form:

3-D rotation matrices are of this form:

Example: `[0 0 1; 0 1 0; -1 0 0]`

## Output Arguments

**`tform` — Homogeneous transformation**
3-by-3-by-*n* array | 4-by-4-by-*n* array

Homogeneous transformation, returned as a 3-by-3-by-*n* array or 4-by-4-by-*n* array. *n* is the number of homogeneous transformations. When using the transformation matrix, premultiply it by the coordinates to be transformed (as opposed to postmultiplying).

2-D homogeneous transformation matrices are of this form:

$$T = \begin{bmatrix} r_{11} & r_{12} & t_1 \\ r_{21} & r_{22} & t_2 \\ 0 & 0 & 1 \end{bmatrix}$$

3-D homogeneous transformation matrices are of this form:

$$T = \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_1 \\ r_{21} & r_{22} & r_{23} & t_2 \\ r_{31} & r_{32} & r_{33} & t_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Example: `[0 0 1 0; 0 1 0 0; -1 0 0 0; 0 0 0 1]`

## More About

### 2-D Homogeneous Transformation Matrix

2-D homogeneous transformation matrices consist of both an SO(2) rotation and an *xy*-translation.

To read more about SO(2) rotations, see the “2-D Orthonormal Rotation Matrix” on page 2-1512 section of the `so2` object.

The translation is along the *x*-, *y*-, and *z*-axes as a three-element column vector:

$$t = \begin{bmatrix} x \\ y \end{bmatrix}$$

The SO(2) rotation matrix *R* is applied to the translation vector *t* to create the homogeneous translation matrix *T*. The rotation matrix is present in the upper-left of the transformation matrix as 2-by-2 submatrix, and the translation vector is present as a two-element vector in the last column.

$$T = \begin{bmatrix} R & t \\ 0_{1 \times 2} & 1 \end{bmatrix} = \begin{bmatrix} I_2 & t \\ 0_{1 \times 2} & 1 \end{bmatrix} \cdot \begin{bmatrix} R & 0 \\ 0_{1 \times 2} & 1 \end{bmatrix}$$

### 3-D Homogeneous Transformation Matrix

3-D homogeneous transformation matrices consist of both an SO(3) rotation and an *xyz*-translation.

To read more about SO(3) rotations, see the “3-D Orthonormal Rotation Matrix” on page 2-1508 section of the `so3` object.

The translation is along the *x*-, *y*-, and *z*-axes as a three-element column vector:

$$t = \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

The SO(3) rotation matrix $R$ is applied to the translation vector $t$ to create the homogeneous translation matrix $T$. The rotation matrix is present in the upper-left of the transformation matrix as 3-by-3 submatrix, and the translation vector is present as a three-element vector in the last column.

$$T = \begin{bmatrix} R & t \\ 0_{1x3} & 1 \end{bmatrix} = \begin{bmatrix} I_3 & t \\ 0_{1x3} & 1 \end{bmatrix} \cdot \begin{bmatrix} R & 0 \\ 0_{1x3} & 1 \end{bmatrix}$$

## Version History

**Introduced in R2015a**

### R2023a: `rotm2tform` Supports 2-D Rotation Matrices

The `rotm` argument now accepts 2-D rotation matrices as a 2-by-2-by-*n* array and `rotm2tform` outputs 2-D transformation matrices as a 3-by-3-by-*n* array.

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`tform2rotm` | `se2` | `se3` | `so2` | `so3`

# semread

Read data from SEM almanac file

## Syntax

```
[data,title] = semread(filename)
[data,title] = semread(filename,GPSWeekEpoch=refdate)
```

## Description

`[data,title] = semread(filename)` reads data from the SEM (System Effectiveness Model) almanac file for the date specified by `filename`, and returns the parameters of each associated satellite as a timetable, as well as the almanac title.

`[data,title] = semread(filename,GPSWeekEpoch=refdate)` specifies the reference date from which the SEM almanac file counts the GPS (Global Positioning System) week number.

## Examples

### Read GPS Navigation Message Data from SEM Almanac File

Download the SEM almanac file from NAVCEN website and parse it. Specify the date for which the file is to be downloaded.

```
d = datetime("today") - 2;
```

Create the URL.

```
baseURL = "https://www.navcen.uscg.gov/sites/default/files/gps/almanac/";
almanacType = "/sem/";
almanacExtension = ".al3";
url = baseURL + d.Year + almanacType + day(d,"dayofyear") + ...
      almanacExtension;
```

Specify the file name.

```
filename = "semalmanac" + "_" + d.Year + "-" + ...
           d.Month + "-" + d.Day + ".al3";
```

Save the file.

```
websave(filename,url);
```

Get the orbital parameters from the downloaded SEM almanac file.

```
[data,title] = semread(filename)
```

```
data=31×16 timetable
            Time            GPSWeekNumber    GPSTimeOfApplicability    PRNNumber    SVN    Averag
    ____________________    _____________    ______________________    _________    ___    ______
```

```
    17-Jul-2022 17:03:42        2219               61440              1        63
    17-Jul-2022 17:03:42        2219               61440              2        61
    17-Jul-2022 17:03:42        2219               61440              3        69
    17-Jul-2022 17:03:42        2219               61440              4        74
    17-Jul-2022 17:03:42        2219               61440              5        50
    17-Jul-2022 17:03:42        2219               61440              6        67
    17-Jul-2022 17:03:42        2219               61440              7        48
    17-Jul-2022 17:03:42        2219               61440              8        72
    17-Jul-2022 17:03:42        2219               61440              9        68
    17-Jul-2022 17:03:42        2219               61440             10        73
    17-Jul-2022 17:03:42        2219               61440             11        78
    17-Jul-2022 17:03:42        2219               61440             12        58
    17-Jul-2022 17:03:42        2219               61440             13        43
    17-Jul-2022 17:03:42        2219               61440             14        77
    17-Jul-2022 17:03:42        2219               61440             15        55
    17-Jul-2022 17:03:42        2219               61440             16        56
      ⋮
```

```
title = 
'CURRENT.ALM'
```

### View Satellite Positions from SEM Almanac File for Receiver Position

Read GPS navigation message data from a SEM almanac file.

```
gpsData = semread("semalmanac_2022-4-10.al3");
```

Get the satellite positions, velocities, and IDs at the first time step.

```
t = gpsData.Time(1);
[satPos,satVel,satID] = gnssconstellation(t,gpsData,GNSSFileType="SEM");
```

Specify a GNSS receiver position in geodetic coordinates (latitude, longitude, and altitude).

```
recPos = [42 -71 50]; % Natick, MA
```

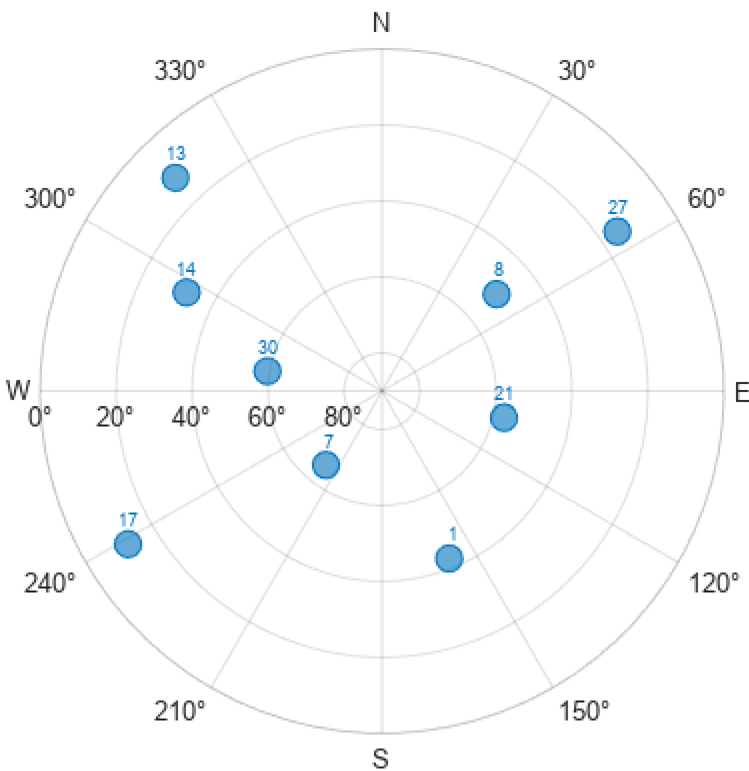
Get the azimuth and elevation look angles of the satellite positions for the specified receiver position. The `isVis` output indicates which satellites are visible. Find the total number of visible satellites by using `nnz`.

```
[az,el,isVis] = lookangles(recPos,satPos);
fprintf('%d satellites visible at %s.\n',nnz(isVis),t);
```

```
9 satellites visible at 12-Apr-2022 16:50:54.
```

Visualize all the visible satellites.

```
skyplot(az(isVis),el(isVis),satID(isVis))
```




#### Plot Trajectories of Satellites Over Time from SEM Almanac File

Read GPS navigation message data from a SEM almanac file.

```
gpsData = semread("semalmanac_2022-4-10.al3");
```

Specify the relevant time-stepping information.

```
startTime = gpsData.Time(1);
numHours = 12;
secondsPerHour = 3600;
dt = 60;
timeElapsed = 0:dt:(numHours*secondsPerHour);
t = startTime + seconds(timeElapsed);
```

Specify a GNSS receiver position in geodetic coordinates (latitude, longitude, and altitude).

```
recPos = [42 -71 50]; % Natick, MA
```

Get the azimuth and elevation look angles for the all the positions of the satellites for the specified receiver position.

```
numSats = numel(gpsData.PRNNumber); % Number of satellites
[allAz,allEl] = deal(NaN(numel(t),numSats));
for i = 1:numel(t)
```

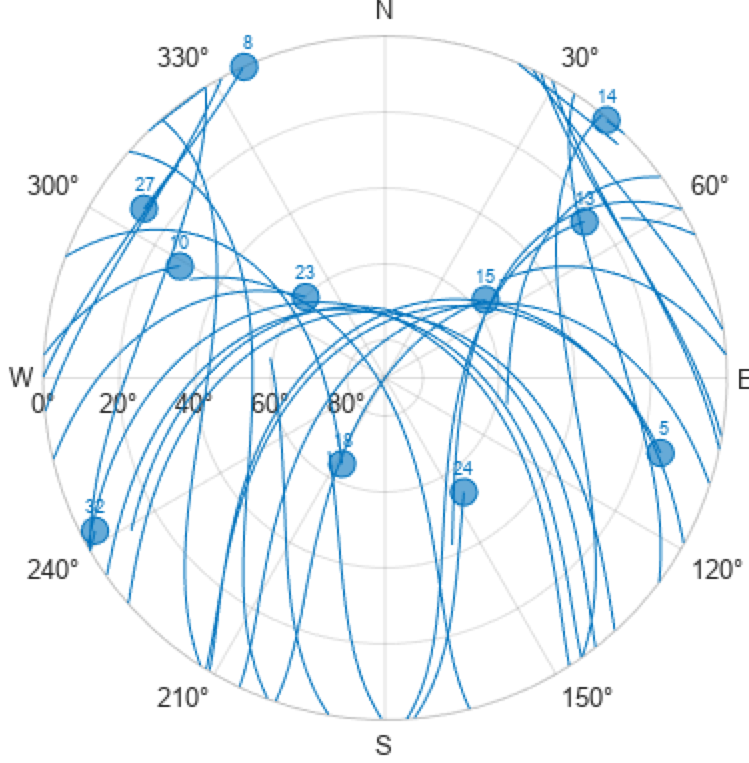
```
    [satPos,~,satID] = gnssconstellation(t(i),gpsData,GNSSFileType="SEM");
    [az,el,vis] = lookangles(recPos,satPos);
    allAz(i,:) = az;
    allEl(i,:) = el;
end
```

Mark all satellites below the horizon as `NaN` for no visibility.

```
allEl(allEl < 0) = NaN;
```

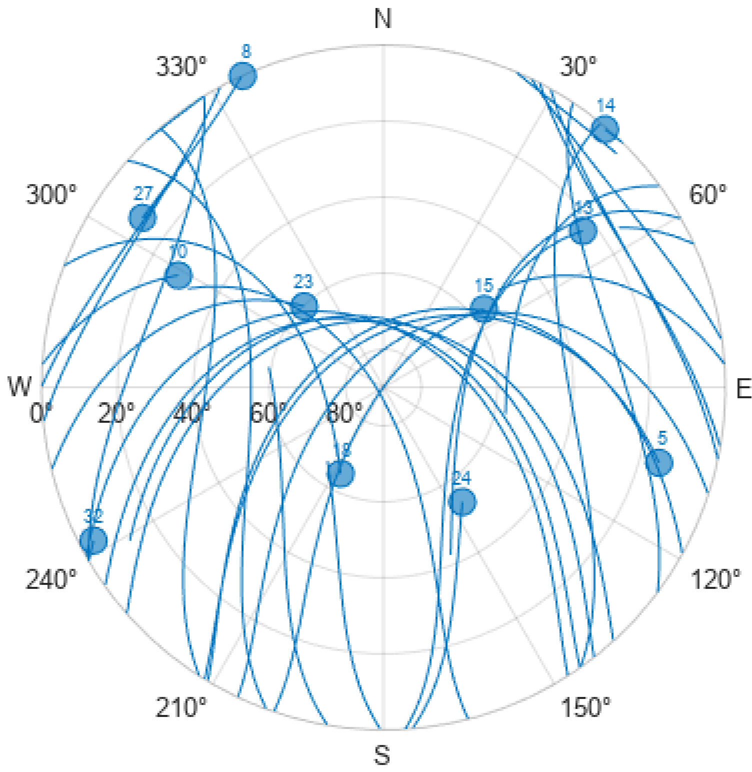
Visualize the trajectories of the satellites.

```
figure
skyplot(allAz,allEl,satID)
```




Animate the trajectories of the satellites.

```
figure
sp = skyplot(allAz(1,:),allEl(1,:),satID);
for i = 1:size(allAz, 1)
    set(sp,AzimuthData=allAz(1:i,:),ElevationData=allEl(1:i,:));
    drawnow
end
```




## Input Arguments

**filename — SEM almanac file name**
string scalar | character vector

SEM almanac file name, specified as a string scalar or character vector. The file name can include an absolute path, relative path, or no path. The file name can also include the file extensions.

Example: "semalmanac_2022-1-18.al3"

Example: "mydir/semalmanac_2022-1-18.al3"

Example: "C:/mydir/semalmanac_2022-1-18.al3"

Data Types: char | string

**refdate — Reference date**
"06-Jan-1980" | "21-Aug-1999" | "06-Apr-2019"

Reference date, specified as one of these valid datetime strings that coincide with the GPS week number rollover dates:

- "06-Jan-1980"
- "21-Aug-1999"
- "06-Apr-2019"

These dates occur every 1024 weeks, starting from January 6, 1980 at 00:00 (UTC). The default value is a `datetime` string that coincides with the most recent GPS week number rollover date before the current day.

Example: `GPSWeekEpoch="21-Aug-1999"`

Data Types: `char` | `string`

## Output Arguments

**`data` — Parameters of each satellite**
timetable

Parameters of each satellite, returned as a `timetable` with a row for each record and a column for each parameter in that record. Find more information on the SEM almanac parameters definition, see the Table 40-II in *ICD-GPS-240D* [2].

| Parameters | Data Type | Description |
|---|---|---|
| `Time` | `datetime` | GPS clock time, calculated using `GPSWeekNumber` and `GPSTimeOfApplicability`. |
| `GPSWeekNumber` | `double` | GPS week number, continuous, not `mod(1024)`. |
| `GPSTimeOfApplicability` | `double` | Number of seconds since the beginning of the GPS week number. |
| `PRNNumber` | `double` | Satellite pseudorandom noise number. |
| `SVN` | `double` | Space vehicle reference number of the satellite. |
| `AverageURANumber` | `double` | Average URA number of the satellite. |
| `Eccentricity` | `double` | Eccentricity of the satellite. |
| `InclinationOffset` | `double` | Inclination angle offset from 54 degrees, in semicircles. |
| `RateOfRightAscension` | `double` | Rate of change in the measurement of the angle of right ascension, in semicircles per second. |
| `SqrtOfSemiMajorAxis` | `double` | Square root of the semimajor axis, in meters$^{1/2}$. |
| `GeographicLongitudeOfOrbitalPlane` | `double` | Geographic longitude of the orbital plane at the weekly epoch, in semicircles. |
| `ArgumentOfPerigee` | `double` | Angle from the equator to perigee, in semicircles. |

| Parameters | Data Type | Description |
|---|---|---|
| `MeanAnomaly` | `double` | Angle of the position of the satellite in its orbit relative to perigee, in semicircles. |
| `ZerothOrderClockCorrection` | `double` | Satellite almanac zeroth-order clock correction term, in seconds. |
| `FirstOrderClockCorrection` | `double` | Satellite almanac first-order clock correction term, in seconds per second. |
| `SatelliteHealth` | `double` | Satellite vehicle health data code. |
| `SatelliteConfiguration` | `double` | Satellite vehicle configuration code. |

**`title` — Almanac title**
character vector

Almanac title, returned as a character vector.

## Tips

- To download SEM almanac files from the NAVCEN website for the current date, you must specify a date 2 days before the current date because the GPS time of applicability is approximately 70 hours later than the transmission time of the almanac data set. See the "Read GPS Navigation Message Data from SEM Almanac File" on page 1-263 example for more details.

# Version History

**Introduced in R2022b**

## References

[1] Science Applications International Corporation. NAVSTAR GPS Space Segment/Navigation User Interfaces. IS-GPS-200M. Los Angeles, CA: United States Space Force Space Systems Command, approved May 21, 2021. https://www.navcen.uscg.gov/sites/default/files/pdf/gps/IS_GPS_200M.pdf.

[2] Science Applications International Corporation. NAVSTAR GPS Space Segment/Navigation User Interfaces. ICD-GPS-240D. Los Angeles, CA: United States Space Force Space Systems Command, approved May 21, 2021. https://www.navcen.uscg.gov/sites/default/files/pdf/gps/ICD_GPS_240D.pdf.

[3] United States Coast Guard. "GPS Almanacs, NANUs, and OPS Advisories Archives." US Coast Guard Navigation Center. Accessed May 6, 2022. https://www.navcen.uscg.gov/archives.

## See Also

`rinexread` | `yumaread` | `gnssconstellation` | `skyplot` | `lookangles` | `websave`

# show

Visualize path segment

## Syntax

```
show(pathSeg)
show(pathSeg,Name,Value)
```

## Description

`show(pathSeg)` plots the path segment with start and goal positions and their headings.

`show(pathSeg,Name,Value)` also specifies `Name,Value` pairs to control display settings.

## Examples

### Connect Poses Using Dubins Connection Path

Create a `dubinsConnection` object.

```
dubConnObj = dubinsConnection;
```

Define start and goal poses as `[x y theta]` vectors.

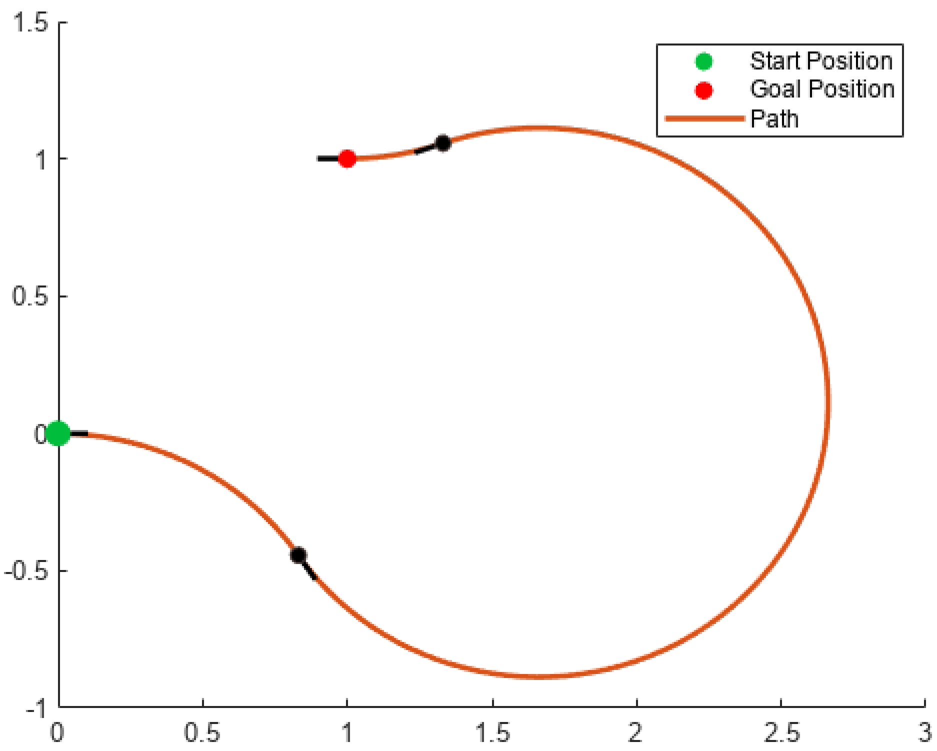
```
startPose = [0 0 0];
goalPose = [1 1 pi];
```

Calculate a valid path segment to connect the poses.

```
[pathSegObj, pathCosts] = connect(dubConnObj,startPose,goalPose);
```

Show the generated path.

```
show(pathSegObj{1})
```




#### Modify Connection Types for Reeds-Shepp Path

Create a `reedsSheppConnection` object.

```
reedsConnObj = reedsSheppConnection;
```

Define start and goal poses as `[x y theta]` vectors.

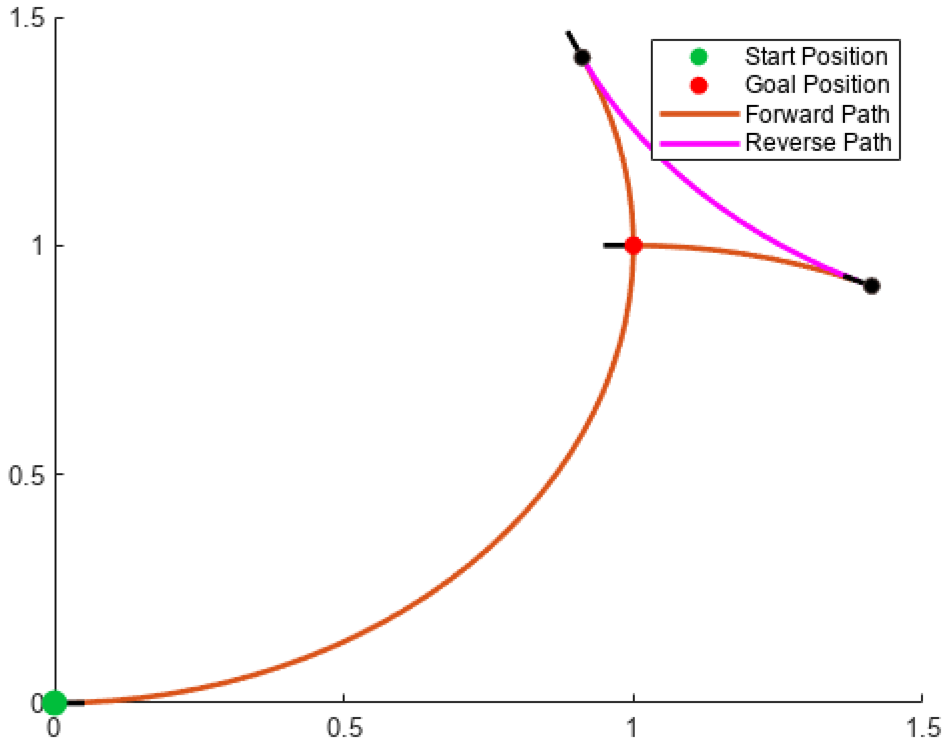
```
startPose = [0 0 0];
goalPose = [1 1 pi];
```

Calculate a valid path segment to connect the poses.

```
[pathSegObj,pathCosts] = connect(reedsConnObj,startPose,goalPose);
```

Show the generated path. Notice the direction of the turns.

```
show(pathSegObj{1})
```




```
pathSegObj{1}.MotionTypes
```

```
ans = 1x5 cell
    {'L'}    {'R'}    {'L'}    {'N'}    {'N'}
```

```
pathSegObj{1}.MotionDirections
```

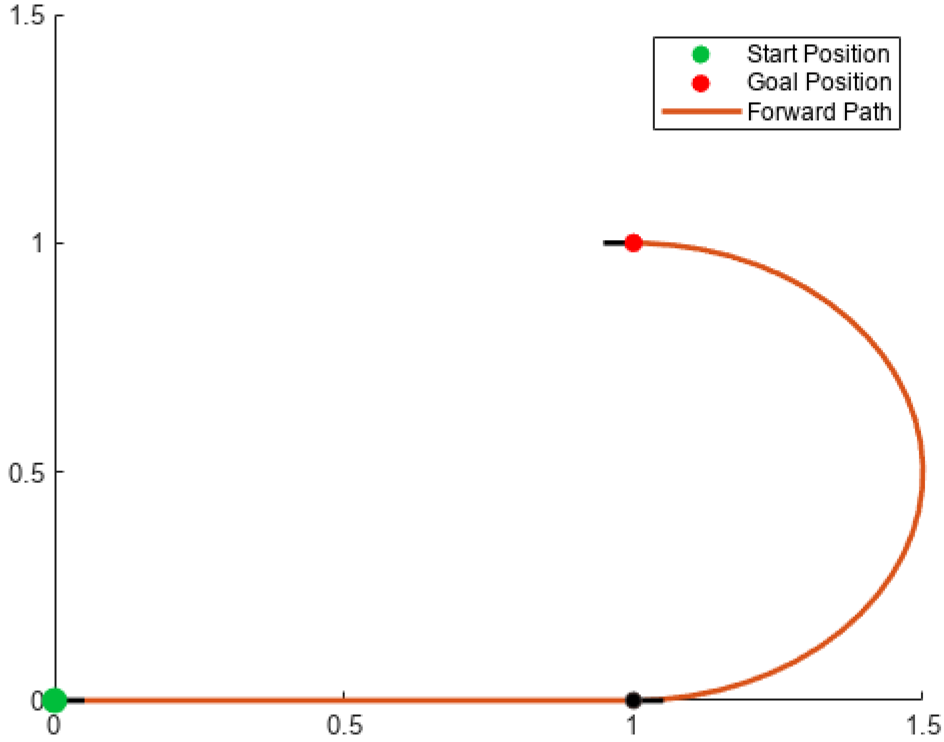
```
ans = 1×5

     1    -1     1     1     1
```

Disable this specific motion sequence in a new connection object. Reduce the `MinTurningRadius` if the robot is more maneuverable. Increase the reverse cost to reduce the likelihood of reverse directions being used. Connect the poses again to get a different path.

```
reedsConnObj = reedsSheppConnection('DisabledPathTypes',{'LpRnLp'});
reedsConnObj.MinTurningRadius = 0.5;
reedsConnObj.ReverseCost = 5;

[pathSegObj,pathCosts] = connect(reedsConnObj,startPose,goalPose);
pathSegObj{1}.MotionTypes
```

```
ans = 1x5 cell
    {'L'}    {'S'}    {'L'}    {'N'}    {'N'}
```

```
show(pathSegObj{1})
xlim([0 1.5])
ylim([0 1.5])
```




**Interpolate Poses For Dubins Path**

Create a `dubinsConnection` object.

```
dubConnObj = dubinsConnection;
```

Define start and goal poses as `[x y theta]` vectors.

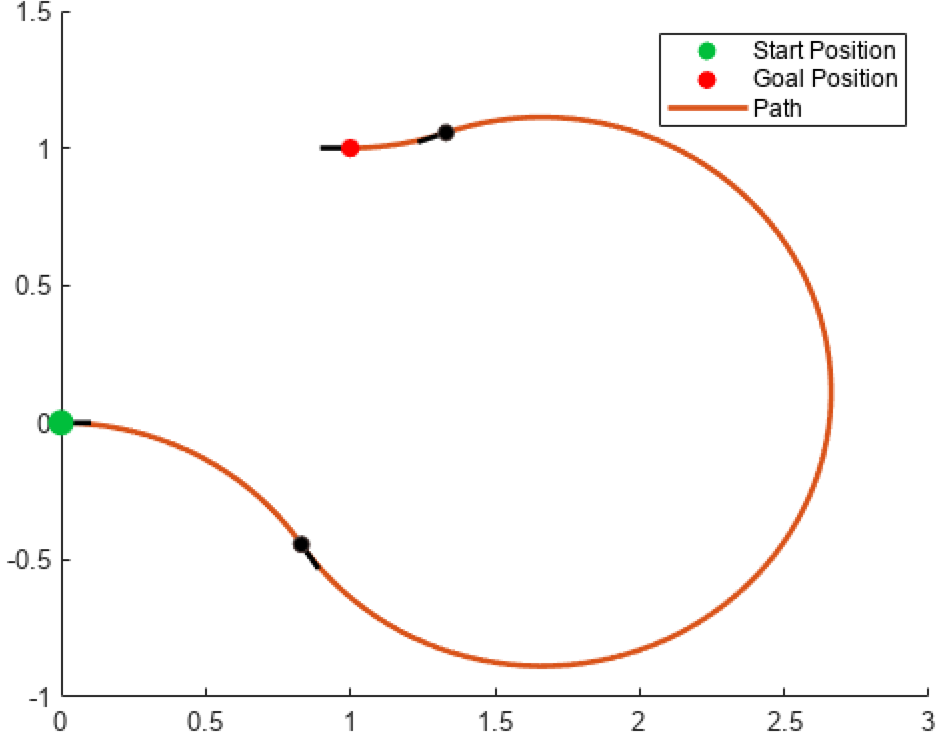
```
startPose = [0 0 0];
goalPose = [1 1 pi];
```

Calculate a valid path segment to connect the poses.

```
[pathSegObj,pathCosts] = connect(dubConnObj,startPose,goalPose);
```

Show the generated path.

```
show(pathSegObj{1})
```



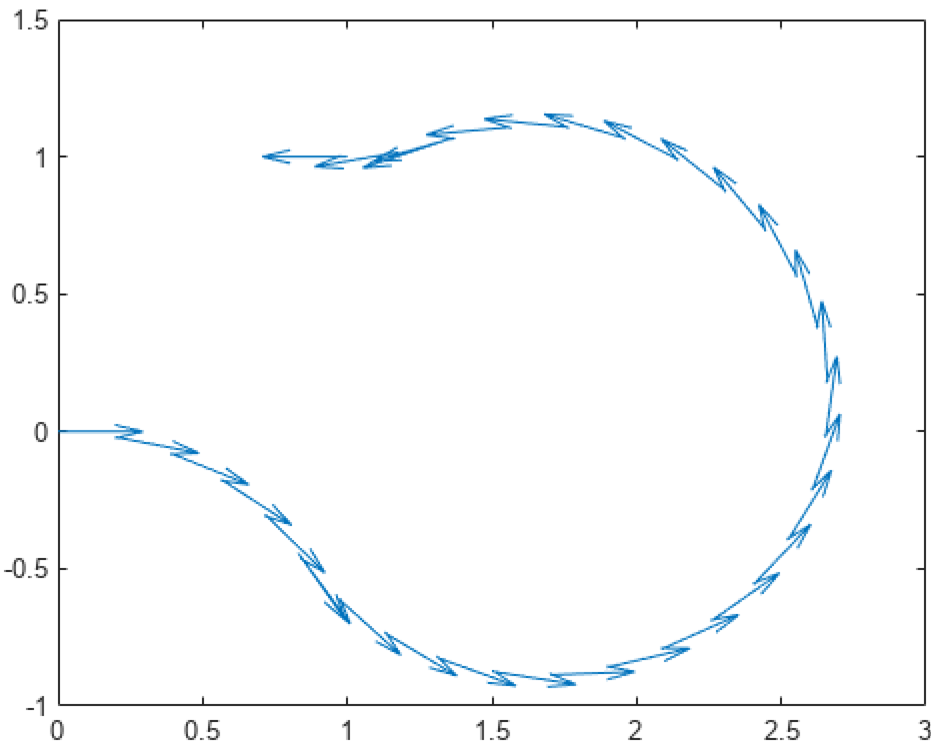

Interpolate poses along the path. Get a pose every 0.2 meters, including the transitions between turns.

```
length = pathSegObj{1}.Length;
poses = interpolate(pathSegObj{1},0:0.2:length)
```

```
poses = 32×3

         0         0         0
    0.1987   -0.0199    6.0832
    0.3894   -0.0789    5.8832
    0.5646   -0.1747    5.6832
    0.7174   -0.3033    5.4832
    0.8309   -0.4436    5.3024
    0.8418   -0.4595    5.3216
    0.9718   -0.6110    5.5216
    1.1293   -0.7337    5.7216
    1.3081   -0.8226    5.9216
      ⋮
```

Use the `quiver` function to plot these poses.

```
quiver(poses(:,1),poses(:,2),cos(poses(:,3)),sin(poses(:,3)),0.5)
```




## Input Arguments

**pathSeg — Path segment**
`dubinsPathSegment` object | `reedsSheppPathSegment` object

Path segment, specified as a `dubinsPathSegment` or `reedsSheppPathSegment` object.

### Name-Value Pair Arguments

Specify optional pairs of arguments as `Name1=Value1,...,NameN=ValueN`, where `Name` is the argument name and `Value` is the corresponding value. Name-value arguments must appear after other arguments, but the order of the pairs does not matter.

*Before R2021a, use commas to separate each name and value, and enclose* `Name` *in quotes.*

Example: `'Headings',{'transitions'}`

**Parent — Axes to plot path onto**
`Axes` handle

Axes to plot path onto, specified as an `Axes` handle.

**Headings — Heading angles to display**
cell array of character vector or string scalars

Heading angles to display, specified as a cell array of character vector or string scalars. Options are any combination of `'start'`,`'goal'`, and `'transitions'`. To disable all heading displays, specify `{''}`.

**`Positions` — Positions to display**
`'both'` (default) | `'start'` | `'goal'` | `'none'`

Positions to display, specified as `'both'`, `'start'`, `'goal'`, or `'none'`. The start position is marked with green, and the goal position is marked with red.

**`HeadingLength` — Length of heading**
positive numeric scalar

Length of heading, specified as positive numeric scalar. By default the value is calculated according to the `x`- and `y`-axis limits of the plot.

Data Types: `double`

# Version History

**Introduced in R2019b**

## See Also

**Functions**
`interpolate` | `connect`

**Objects**
`dubinsConnection` | `dubinsPathSegment` | `reedsSheppConnection` | `reedsSheppPathSegment`

# skyplot

Plot satellite azimuth and elevation data

## Syntax

```
skyplot(azdata,eldata)
skyplot(azdata,eldata,labeldata)
skyplot(status)
skyplot( ___ ,Name,Value)

skyplot(parent, ___ )
h = skyplot( ___ )
```

## Description

`skyplot(azdata,eldata)` creates a sky plot using the azimuth and elevation data specified as matrices in degrees. Azimuth angles are measured in degrees, clockwise-positive from the North direction. Elevation angles are measured from the horizon line with 90 degrees being directly up. For details about the sky plot figure elements, see “Main Sky Plot Elements” on page 1-284.

`skyplot(azdata,eldata,labeldata)` specifies data labels as a string array with elements corresponding to each data point in the `azdata` and `eldata` inputs.

`skyplot(status)` specifies the azimuth and elevation data in a structure with fields `SatelliteAzimuth` and `SatelliteElevation`.

`skyplot( ___ ,Name,Value)` specifies options using one or more name-value arguments in addition to the input arguments in previous syntaxes. The name-value arguments are properties of the `SkyPlotChart` object. For a list of properties, see SkyPlotChart Properties.

`skyplot(parent, ___ )` creates the sky plot in the figure, panel, or tab specified by `parent`.

`h = skyplot( ___ )` returns the sky plot as a `SkyPlotChart` object, `h`. Use `h` to modify the properties of the chart after creating it. For a list of properties, see SkyPlotChart Properties.

## Examples

### View Satellite Positions from GNSS Sensor

Create a GNSS sensor model as a `gnssSensor` System object™.

```
gnss = gnssSensor;
```

Specify the position and velocity of the sensor. Simulate the sensor readings and get status from visible satellites. Store the azimuth and elevation angles as vectors.

```
pos = [0 0 0];
vel = [0 0 0];
[~, ~, status] = gnss(pos, vel);
```

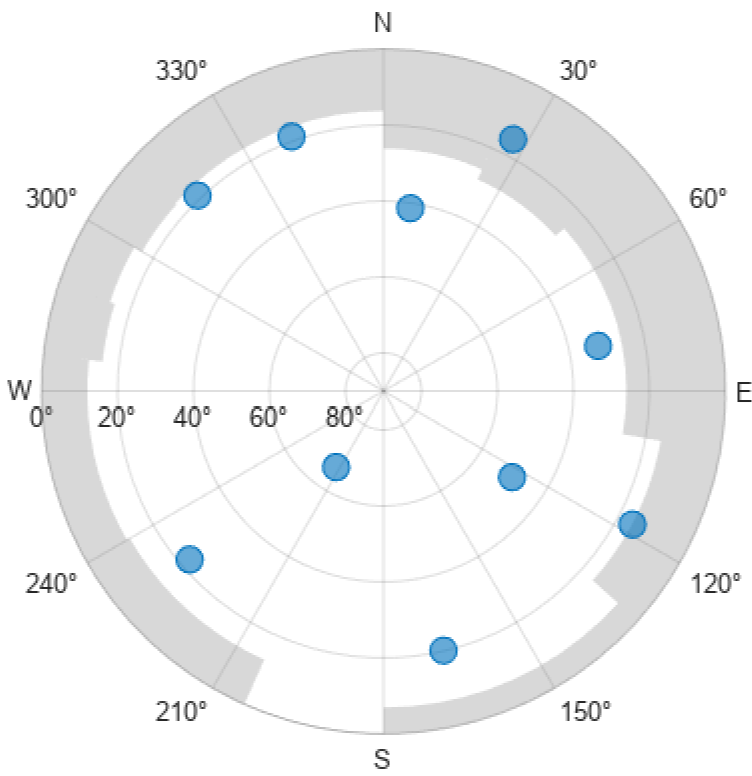
```
satAz = status.SatelliteAzimuth;
satEl = status.SatelliteElevation;
```

Create random local elevation masks, with a maximum elevation of 30 degrees, to act as the local environment.

```
rng(8)
terrainMaskElevations = 30*rand(1,12); % elevations (degrees)
terrainMaskEdges = [0 24 48 100 132 180 204 240 276 288 300 312 360]; % azimuth edges (degrees)
```

Plot the satellite positions with the elevation masks.

```
skyplot(satAz,satEl,MaskElevation=terrainMaskElevations,MaskAzimuthEdges=terrainMaskEdges);
```

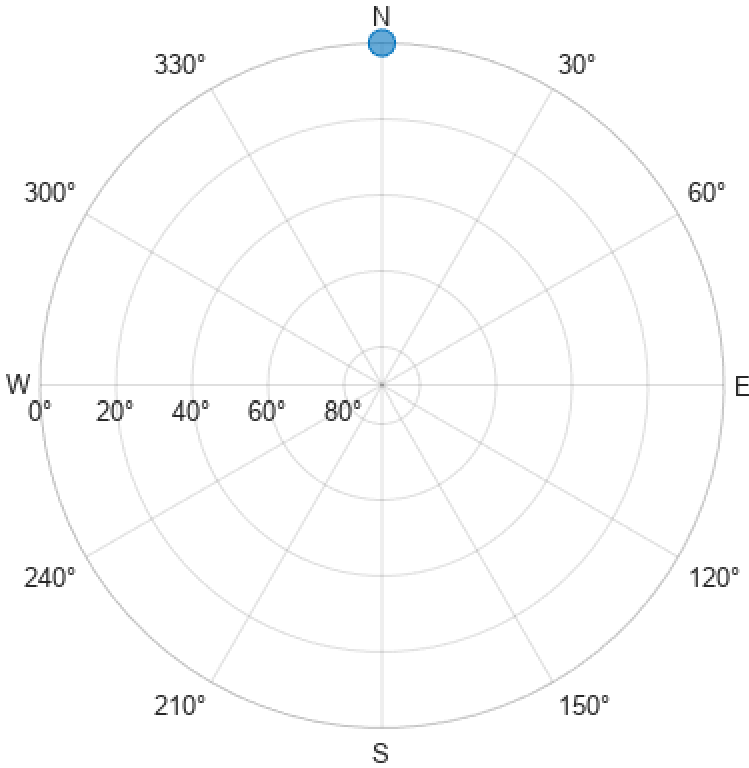



### Plot Series of Satellite Positions Over Time

Animate the trajectory of satellite positions over time from a GNSS sensor.

Initialize the sky plot figure. Specify the relevant time-stepping information.

```
skyplotHandle = skyplot(0,0);
```




```
numHours = 12;
dt = 100;
numSeconds = numHours * 60 * 60;
numSimSteps = numSeconds/dt;
```

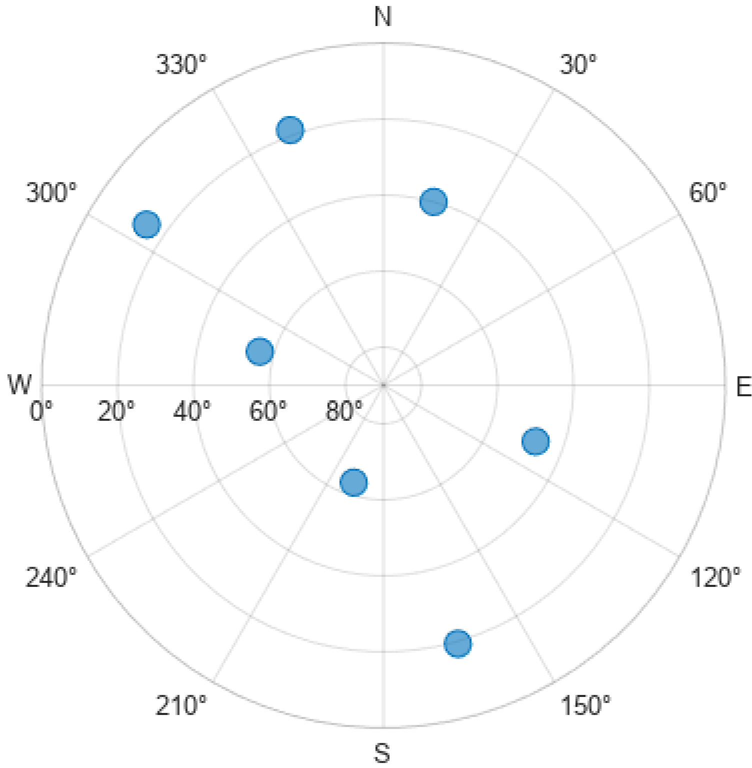
Create a GNSS sensor model as a `gnssSensor` System Object™.

```
gnss = gnssSensor('SampleRate', 1/dt);
```

Iterate through the time steps and do the following:

- Simulate the sensor readings. Specify the zero postion and velocity for the stationary sensor.
- Store the azimuth and elevation angles as vectors.
- Set the `AzimuthData` and `ElevationData` properties of the `SkyPlotChart` handle directly.

```
for i = 1:numSimSteps

    [~, ~, status] = gnss([0 0 0],[0 0 0]);

    satAz = status.SatelliteAzimuth;
    satEl = status.SatelliteElevation;

    set(skyplotHandle,'AzimuthData',satAz,'ElevationData',satEl);

    drawnow
end
```




**View Satellite Positions For Different Groups**

Load the azimuth and elevation data from a logfile generated by an Adafruit® GPS satellite sensor. The data provided in this example contains the azimuth and elevation of each satellite and the pseudorandom noise (PRN) codes. Store these values as vectors.

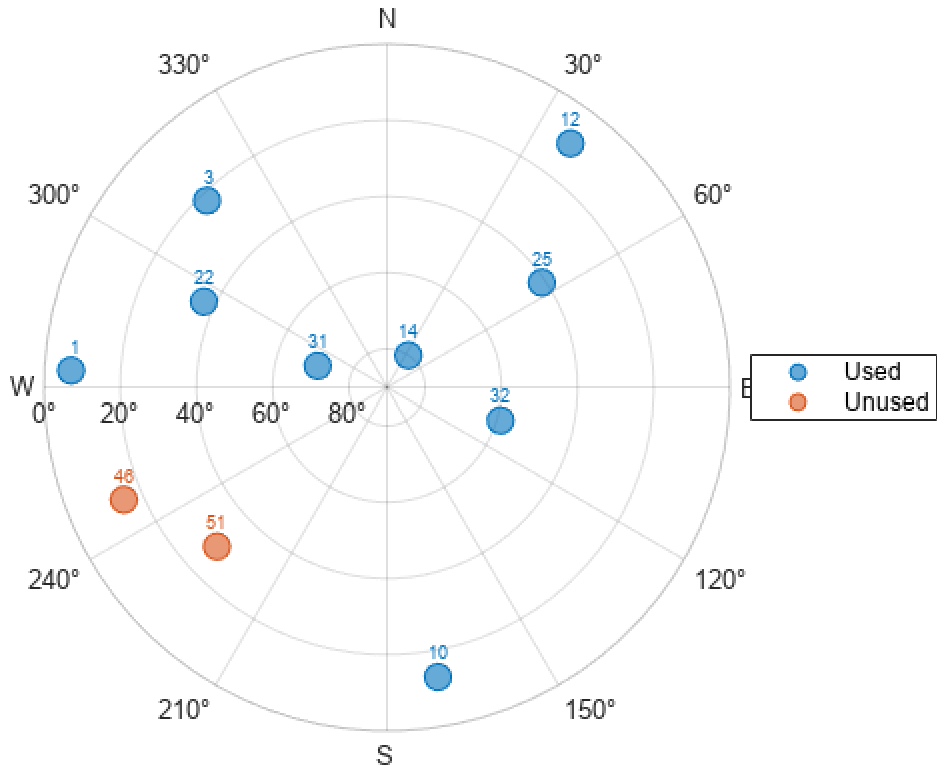
```
load('gpsHWInfo','hwInfo')
satAz = hwInfo.SatelliteAzimuths;
satEl = hwInfo.SatelliteElevations;
prn = hwInfo.SatellitePRNs;
```

Separate the satellites based on the PRN codes. To correlate each position with a group, create a `categorical` array. For this set of satellites, only the ones with PRNs less than 32 are used in the positioning solution.

```
isUnused = (prn > 32);
group = categorical(isUnused,[false true],["Used in Positioning Solution" "Unused"]);
```

Visualize the satellites and specify the categorical groups in the `GroupData` name-value argument. Specify the PRN as the label for each point. Show the legend.

```
skyplot(satAz,satEl,prn,GroupData=group)
legend('Used','Unused')
```




**Visualize Satellite Trajectories in Skyplot**

Specify the receiver position, RINEX navigation file, mask angle, time step size, and number of hours of data to sample from the RINEX file.

```
recPos = [42 -71 50];
navfile = "GODS00USA_R_20211750000_01D_GN.rnx";
maskAngle = 25;
dt = 60; % seconds
numHours = 4;
```

Read the navigation file, and get the GPS data of all satellites captured in the file.

```
data = rinexread(navfile);
[~,satIdx] = unique(data.GPS.SatelliteID);
navmsg = data.GPS(satIdx,:);
```

Set the starting time to the initial time of the navigation message. Then, create the time vector `t`.

```
startTime = navmsg.Time(1);
secondsPerHour = 3600;
timeElapsed = 0:dt:(secondsPerHour*numHours);
t = startTime + seconds(timeElapsed);
```

Initialize vectors for azimuth and elevation. Then, collect azimuth and elevation data at times `t` for all satellites.

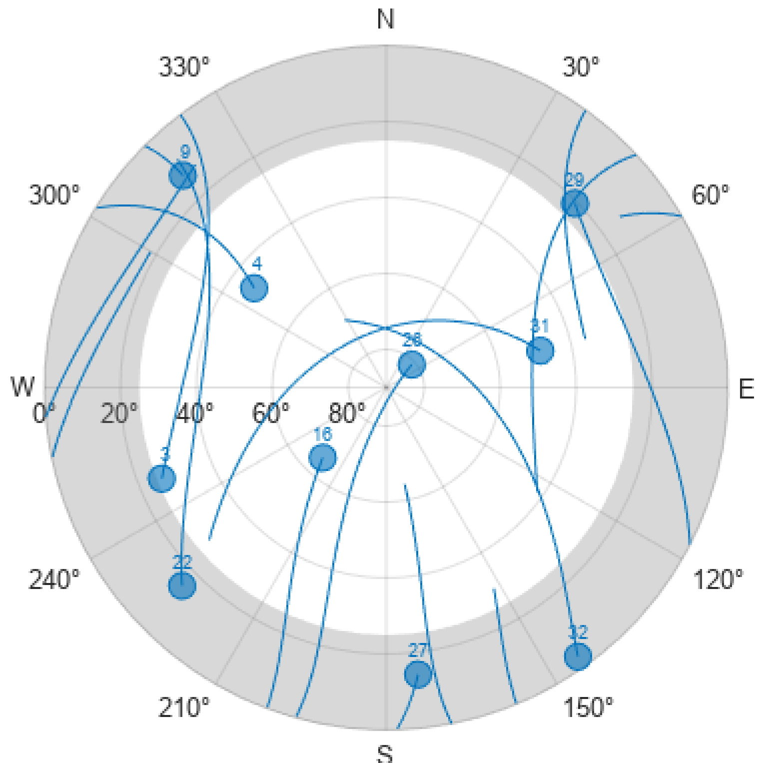
```
numSats = numel(navmsg.SatelliteID);
allAz = NaN(numel(t),numSats);
allEl = allAz;
for idx = 1:numel(t)
    [satPos,~,satID] = gnssconstellation(t(idx),RINEXData=navmsg);
    [az,el,vis] = lookangles(recPos,satPos,maskAngle);
    allAz(idx,:) = az;
    allEl(idx,:) = el;
end
```

Mark all satellites below the horizon with an elevation less than `0` as missing.

```
allEl(allEl < 0) = missing;
```

Display the satellite trajectories as an animation by creating a skyplot and updating the `AzimuthData` and `ElevationData` properties.

```
figure
sp = skyplot(allAz(1,:),allEl(1,:),satID,MaskElevation=maskAngle);
for idx = 1:size(allAz, 1)
    set(sp,AzimuthData=allAz(1:idx,:),ElevationData=allEl(1:idx,:));
    drawnow limitrate
end
```



## Input Arguments

**`azdata` — Azimuth angles for visible satellite positions**
*n*-element vector of angles | *t*-by-*n* matrix of angles

Azimuth angles for visible satellite positions, specified as an *n*-element vector of angles or *t*-by-*n* matrix of angles. *n* is the number of visible satellite positions in the plot, and *t* is the number of time steps of the satellites. Azimuth angles are measured in degrees, clockwise-positive from the north direction.

Example: `[25 45 182 356]` specifies the azimuth angles for four satellites at one time step.

Data Types: `double`

**`eldata` — Elevation angles for visible satellite positions**
*n*-element vector of angles | *t*-by-*n* matrix of angles

Elevation angles for visible satellite positions, specified as an *n*-element vector of angles or *t*-by-*n* matrix of angles. *n* is the number of visible satellite positions in the plot, and *t* is the number of time steps of the satellites. Elevation angles are measured from the horizon line with 90 degrees being directly up.

Example: `[45 90 27 74]` specifies the elevation angles for four satellites at one time step.

Data Types: `double`

**`labeldata` — Labels for visible satellite positions**
*n*-element string array

Labels for visible satellite positions, specified as an *n*-element string array. *n* is the number of visible satellite positions in the plot.

Example: `["G1" "G11" "G7" "G3"]`

Data Types: `string`

**`status` — Satellite status**
structure array

Satellite status, specified as a structure array with fields `SatelliteAzimuth` and `SatelliteElevation`. Typically, this status structure comes from a `gnssSensor` object, which simulates satellite positions and velocities.

Example: `gnss = gnssSensor; [~,~,status] = gnss(position,velocity)`

Data Types: `struct`

**`parent` — Parent container**
`Figure` object | `Panel` object | `Tab` object | `TiledChartLayout` object | `GridLayout` object

Parent container, specified as a `Figure`, `Panel`, `Tab`, `TiledChartLayout`, or `GridLayout` object.

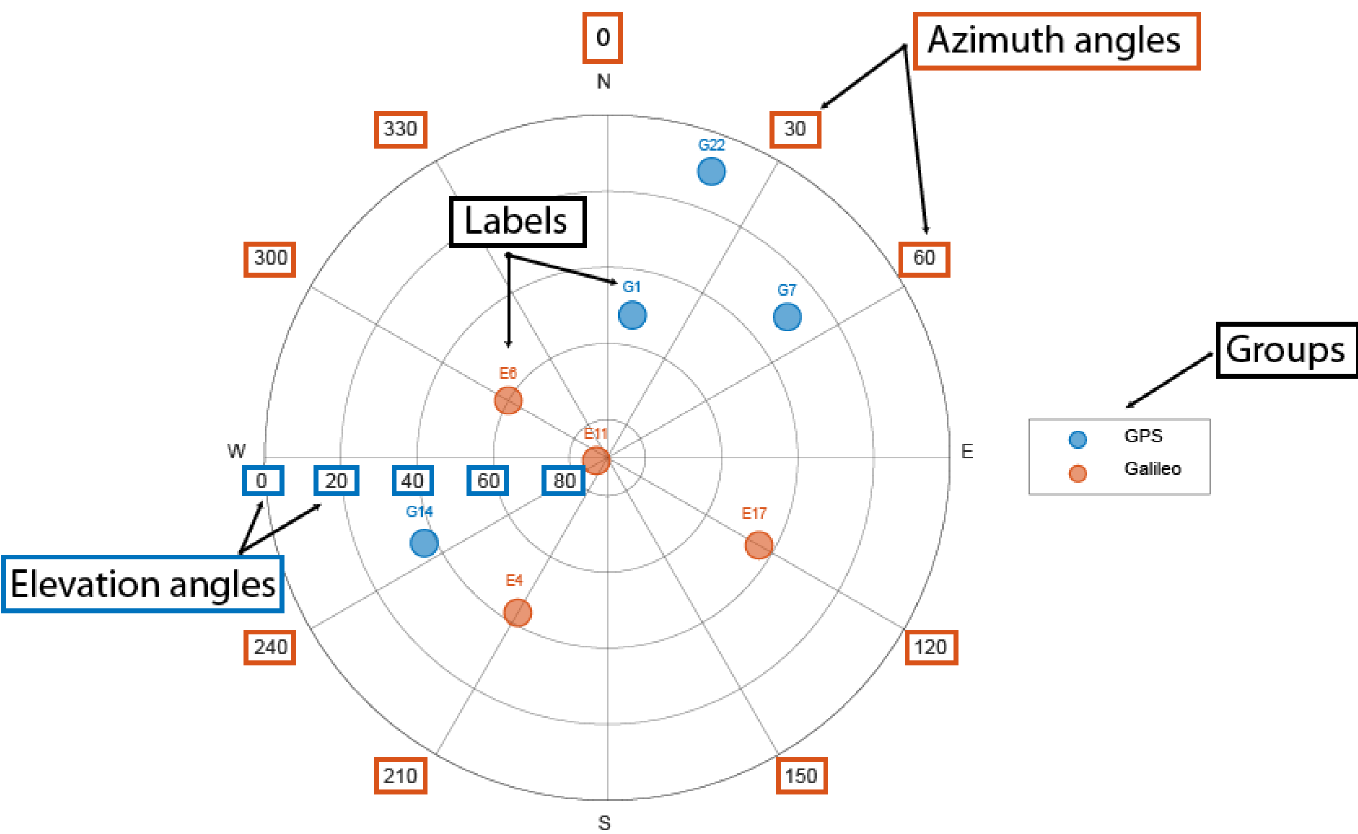
## Output Arguments

**`h` — Sky plot chart**
`SkyPlotChart` object

Sky plot chart, returned as a SkyPlotChart object, which is a standalone visualization on page 1-284. Use h to set properties on the sky plot chart. For more information, see SkyPlotChart Properties.

## More About

### Main Sky Plot Elements




The main elements of the figure are:

- Azimuth axes — Specified by the azdata input argument, azimuth angle positions are measured clockwise-positive from the North direction.
- Elevation axes —Specified by the eldata input argument, elevation angle positions are measured from the horizon line with 90 degrees being directly up.
- Labels — Specified by the labeldata input argument as a string array with an element for each point in the azdata and eldata vectors.
- Groups — Specified by the GroupData property, a categorical array defines the group for each satellite position.

### Standalone Visualization

A standalone visualization is a chart designed for a special purpose that works independently from other charts. Unlike other charts such as plot and surf, a standalone visualization has a preconfigured axes object built into it, and some customizations are not available. A standalone visualization also has these characteristics:

- It cannot be combined with other graphics elements, such as lines, patches, or surfaces. Thus, the `hold` command is not supported.
- The `gca` function can return the chart object as the current axes.
- You can pass the chart object to many MATLAB functions that accept an axes object as an input argument. For example, you can pass the chart object to the `title` function.

# Version History

**Introduced in R2021a**

### R2022b: `skyplot` supports azimuth and elevation trajectories and elevation masks

- The `azdata` and `eldata` arguments now accept matrices, enabling you to represent trajectories by adding azimuth and elevation data for satellites at multiple time steps.
- Elevation angle masks are now supported using these new `SkyPlotChart` properties:
  - `MaskElevation`
  - `MaskAlpha`
  - `MaskColor`
  - `MaskAzimuthEdges`
  - `MaskAzimuthEdgesMode`

## See Also

**Functions**
`polarscatter`

**Properties**
SkyPlotChart Properties

**Objects**
`gnssSensor` | `nmeaParser`

# tform2axang

Convert homogeneous transformation to axis-angle rotation

## Syntax

```
axang = tform2axang(tform)
```

## Description

`axang = tform2axang(tform)` converts the rotational component of a homogeneous transformation, `tform`, to an axis-angle rotation, `axang`. The translational components of `tform` are ignored. The input homogeneous transformation must be in the premultiply form for transformations.

## Examples

### Convert Homogeneous Transformation to Axis-Angle Rotation

```
tform = [1 0 0 0; 0 0 -1 0; 0 1 0 0; 0 0 0 1];
axang = tform2axang(tform)
```

```
axang = 1×4

    1.0000         0         0    1.5708
```

## Input Arguments

**`tform` — Homogeneous transformation**
4-by-4-by-*n* matrix

Homogeneous transformation, specified by a 4-by-4-by-*n* matrix of *n* homogeneous transformations. The input homogeneous transformation must be in the premultiply form for transformations.

Example: `[0 0 1 0; 0 1 0 0; -1 0 0 0; 0 0 0 1]`

## Output Arguments

**axang — Rotation given in axis-angle form**
*n*-by-4 matrix

Rotation given in axis-angle form, specified as an *n*-by-4 matrix of *n* axis-angle rotations. The first three elements of every row specify the rotation axes, and the last element defines the rotation angle (in radians).

Example: `[1 0 0 pi/2]`

# Version History

**Introduced in R2015a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`axang2tform` | `se3`

# tform2eul

Extract Euler angles from homogeneous transformation

## Syntax

```
eul = tform2eul(tform)
eul = tform2eul(tform, sequence)
[eul,eulAlt] = tform2eul( ___ )
```

## Description

`eul = tform2eul(tform)` extracts the rotational component from a homogeneous transformation, `tform`, and returns it as Euler angles, `eul`. The translational components of `tform` are ignored. The input homogeneous transformation must be in the premultiply form for transformations. The default order for Euler angle rotations is `"ZYX"`.

`eul = tform2eul(tform, sequence)` extracts the Euler angles, `eul`, from a homogeneous transformation, `tform`, using the specified rotation sequence, `sequence`. The default order for Euler angle rotations is `"ZYX"`.

`[eul,eulAlt] = tform2eul( ___ )` also returns an alternate set of Euler angles that represents the same rotation `eulAlt`.

## Examples

### Extract Euler Angles from Homogeneous Transformation Matrix

```
tform = [1 0 0 0.5; 0 -1 0 5; 0 0 -1 -1.2; 0 0 0 1];
eulZYX = tform2eul(tform)
```

```
eulZYX = 1×3

         0         0    3.1416
```

### Extract Euler Angles from Homogeneous Transformation Matrix Using ZYZ Rotation

```
tform = [1 0 0 0.5; 0 -1 0 5; 0 0 -1 -1.2; 0 0 0 1];
eulZYZ = tform2eul(tform,'ZYZ')
```

```
eulZYZ = 1×3

         0   -3.1416    3.1416
```

## Input Arguments

### `tform` — Homogeneous transformation

4-by-4-by-*n* matrix

Homogeneous transformation, specified by a 4-by-4-by-*n* matrix of *n* homogeneous transformations. The input homogeneous transformation must be in the premultiply form for transformations.

Example: `[0 0 1 0; 0 1 0 0; -1 0 0 0; 0 0 0 1]`

### `sequence` — Axis-rotation sequence

`"ZYX"` (default) | `"ZYZ"` | `"ZXY"` | `"ZXZ"` | `"YXY"` | `"YZX"` | `"YXZ"` | `"YZY"` | `"XYX"` | `"XYZ"` | `"XZX"` | `"XZY"`

Axis-rotation sequence for the Euler angles, specified as one of these string scalars:

- `"ZYX"` (default)
- `"ZYZ"`
- `"ZXY"`
- `"ZXZ"`
- `"YXY"`
- `"YZX"`
- `"YXZ"`
- `"YZY"`
- `"XYX"`
- `"XYZ"`
- `"XZX"`
- `"XZY"`

Each character indicates the corresponding axis. For example, if the sequence is `"ZYX"`, then the three specified Euler angles are interpreted in order as a rotation around the *z*-axis, a rotation around the *y*-axis, and a rotation around the *x*-axis. When applying this rotation to a point, it will apply the axis rotations in the order *x*, then *y*, then *z*.

Data Types: `string` | `char`

## Output Arguments

### `eul` — Euler rotation angles

*n*-by-3 matrix

Euler rotation angles in radians, returned as an *n*-by-3 array of Euler rotation angles. Each row represents one Euler angle set.

Example: `[0 0 1.5708]`

### `eulAlt` — Alternate Euler rotation angle solution

*n*-by-3 matrix

Alternate Euler rotation angle solution in radians, returned as an *n*-by-3 array of Euler rotation angles. Each row represents one Euler angle set.

Example: `[0 0 1.5708]`

## Version History

**Introduced in R2015a**

#### R2020a: Alternate Euler angle output

`tform2eul` now optionally outputs an alternate set of Euler angles `eulAlt` that also represent the same rotation as the original output Euler angles `eul`. So if you use `eul` or `eulAlt` to rotate a point, the resulting point is the same.

#### R2023a: Additional Euler sequence support

`tform2eul` supports additional Euler sequences for the `sequences` argument. These are all the supported Euler sequences:

- `"ZYX"`
- `"ZYZ"`
- `"ZXY"`
- `"ZXZ"`
- `"YXY"`
- `"YZX"`
- `"YXZ"`
- `"YZY"`
- `"XYX"`
- `"XYZ"`
- `"XZX"`
- `"XZY"`

## Extended Capabilities

#### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`eul2tform` | `se2` | `se3`

# tform2quat

Extract quaternion from homogeneous transformation

## Syntax

```
quat = tform2quat(tform)
```

## Description

`quat = tform2quat(tform)` extracts the rotational component from a homogeneous transformation, `tform`, and returns it as a quaternion, `quat`. The translational components of `tform` are ignored. The input homogeneous transformation must be in the premultiply form for transformations.

## Examples

### Extract Quaternion from Homogeneous Transformation

```
tform = [1 0 0 0; 0 -1 0 0; 0 0 -1 0; 0 0 0 1];
quat = tform2quat(tform)
```

```
quat = 1×4

     0     1     0     0
```

## Input Arguments

**`tform` — Homogeneous transformation**
4-by-4-by-*n* matrix

Homogeneous transformation, specified by a 4-by-4-by-*n* matrix of *n* homogeneous transformations. The input homogeneous transformation must be in the premultiply form for transformations.

Example: `[0 0 1 0; 0 1 0 0; -1 0 0 0; 0 0 0 1]`

## Output Arguments

**`quat` — Unit quaternion**
*n*-by-4 matrix

Unit quaternion, returned as an *n*-by-4 matrix containing *n* quaternions. Each quaternion, one per row, is of the form $q = [w\ x\ y\ z]$, with $w$ as the scalar number.

Example: `[0.7071 0.7071 0 0]`

# Version History

**Introduced in R2015a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`quat2tform` | `se3` | `quaternion`

# tform2rotm

Extract rotation matrix from homogeneous transformation

## Syntax

```
rotm = tform2rotm(tform)
```

## Description

`rotm = tform2rotm(tform)` extracts the rotational component from a homogeneous transformation, `tform`, and returns it as an orthonormal rotation matrix, `rotm`. The translational components of `tform` are ignored. The input homogeneous transformation must be in the pre-multiply form for transformations. When using the rotation matrix, premultiply it with the coordinates to be rotated (as opposed to postmultiplying).

## Examples

### Convert Homogeneous Transformation to Rotation Matrix

```
tform = [1 0 0 0; 0 -1 0 0; 0 0 -1 0; 0 0 0 1];
rotm = tform2rotm(tform)
```

```
rotm = 3×3

     1     0     0
     0    -1     0
     0     0    -1
```

## Input Arguments

**`tform` — Homogeneous transformation**
3-by-3-by-*n* array | 4-by-4-by-*n* array

Homogeneous transformation, specified as a 3-by-3-by-*n* array or 4-by-4-by-*n* array. *n* is the number of homogeneous transformations. The input homogeneous transformation must be in the premultiplied form for transformations.

2-D homogeneous transformation matrices are of the form:

$$T = \begin{bmatrix} r_{11} & r_{12} & t_1 \\ r_{21} & r_{22} & t_2 \\ 0 & 0 & 1 \end{bmatrix}$$

3-D homogeneous transformation matrices are of the form:

$$T = \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_1 \\ r_{21} & r_{22} & r_{23} & t_2 \\ r_{31} & r_{32} & r_{33} & t_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Example: `[0 0 1 0; 0 1 0 0; -1 0 0 0; 0 0 0 1]`

## Output Arguments

### `rotm` — Rotation matrix

2-by-2-by-*n* array | 3-by-3-by-*n* array

Rotation matrix, returned as a 2-by-2-*n* array or 3-by-3-by-*n* array containing *n* rotation matrices. Each rotation matrix in the array has either a size of 2-by-2 or 3-by-3 and is orthonormal. When using the rotation matrix, premultiply it with the coordinates to be rotated (as opposed to postmultiplying).

2-D rotation matrices are of the form:

$$rotation = \begin{bmatrix} r_{11} & r_{12} \\ r_{21} & r_{22} \end{bmatrix}$$

3-D rotation matrices are of the form:

$$rotation = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{11} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix}$$

Example: `[0 0 1; 0 1 0; -1 0 0]`

## More About

### Homogeneous Transformation Matrices

Homogeneous transformation matrices consist of both an orthogonal rotation and a translation.

#### 2-D Transformations

2-D transformations have a rotation $\theta$ about the z-axis:

$$R_z(\theta) = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}$$

, and a translation along the $x$ and $y$ axis:

$$t = \begin{bmatrix} x \\ y \end{bmatrix}$$

, resulting in the 2-D transformation matrix of the form:

$$T = \begin{bmatrix} R & t \\ 0_{1\times 2} & 1 \end{bmatrix} = \begin{bmatrix} I_2 & t \\ 0_{1\times 2} & 1 \end{bmatrix} \cdot \begin{bmatrix} R & 0 \\ 0_{1\times 2} & 1 \end{bmatrix}$$

#### 3-D Transformations

3-D transformations contain information about three rotations about the x-, y-, and z-axes:

$$R_x(\phi) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & \sin\phi \\ 0 & -\sin\phi & \cos\phi \end{bmatrix}, R_y(\psi) = \begin{bmatrix} \cos\psi & 0 & \sin\psi \\ 0 & 1 & 0 \\ -\sin\psi & 0 & \cos\psi \end{bmatrix}, R_z(\theta) = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

and after multiplying become the rotation about the xyz-axes:

$$R_{xyz} = R_x(\phi)R_y(\psi)R_z(\theta) =$$
$$\begin{bmatrix} \cos\phi\cos\psi\cos\theta - \sin\phi\sin\theta & -\cos\phi\cos\psi\sin\theta - \sin\phi\cos\theta & \cos\phi\sin\psi \\ \sin\phi\cos\psi\cos\theta + \cos\phi\sin\theta & -\sin\phi\cos\psi\sin\theta + \cos\phi\cos\theta & \sin\phi\sin\psi \\ -\sin\psi\cos\theta & \sin\psi\sin\theta & \cos\psi \end{bmatrix}$$

and a translation along the *x*-, *y*-, and *z*-axis:

$$t = \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

, resulting in the 3-D transformation matrix of the form:

$$T = \begin{bmatrix} R & t \\ 0_{1x3} & 1 \end{bmatrix} = \begin{bmatrix} I_3 & t \\ 0_{1x3} & 1 \end{bmatrix} \cdot \begin{bmatrix} R & 0 \\ 0_{1x3} & 1 \end{bmatrix}$$

## Version History

**Introduced in R2015a**

#### R2023a: `tform2rotm` Supports 2-D Homogeneous Transformation Matrices

The `tform` argument now accepts 2-D homogeneous transformation matrices as a 3-by-3-by-*n* array and `tform2rotm` outputs 2-D rotation matrices 2-by-2-by-*n* array.

## Extended Capabilities

#### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`rotm2tform` | `se2` | `se3` | `so2` | `so3`

# tform2trvec

Extract translation vector from homogeneous transformation

## Syntax

```
trvec = tform2trvec(tform)
```

## Description

`trvec = tform2trvec(tform)` extracts the Cartesian representation of the translation vector `trvec` from the homogeneous transformation `tform`. The rotational components of `tform` are ignored. The input homogeneous transformation must be in the premultiplied form for transformations.

## Examples

### Extract Translation Vector from Homogeneous Transformation

```
tform = [1 0 0 0.5; 0 -1 0 5; 0 0 -1 -1.2; 0 0 0 1];
trvec = tform2trvec(tform)
```

```
trvec = 1×3

    0.5000    5.0000   -1.2000
```

## Input Arguments

**`tform` — Homogeneous transformation**
3-by-3-by-*n* array | 4-by-4-by-*n* array

Homogeneous transformation, specified as a 3-by-3-by-*n* array or 4-by-4-by-*n* array. *n* is the number of homogeneous transformations. The input homogeneous transformation must be in the premultiplied form for transformations.

2-D homogeneous transformation matrices are of the form:

$$T = \begin{bmatrix} r_{11} & r_{12} & t_1 \\ r_{21} & r_{22} & t_2 \\ 0 & 0 & 1 \end{bmatrix}$$

3-D homogeneous transformation matrices are of the form:

$$T = \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_1 \\ r_{21} & r_{22} & r_{23} & t_2 \\ r_{31} & r_{32} & r_{33} & t_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Example: `[0 0 1 0; 0 1 0 0; -1 0 0 0; 0 0 0 1]`

## Output Arguments

### `trvec` — Cartesian representation of translation vector

*n*-by-2 matrix | *n*-by-3 matrix

Cartesian representation of a translation vector, returned as an *n*-by-2 matrix if `tform` is a 3-by-3-by-*n* array and an *n*-by-3 matrix if `tform` is a 4-by-4-by-*n* array. *n* is the number of translation vectors. Each vector is of the form [*x y*] or [*x y z*].

Example: `[0.5 6 100]`

## More About

### Homogeneous Transformation Matrices

Homogeneous transformation matrices consist of both an orthogonal rotation and a translation.

#### 2-D Transformations

2-D transformations have a rotation $\theta$ about the z-axis:

$$R_z(\theta) = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}$$

, and a translation along the *x* and *y* axis:

$$t = \begin{bmatrix} x \\ y \end{bmatrix}$$

, resulting in the 2-D transformation matrix of the form:

$$T = \begin{bmatrix} R & t \\ 0_{1\times 2} & 1 \end{bmatrix} = \begin{bmatrix} I_2 & t \\ 0_{1\times 2} & 1 \end{bmatrix} \cdot \begin{bmatrix} R & 0 \\ 0_{1\times 2} & 1 \end{bmatrix}$$

#### 3-D Transformations

3-D transformations contain information about three rotations about the x-, y-, and z-axes:

$$R_x(\phi) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & \sin\phi \\ 0 & -\sin\phi & \cos\phi \end{bmatrix}, R_y(\psi) = \begin{bmatrix} \cos\psi & 0 & \sin\psi \\ 0 & 1 & 0 \\ -\sin\psi & 0 & \cos\psi \end{bmatrix}, R_z(\theta) = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

and after multiplying become the rotation about the xyz-axes:

$$R_{xyz} = R_x(\phi)R_y(\psi)R_z(\theta) =$$
$$\begin{bmatrix} \cos\phi\cos\psi\cos\theta - \sin\phi\sin\theta & -\cos\phi\cos\psi\sin\theta - \sin\phi\cos\theta & \cos\phi\sin\psi \\ \sin\phi\cos\psi\cos\theta + \cos\phi\sin\theta & -\sin\phi\cos\psi\sin\theta + \cos\phi\cos\theta & \sin\phi\sin\psi \\ -\sin\psi\cos\theta & \sin\psi\sin\theta & \cos\psi \end{bmatrix}$$

and a translation along the *x*-, *y*-, and *z*-axis:

$$t = \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

, resulting in the 3-D transformation matrix of the form:

$$T = \begin{bmatrix} R & t \\ 0_{1x3} & 1 \end{bmatrix} = \begin{bmatrix} I_3 & t \\ 0_{1x3} & 1 \end{bmatrix} \cdot \begin{bmatrix} R & 0 \\ 0_{1x3} & 1 \end{bmatrix}$$

# Version History

**Introduced in R2015a**

### R2023a: `tform2trvec` Supports 2-D Homogeneous Transformation Matrices

The `tform` argument now accepts 2-D homogeneous transformation matrices as a 3-by-3-by-*n* array and `tform2trvec` outputs a *n*-by-2 matrix of 2-D translation vectors.

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`trvec2tform` | `se2` | `se3`

# transformMotion

Compute motion quantities between two relatively fixed frames

## Syntax

```
[posS,orientS,velS,accS,angvelS] = transformMotion(posSFromP,orientSFromP,
posP)
[ ___ ] = transformMotion(posSFromP,orientSFromP,posP,orientP)
[ ___ ] = transformMotion(posSFromP,orientSFromP,posP,orientP,velP)
[ ___ ] = transformMotion(posSFromP,orientSFromP,posP,orientP,velP,accP)
[ ___ ] = transformMotion(posSFromP,orientSFromP,posP,orientP,velP,accP,
angvelP)
```

## Description

`[posS,orientS,velS,accS,angvelS] = transformMotion(posSFromP,orientSFromP, posP)` computes motion quantities of the sensor frame relative to the navigation frame (`posS`, `orientS`, `velS`, `accS`, and `angvelS`) using the position of sensor frame relative to the platform frame, `posSFromP`, the orientation of the sensor frame relative to the platform frame, `orientSFromP`, and the position of the platform frame relative to the navigation frame, `posP`. Note that the position and orientation between the sensor frame and the platform frame are assumed to be fixed. Also, the unspecified quantities between the navigation frame and the platform frame (such as orientation, velocity, and acceleration) are assumed to be zero.

`[ ___ ] = transformMotion(posSFromP,orientSFromP,posP,orientP)` additionally specifies the orientation of the platform frame relative to the navigation frame, `orientP`. The output arguments are the same as those of the previous syntax.

`[ ___ ] = transformMotion(posSFromP,orientSFromP,posP,orientP,velP)` additionally specifies the velocity of the platform frame relative to the navigation frame, `velP`. The output arguments are the same as those of the previous syntax.

`[ ___ ] = transformMotion(posSFromP,orientSFromP,posP,orientP,velP,accP)` additionally specifies the acceleration of the platform frame relative to the navigation frame, `accP`. The output arguments are the same as those of the previous syntax.

`[ ___ ] = transformMotion(posSFromP,orientSFromP,posP,orientP,velP,accP, angvelP)` additionally specifies the angular velocity of the platform frame relative to the navigation frame, `angvelP`. The output arguments are the same as those of the previous syntax.

## Examples

### Transform State to Sensor Frame

Define the pose, velocity, and acceleration of the platform frame relative to the navigation frame.

```
posPlat = [20 -1 0];
orientPlat = quaternion(1, 0, 0, 0);
velPlat = [0 0 0];
```

```
accPlat = [0 0 0];
angvelPlat = [0 0 1];
```

Define the position and orientation offset of IMU sensor frame relative to the platform frame.

```
posPlat2IMU = [1 2 3];
orientPlat2IMU = quaternion([45 0 0], 'eulerd', 'ZYX', 'frame');
```

Calculate the motion quantities of the sensor frame relative to the navigation frame and print the results.

```
[posIMU, orientIMU, velIMU, accIMU, angvelIMU] ...
    = transformMotion(posPlat2IMU, orientPlat2IMU, ...
    posPlat, orientPlat, velPlat, accPlat, angvelPlat);

fprintf('IMU position is:\n');

IMU position is:

fprintf('%.2f %.2f %.2f\n', posIMU);

21.00 1.00 3.00

orientIMU

orientIMU = quaternion
     0.92388 +       0i +       0j + 0.38268k


velIMU

velIMU = 1×3

    -2     1     0


accPlat

accPlat = 1×3

     0     0     0
```

## Input Arguments

**posSFromP — Position of sensor frame relative to platform frame**
1-by-3 vector of real scalars

Position of the sensor frame relative to the platform frame, specified as a 1-by-3 vector of real scalars.

Example: [1 2 3]

**orientSFromP — Orientation of sensor frame relative to platform frame**
quaternion | 3-by-3 rotation matrix

Orientation of the sensor frame relative to the platform frame, specified as a quaternion or a 3-by-3 rotation matrix.

Example: `quaternion(1,0,0,0)`

**`posP` — Position of platform frame relative to navigation frame**
*N*-by-3 matrix of real scalars

Position of platform frame relative to navigation frame, specified as an *N*-by-3 matrix of real scalars. *N* is the number of position quantities.

Example: `[1 2 3]`

**`orientP` — Orientation of platform frame relative to navigation frame**
*N*-by-1 array of `quaternion` | 3-by-3-by-*N* array of scalars

Orientation of platform frame relative to navigation frame, specified as an *N*-by-1 array of quaternions, or a 3-by-3-by-*N* array of scalars. Each 3-by-3 matrix must be a rotation matrix. *N* is the number of orientation quantities.

Example: `quaternion(1,0,0,0)`

**`velP` — Velocity of platform frame relative to navigation frame**
*N*-by-3 matrix of real scalars

Velocity of platform frame relative to navigation frame, specified as an *N*-by-3 matrix of real scalars. *N* is the number of velocity quantities.

Example: `[ 4 8 6]`

**`accP` — Acceleration of platform frame relative to navigation frame**
*N*-by-3 matrix of real scalars

Acceleration of platform frame relative to navigation frame, specified as an *N*-by-3 matrix of real scalars. *N* is the number of acceleration quantities.

Example: `[4 8 6]`

**`angvelP` — Angular velocity of platform frame relative to navigation frame**
*N*-by-3 matrix of real scalars

Angular velocity of platform frame relative to navigation frame, specified as an *N*-by-3 matrix of real scalars. *N* is the number of angular velocity quantities.

Example: `[4 2 3]`

## Output Arguments

**`posS` — Position of sensor frame relative to navigation frame**
*N*-by-3 matrix of real scalars

Position of sensor frame relative to navigation frame, returned as an *N*-by-3 matrix of real scalars. *N* is the number of position quantities specified by the `posP` input.

**`orientS` — Orientation of sensor frame relative to navigation frame**
*N*-by-1 array of `quaternion` | 3-by-3-by-*N* array of scalars

Orientation of sensor frame relative to navigation frame, returned as an *N*-by-1 array of quaternions, or a 3-by-3-by-*N* array of scalars. *N* is the number of orientation quantities specified by the `orientP` input. The returned orientation quantity type is same with the `orientP` input.

**velS — Velocity of sensor frame relative to navigation frame**
*N*-by-3 matrix of real scalars

Velocity of sensor frame relative to navigation frame, returned as an *N*-by-3 matrix of real scalars. *N* is the number of position quantities specified by the `velP` input.

**accS — Acceleration of sensor frame relative to navigation frame**
*N*-by-3 matrix of real scalars

Acceleration of sensor frame relative to navigation frame, returned as an *N*-by-3 matrix of real scalars. *N* is the number of position quantities specified by the `accP` input.

**angvelS — Angular velocity of sensor frame relative to navigation frame**
*N*-by-3 matrix of real scalars

Angular velocity of sensor frame relative to navigation frame, returned as an *N*-by-3 matrix of real scalars. *N* is the number of position quantities specified by the `angvelP` input.

## More About

### Motion Quantities Used in `transformMotion`

The `transformMotion` function calculates the motion quantities of the sensor frame (*S*), which is fixed on a rigid platform, relative to the navigation frame (*N*) using the mounting information of the sensor on the platform and the motion information of the platform frame (*P*).

As shown in the figure, the position and orientation of the platform frame and the sensor frame are fixed on the platform. The position of the sensor frame relative to the platform frame is $p_{SP}$, and the orientation of the sensor frame relative to the platform frame is $r_{SP}$. Since the two frames are both fixed, $p_{SP}$ and $r_{SP}$ are constant.

To compute the motion quantities of the sensor frame relative to the navigation frame, the quantities describing the motion of the platform frame relative to the navigation frame are required. These quantities include: the platform position ($p_{PN}$), orientation ($r_{PN}$), velocity, acceleration, angular velocity, and angular acceleration relative to the navigation frame. You can specify these quantities through the function input arguments except the angular acceleration, which is always assumed to be zero in the function. The unspecified quantities are also assumed to be zero.

# Version History

**Introduced in R2020a**

## See Also

`quaternion` | `rotvec`

# transformScan

Transform laser scan based on relative pose

## Syntax

`transScan = transformScan(scan,relPose)`

`[transRanges,transAngles] = transformScan(ranges,angles,relPose)`

## Description

`transScan = transformScan(scan,relPose)` transforms the laser scan specified in `scan` by using the specified relative pose, `relPose`.

`[transRanges,transAngles] = transformScan(ranges,angles,relPose)` transforms the laser scan specified in `ranges` and `angles` by using the specified relative pose, `relPose`.

## Examples

### Transform Laser Scans

Create a `lidarScan` object. Specify the ranges and angles as vectors.

```
refRanges = 5*ones(1,300);
refAngles = linspace(-pi/2,pi/2,300);
refScan = lidarScan(refRanges,refAngles);
```

Translate the laser scan by an `[x y]` offset of `(0.5,0.2)`.

```
transformedScan = transformScan(refScan,[0.5 0.2 0]);
```

Rotate the laser scan by 20 degrees.

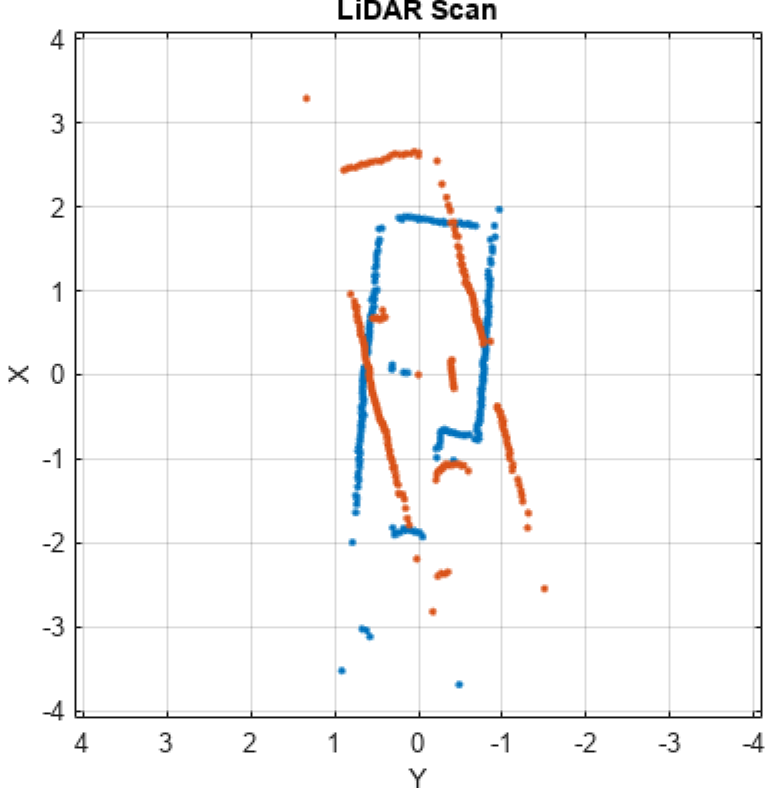
```
rotateScan = transformScan(refScan,[0,0,deg2rad(20)]);
```

### Use Scan Matching to Transform Scans

Use the `matchScans` function to find the relative transformation between two lidar scans. Then, transform the second scan into the coordinate frame of the first scan.

Load a pair of lidar scans as a pair of `lidarScan` objects. They are two scans of the same scene with a change in relative pose.

```
load tb3_scanPair.mat
plot(s1)
hold on
plot(s2)
hold off
```




The relative pose is estimated from an odometry sensor and provided as a variable, `initGuess`, as `[x y theta]`.

```
disp(initGuess)
```

```
   -0.7000    0.1500   -0.3254
```

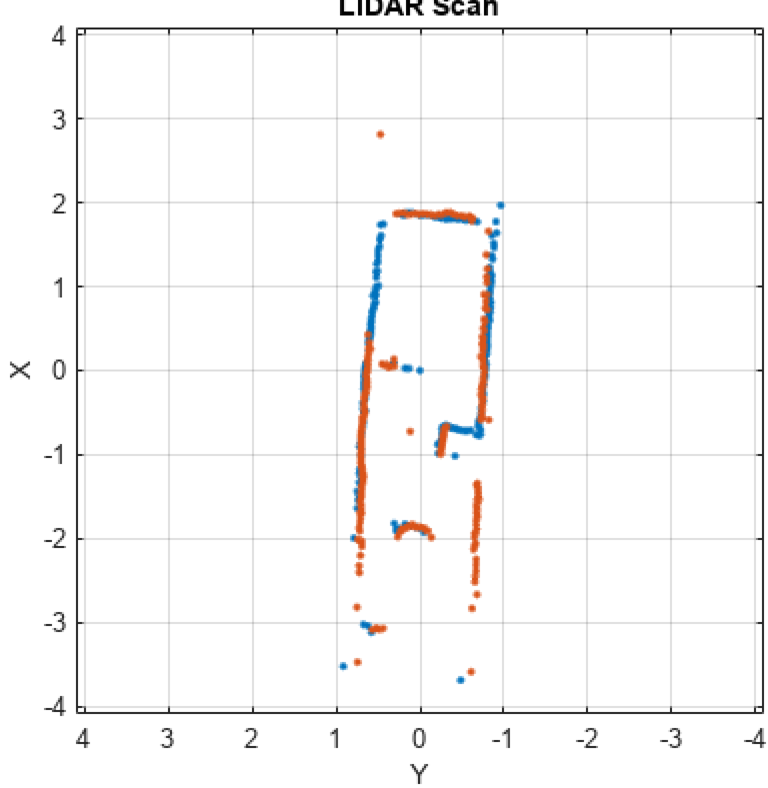
Use scan matching to find the relative pose between the two laser scans and specify the initial guess for the pose.

```
pose = matchScans(s2,s1,"InitialPose",initGuess);
disp(pose)
```

```
   -0.7213    0.1160   -0.2854
```

Transform the second scan to the coordinate frame of the first scan. Plot the two scans to see that they now overlap.

```
s2Transformed = transformScan(s2,pose);
plot(s1)
hold on
plot(s2Transformed)
hold off
```




## Input Arguments

**scan — Lidar scan readings**
lidarScan object

Lidar scan readings, specified as a lidarScan object.

**ranges — Range values from scan data**
vector

Range values from scan data, specified as a vector in meters. These range values are distances from a sensor at specified angles. The vector must be the same length as the corresponding angles vector.

**angles — Angle values from scan data**
vector

Angle values from scan data, specified as a vector in radians. These angle values are the specific angles of the specified ranges. The vector must be the same length as the corresponding ranges vector.

**relPose — Relative pose of current scan**
[x y theta]

Relative pose of current scan, specified as [x y theta], where [x y] is the translation in meters and theta is the rotation in radians.

## Output Arguments

**`transScan` — Transformed lidar scan readings**
`lidarScan` object

Transformed lidar scan readings, specified as a `lidarScan` object.

**`transRanges` — Range values of transformed scan**
vector

Range values of transformed scan, returned as a vector in meters. These range values are distances from a sensor at specified `transAngles`. The vector is the same length as the corresponding `transAngles` vector.

**`transAngles` — Angle values from scan data**
vector

Angle values of transformed scan, returned as a vector in radians. These angle values are the specific angles of the specified `transRanges`. The vector is the same length as the corresponding `ranges` vector.

# Version History

**Introduced in R2017a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

`matchScans` | `controllerVFH` | `monteCarloLocalization`

**Topics**
"Estimate Robot Pose with Scan Matching"

# trimLoopClosures

Optimize pose graph and remove bad loop closures

## Syntax

```
poseGraphUpdated = trimLoopClosures(poseGraphObj,trimParams,solverOptions)
[poseGraphUpdated,trimInfo] = trimLoopClosures(poseGraphObj,trimParams,
solverOptions)
```

## Description

`poseGraphUpdated = trimLoopClosures(poseGraphObj,trimParams,solverOptions)` optimizes the pose graph to best satisfy the edge constrains and removes any bad loop closure edges based on the residual error parameters specified in `trimParams`. Create the `solverOptions` input using the `poseGraphSolverOptions` function.

The function implements the graduated non-convexity (GNC) method with truncated least squares (TLS) robust cost in combination with the non-minimal pose graph solver [1] on page 1-314.

`[poseGraphUpdated,trimInfo] = trimLoopClosures(poseGraphObj,trimParams, solverOptions)` returns additional information related to the trimming process.

## Examples

### Optimize and Trim Loop Closures For 2-D Pose Graphs

Optimize a pose graph based on the nodes and edge constraints. Trim loop closed based on their edge residual errors.

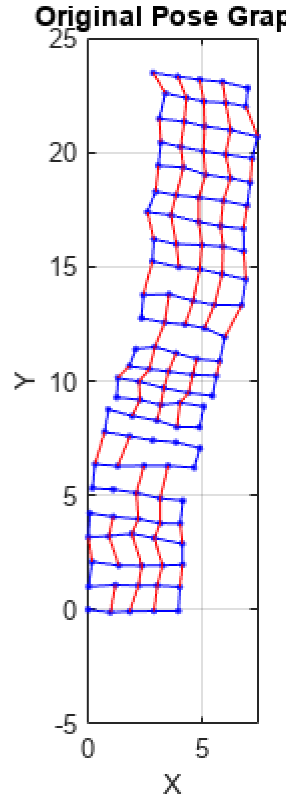
Load the data set that contains a 2-D pose graph. Inspect the `poseGraph` object to view the number of nodes and loop closures.

```
load grid-2d-posegraph.mat pg
disp(pg)
```

```
  poseGraph with properties:

               NumNodes: 120
               NumEdges: 193
    NumLoopClosureEdges: 74
     LoopClosureEdgeIDs: [120 121 122 123 124 125 126 127 128 129 130 131 132 133 134 135 136 137
        LandmarkNodeIDs: [1x0 double]
```

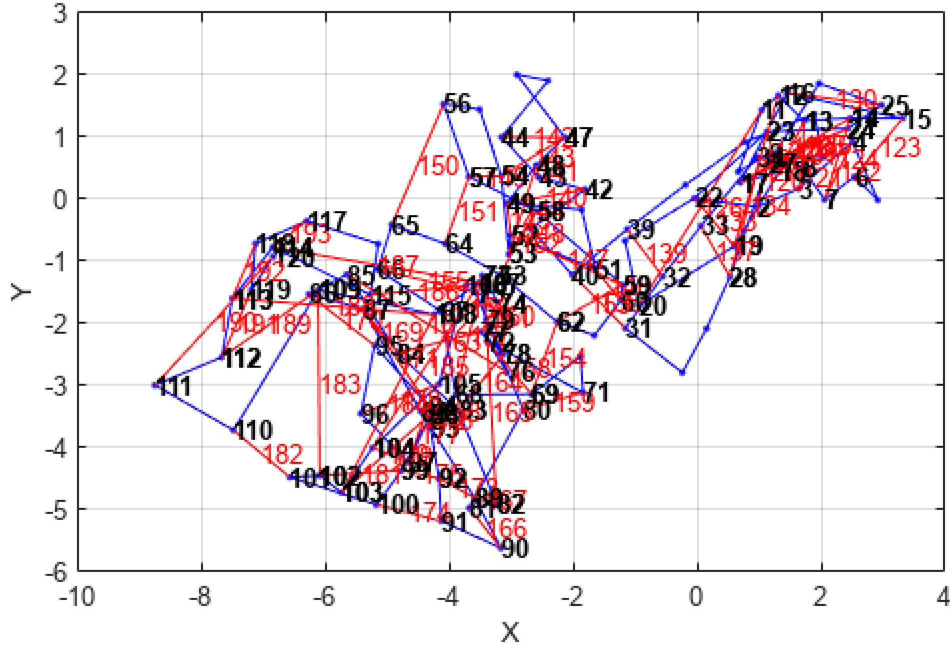
Plot the pose graph with IDs off. Red lines indicate loop closures identified in the dataset. The poses in the graph should follow a grid pattern, but show evidence of drift over time.

```
show(pg,'IDs','off');
title('Original Pose Graph')
```



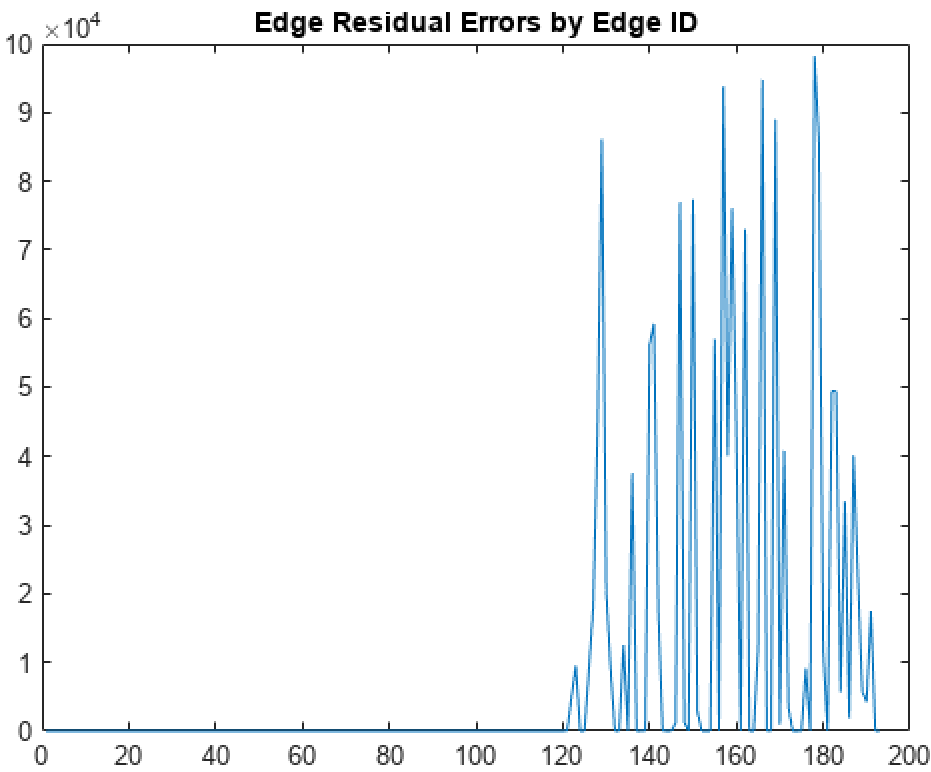

Optimize the pose graph using the `optimizePoseGraph` function. By default, this function uses the `"builtin-trust-region"` solver. Because the pose graph contains some bad loop closures, the resulting pose graph is actual not desirable.

```
pgOptim = optimizePoseGraph(pg);
figure;
show(pgOptim);
```




Look at the edge residual errors for the original pose graph. Large outlier error values at the end indicate bad loop closures.

```
resErrorVec = edgeResidualErrors(pg);
plot(resErrorVec);
title('Edge Residual Errors by Edge ID')
```




Certain loop closures should be trimmed from the pose graph based on their residual error. Use the `trimLoopClosures` function to trim these bad loop closures. Set the maximum and truncation threshold for the trimmer parameters. This threshold is set based on the measurement accuracy and should be tuned for your system.

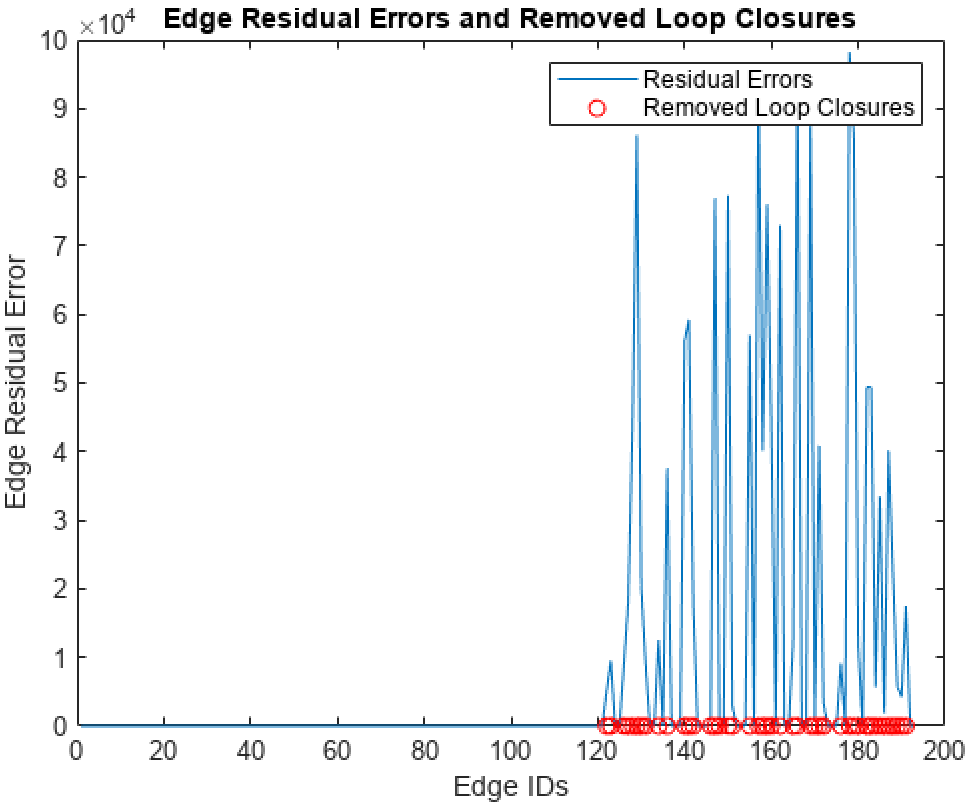
```
trimParams.MaxIterations = 100;
trimParams.TruncationThreshold = 25;

solverOptions = poseGraphSolverOptions;
```

Use the `trimLoopClosures` function with the trimmer parameters and solver options.

```
[pgNew, trimInfo, debugInfo] = trimLoopClosures(pg,trimParams,solverOptions);
```

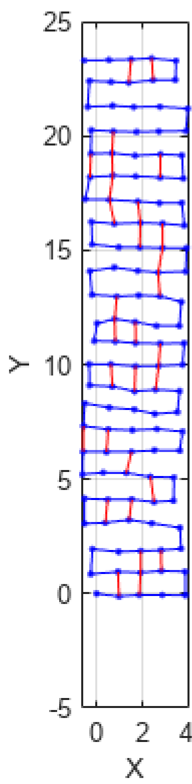
From the `trimInfo` output, plot the loop closures removed from the optimized pose graph. By plotting with the residual errors plot before, you can see the large error loop closures were removed.

```
removedLCs = trimInfo.LoopClosuresToRemove;

hold on
plot(removedLCs,zeros(length(removedLCs)),'or')
title('Edge Residual Errors and Removed Loop Closures')
legend('Residual Errors', 'Removed Loop Closures')
xlabel('Edge IDs')
ylabel('Edge Residual Error')
hold off
```




Show the new pose graph with the bad loop closures trimmed.

```
show(pgNew,"IDs","off");
```




## Input Arguments

**poseGraphObj — Pose graph**
poseGraph object | poseGraph3D object

Pose graph, specified as a poseGraph or poseGraph3D object.

**trimParams — Residual error parameters for trimming**
structure

Residual error parameters for trimming loop closures, specified as a structure with fields:

- MaxIterations — Maximum number of iterations allowed for loop closure trimming, specified as a positive integer. In one trimming iteration, the pose graph is optimized based on the solver options and any edges outside the TruncationThreshold are trimmed.
- TruncationThreshold — Maximum allowed residual error for an edge. This value depends heavily on the pose graph you specify in poseGraphObj. To find a proper threshold based on all the errors, use the edgeResidualErrors function for the pose graph.

Example: struct('MaxIterations',10,'TruncationThreshold',20)

Data Types: struct

**solverOptions — Pose graph solver options**
poseGraphSolverOptions parameters

Pose graph solver options, specified as a set of parameters generated by calling the `poseGraphSolverOptions` function. The function generates a set of solver options with default values for the specified pose graph solver type:

```
pgSolverTrustRegion = poseGraphSolverOptions('builtin-trust-region')
```

```
pgSolverTrustRegion = 

TrustRegion (builtin-trust-region-dogleg) options:

               MaxIterations: 300
                     MaxTime: 10
           FunctionTolerance: 1.0000e-08
           GradientTolerance: 5.0000e-09
               StepTolerance: 1.0000e-12
    InitialTrustRegionRadius: 100
               VerboseOutput: 'off'
```

```
pgSolverG2o = poseGraphSolverOptions('g2o-levenberg-marquardt')
```

```
pgSolverG2o = 

G2oLevenbergMarquardt (g2o-levenberg-marquardt) options:

        MaxIterations: 300
              MaxTime: 10
    FunctionTolerance: 1.0000e-09
        VerboseOutput: 'off'
```

Modify the options to tune the solver parameters using dot notation.

```
pgSolverG2o.MaxIterations = 200;
```

## Output Arguments

### `poseGraphUpdated` — Pose graph with trimmed looped closures

`poseGraph` object | `poseGraph3D` object

Pose graph with trimmed looped closures, specified as a `poseGraph` or `poseGraph3D` object.

### `trimInfo` — Information from trimming process

structure

Information from trimming process, returned as a structure with fields:

- `LoopClosuresToRemove` — Loop closure edge IDs to remove from the input `poseGraphObj`. These loop closures are removed in the output `poseGraphUpdated`.
- `Iterations` — Number of trimming iterations performed.

# Version History

**Introduced in R2020b**

## References

[1] Yang, Heng, et al. “Graduated Non-Convexity for Robust Spatial Perception: From Non-Minimal Solvers to Global Outlier Rejection.” *IEEE Robotics and Automation Letters*, vol. 5, no. 2, Apr. 2020, pp. 1127–34. *DOI.org (Crossref)*, doi:10.1109/LRA.2020.2965893.

## See Also

**Functions**
`poseGraphSolverOptions` | `edgeResidualErrors` | `removeEdges` | `edgeNodePairs` | `edgeConstraints`

**Objects**
`poseGraph` | `poseGraph3D` | `lidarSLAM`

# trvec2tform

Convert translation vector to homogeneous transformation

## Syntax

`tform = trvec2tform(trvec)`

## Description

`tform = trvec2tform(trvec)` converts the Cartesian representation of the translation vector `trvec` to the corresponding homogeneous transformation `tform`. When using the transformation matrix, premultiply it by the coordinates to be transformed (as opposed to postmultiplying).

## Examples

### Convert Translation Vector to Homogeneous Transformation

```
trvec = [0.5 6 100];
tform = trvec2tform(trvec)
```

```
tform = 4×4

    1.0000         0         0    0.5000
         0    1.0000         0    6.0000
         0         0    1.0000  100.0000
         0         0         0    1.0000
```

## Input Arguments

**`trvec` — Cartesian representation of translation vector**
*n*-by-2 matrix | *n*-by-3 matrix

Cartesian representation of a translation vector, specified as an *n*-by-2 matrix if `tform` is a 3-by-3-by-*n* array and an *n*-by-3 matrix if `tform` is a 4-by-4-by-*n* array. *n* is the number of translation vectors. Each vector is of the form [*x y*] or [*x y z*].

Example: `[0.5 6 100]`

## Output Arguments

**`tform` — Homogeneous transformation**
3-by-3-by-*n* array | 4-by-4-by-*n* array

Homogeneous transformation, returned as a 3-by-3-by-*n* array or 4-by-4-by-*n* array. *n* is the number of homogeneous transformations. When using the rotation matrix, premultiply it with the coordinates to be rotated (as opposed to postmultiplying).

Example: `[0 0 1 0; 0 1 0 0; -1 0 0 0; 0 0 0 1]`

2-D homogeneous transformation matrices are of the form:

$$T = \begin{bmatrix} r_{11} & r_{12} & t_1 \\ r_{21} & r_{22} & t_2 \\ 0 & 0 & 1 \end{bmatrix}$$

3-D homogeneous transformation matrices are of the form:

$$T = \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_1 \\ r_{21} & r_{22} & r_{23} & t_2 \\ r_{31} & r_{32} & r_{33} & t_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

## More About

### Homogeneous Transformation Matrices

Homogeneous transformation matrices consist of both an orthogonal rotation and a translation.

#### 2-D Transformations

2-D transformations have a rotation $\theta$ about the z-axis:

$$R_z(\theta) = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}$$

, and a translation along the $x$ and $y$ axis:

$$t = \begin{bmatrix} x \\ y \end{bmatrix}$$

, resulting in the 2-D transformation matrix of the form:

$$T = \begin{bmatrix} R & t \\ 0_{1\times 2} & 1 \end{bmatrix} = \begin{bmatrix} I_2 & t \\ 0_{1\times 2} & 1 \end{bmatrix} \cdot \begin{bmatrix} R & 0 \\ 0_{1\times 2} & 1 \end{bmatrix}$$

#### 3-D Transformations

3-D transformations contain information about three rotations about the x-, y-, and z-axes:

$$R_x(\phi) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & \sin\phi \\ 0 & -\sin\phi & \cos\phi \end{bmatrix}, R_y(\psi) = \begin{bmatrix} \cos\psi & 0 & \sin\psi \\ 0 & 1 & 0 \\ -\sin\psi & 0 & \cos\psi \end{bmatrix}, R_z(\theta) = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

and after multiplying become the rotation about the xyz-axes:

$$R_{xyz} = R_x(\phi)R_y(\psi)R_z(\theta) =$$

$$\begin{bmatrix} \cos\phi\cos\psi\cos\theta - \sin\phi\sin\theta & -\cos\phi\cos\psi\sin\theta - \sin\phi\cos\theta & \cos\phi\sin\psi \\ \sin\phi\cos\psi\cos\theta + \cos\phi\sin\theta & -\sin\phi\cos\psi\sin\theta + \cos\phi\cos\theta & \sin\phi\sin\psi \\ -\sin\psi\cos\theta & \sin\psi\sin\theta & \cos\psi \end{bmatrix}$$

and a translation along the $x$-, $y$-, and $z$-axis:

$$t = \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

, resulting in the 3-D transformation matrix of the form:

$$T = \begin{bmatrix} R & t \\ 0_{1x3} & 1 \end{bmatrix} = \begin{bmatrix} I_3 & t \\ 0_{1x3} & 1 \end{bmatrix} \cdot \begin{bmatrix} R & 0 \\ 0_{1x3} & 1 \end{bmatrix}$$

# Version History

**Introduced in R2015a**

### R2023a: `trvec2tform` Supports 2-D Translation Vectors

The `trvec` argument now accepts 2-D translation vectors as a *n*-by-2 matrix and `trvec2tform` outputs 2-D homogeneous transformation matrices as a 3-by-3-by-*n* array.

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`tform2trvec` | `se2` | `se3`

# tunernoise

Noise structure of fusion filter

## Syntax

```
noiseStruct = tunernoise(filterName)
noiseStruct = tunernoise(filter)
```

## Description

`noiseStruct = tunernoise(filterName)` returns the measurement noise structure for the filter with name specified by the `filterName` input.

`noiseStruct = tunernoise(filter)` returns the measurement noise structure for the filter object.

## Examples

### Obtain Measurement Noise Structure of `insfilterAsync`

Obtain the measurement noise structure of the `insfilterAsync` object.

```
noiseStruct = tunernoise('insfilterAsync')
```

```
noiseStruct = struct with fields:
    AccelerometerNoise: 1
        GyroscopeNoise: 1
     MagnetometerNoise: 1
      GPSPositionNoise: 1
      GPSVelocityNoise: 1
```

### Tune `insfilterAsync` to Optimize Pose Estimate

Load the recorded sensor data and ground truth data.

```
load('insfilterAsyncTuneData.mat');
```

Create timetables for the sensor data and the truth data.

```
sensorData = timetable(Accelerometer, Gyroscope, ...
    Magnetometer, GPSPosition, GPSVelocity, 'SampleRate', 100);
groundTruth = timetable(Orientation, Position, ...
    'SampleRate', 100);
```

Create an `insfilterAsync` filter object that has a few noise properties.

```
filter = insfilterAsync('State', initialState, ...
    'StateCovariance', initialStateCovariance, ...
```

```
    'AccelerometerBiasNoise', 1e-7, ...
    'GyroscopeBiasNoise', 1e-7, ...
    'MagnetometerBiasNoise', 1e-7, ...
    'GeomagneticVectorNoise', 1e-7);
```

Create a tuner configuration object for the filter. Set the maximum iterations to two. Also, set the tunable parameters as the unspecified properties.

```
config = tunerconfig('insfilterAsync','MaxIterations',8);
config.TunableParameters = setdiff(config.TunableParameters, ...
    {'GeomagneticVectorNoise', 'AccelerometerBiasNoise', ...
    'GyroscopeBiasNoise', 'MagnetometerBiasNoise'});
config.TunableParameters
```

```
ans = 1×10 string
    "AccelerationNoise"    "AccelerometerNoise"    "AngularVelocityNoise"    "GPSPositionNoise"
```

Use the tuner noise function to obtain a set of initial sensor noises used in the filter.

```
measNoise = tunernoise('insfilterAsync')
```

```
measNoise = struct with fields:
    AccelerometerNoise: 1
        GyroscopeNoise: 1
     MagnetometerNoise: 1
      GPSPositionNoise: 1
      GPSVelocityNoise: 1
```

Tune the filter and obtain the tuned parameters.

```
tunedParams = tune(filter,measNoise,sensorData,groundTruth,config);
```

```
    Iteration    Parameter               Metric
    _________    _________               ______
    1            AccelerationNoise       2.1345
    1            AccelerometerNoise      2.1264
    1            AngularVelocityNoise    1.9659
    1            GPSPositionNoise        1.9341
    1            GPSVelocityNoise        1.8420
    1            GyroscopeNoise          1.7589
    1            MagnetometerNoise       1.7362
    1            PositionNoise           1.7362
    1            QuaternionNoise         1.7218
    1            VelocityNoise           1.7218
    2            AccelerationNoise       1.7190
    2            AccelerometerNoise      1.7170
    2            AngularVelocityNoise    1.6045
    2            GPSPositionNoise        1.5948
    2            GPSVelocityNoise        1.5323
    2            GyroscopeNoise          1.4803
    2            MagnetometerNoise       1.4703
    2            PositionNoise           1.4703
    2            QuaternionNoise         1.4632
    2            VelocityNoise           1.4632
    3            AccelerationNoise       1.4596
    3            AccelerometerNoise      1.4548
    3            AngularVelocityNoise    1.3923
```

```
3              GPSPositionNoise       1.3810
3              GPSVelocityNoise       1.3322
3              GyroscopeNoise         1.2998
3              MagnetometerNoise      1.2976
3              PositionNoise          1.2976
3              QuaternionNoise        1.2943
3              VelocityNoise          1.2943
4              AccelerationNoise      1.2906
4              AccelerometerNoise     1.2836
4              AngularVelocityNoise   1.2491
4              GPSPositionNoise       1.2258
4              GPSVelocityNoise       1.1880
4              GyroscopeNoise         1.1701
4              MagnetometerNoise      1.1698
4              PositionNoise          1.1698
4              QuaternionNoise        1.1688
4              VelocityNoise          1.1688
5              AccelerationNoise      1.1650
5              AccelerometerNoise     1.1569
5              AngularVelocityNoise   1.1454
5              GPSPositionNoise       1.1100
5              GPSVelocityNoise       1.0778
5              GyroscopeNoise         1.0709
5              MagnetometerNoise      1.0675
5              PositionNoise          1.0675
5              QuaternionNoise        1.0669
5              VelocityNoise          1.0669
6              AccelerationNoise      1.0634
6              AccelerometerNoise     1.0549
6              AngularVelocityNoise   1.0549
6              GPSPositionNoise       1.0180
6              GPSVelocityNoise       0.9866
6              GyroscopeNoise         0.9810
6              MagnetometerNoise      0.9775
6              PositionNoise          0.9775
6              QuaternionNoise        0.9768
6              VelocityNoise          0.9768
7              AccelerationNoise      0.9735
7              AccelerometerNoise     0.9652
7              AngularVelocityNoise   0.9652
7              GPSPositionNoise       0.9283
7              GPSVelocityNoise       0.8997
7              GyroscopeNoise         0.8947
7              MagnetometerNoise      0.8920
7              PositionNoise          0.8920
7              QuaternionNoise        0.8912
7              VelocityNoise          0.8912
8              AccelerationNoise      0.8885
8              AccelerometerNoise     0.8811
8              AngularVelocityNoise   0.8807
8              GPSPositionNoise       0.8479
8              GPSVelocityNoise       0.8238
8              GyroscopeNoise         0.8165
8              MagnetometerNoise      0.8165
8              PositionNoise          0.8165
8              QuaternionNoise        0.8159
8              VelocityNoise          0.8159
```

Fuse the sensor data using the tuned filter.

```
dt = seconds(diff(groundTruth.Time));
N = size(sensorData,1);
qEst = quaternion.zeros(N,1);
posEst = zeros(N,3);
% Iterate the filter for prediction and correction using sensor data.
for ii=1:N
    if ii ~= 1
        predict(filter, dt(ii-1));
    end
    if all(~isnan(Accelerometer(ii,:)))
        fuseaccel(filter,Accelerometer(ii,:), ...
            tunedParams.AccelerometerNoise);
    end
    if all(~isnan(Gyroscope(ii,:)))
        fusegyro(filter, Gyroscope(ii,:), ...
            tunedParams.GyroscopeNoise);
    end
    if all(~isnan(Magnetometer(ii,1)))
        fusemag(filter, Magnetometer(ii,:), ...
            tunedParams.MagnetometerNoise);
    end
    if all(~isnan(GPSPosition(ii,1)))
        fusegps(filter, GPSPosition(ii,:), ...
            tunedParams.GPSPositionNoise, GPSVelocity(ii,:), ...
            tunedParams.GPSVelocityNoise);
    end
    [posEst(ii,:), qEst(ii,:)] = pose(filter);
end
```

Compute the RMS errors.

```
orientationError = rad2deg(dist(qEst, Orientation));
rmsorientationError = sqrt(mean(orientationError.^2))
```

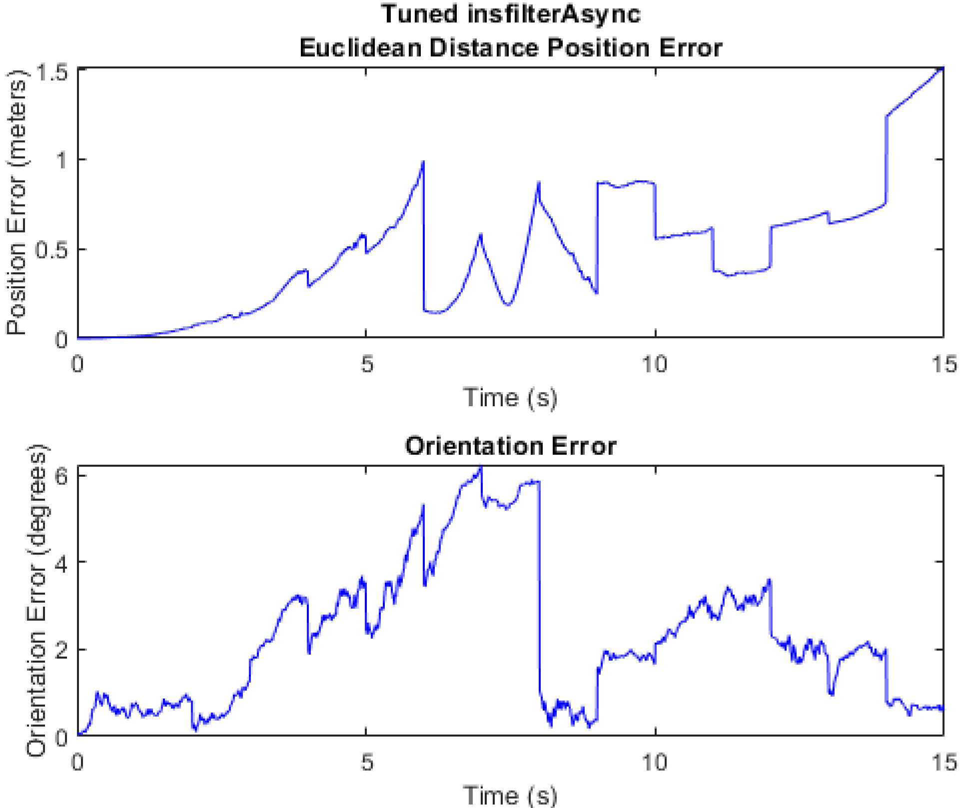
```
rmsorientationError = 2.7801
```

```
positionError = sqrt(sum((posEst - Position).^2, 2));
rmspositionError = sqrt(mean( positionError.^2))
```

```
rmspositionError = 0.5966
```

Visualize the results.

```
figure();
t = (0:N-1)./ groundTruth.Properties.SampleRate;
subplot(2,1,1)
plot(t, positionError, 'b');
title("Tuned insfilterAsync" + newline + "Euclidean Distance Position Error")
xlabel('Time (s)');
ylabel('Position Error (meters)')
subplot(2,1,2)
plot(t, orientationError, 'b');
title("Orientation Error")
xlabel('Time (s)');
ylabel('Orientation Error (degrees)');
```




## Input Arguments

**filterName — Name of fusion filter**
'insfilterAsync' | 'ahrs10filter' | 'insfilterMARG' | 'insfilterNonholonomic' | 'insfitlerErrorState'

Name of fusion filter, specified as specified as one of these:

- 'ahrs10filter'
- 'insfilterAsync'
- 'insfilterMARG'
- 'insfitlerErrorState'
- 'insfilterNonholonomic'

**filter — Fusion filter**
fusion filter object

Fusion filter, specified as one of these fusion filter objects:

- insEKF
- ahrs10filter
- insfilterAsync

- `insfilterMARG`
- `insfilterErrorState`
- `insfilterNonholonomic`

.

## Output Arguments

**`noiseStruct` — Structure of measurement noise**
structure

Structure of measurement noise, returned as a structure. The exact fields of structure depend on the filter object.

For example, the structure contains these fields for the `insfilterAsync` object.

| Field | Description | Default |
|---|---|---|
| `AccelerometerNoise` | Variance of accelerometer noise, specified as a scalar in $(m^2/s)^2$ | 1 |
| `GyroscopeNoise` | Variance of gyroscope noise, specified as a scalar in $(rad/s)^2$ | 1 |
| `MagnetometerNoise` | Variance of magnetometer noise, specified as a scalar in $(\mu T)^2$. | 1 |
| `GPSPositionNoise` | Variance of GPS position noise, specified as a scalar in $m^2$ | 1 |
| `GPSVelocityNoise` | Standard deviation of GPS velocity noise, specified as a scalar in $(m/s)^2$ | 1 |

To use this structure with a `tune` function, change the values of the noise to proper values as initial guesses for tuning the noise. When the function tunes the measurement noise, it tunes all the elements in each field together. For example, if the `AccelerometerNoise` is specified as `diag([1 0.1 1])`, then the tune function varies `AccelerometerNoise` as the product of a scalar and the original `diag([1 0.1 1])`.

# Version History

**Introduced in R2020b**

# tunerPlotPose

Plot filter pose estimates during tuning

## Syntax

```
stopTuning = tunerPlotPose(params,tunerValues)
```

## Description

`stopTuning = tunerPlotPose(params,tunerValues)` plots the current pose estimate, consisting of orientation (and possibly position, depending on the filter), and the ground truth values. `params` contains the best estimates of the filter parameters during the current tuning iteration. `tunerValues` contains information on the tuner configuration, sensor data, and ground truth data. Use this function as the value for the `OutputFcn` property of the `tunerconfig` object to plot the tuning results during iterations.

## Examples

### Visualize Tuning Results Using tunerPlotPose

Create a `tunerconfiguration` object. Set the `tunerPlotPose` function as the output function of the object.

```
tc = tunerconfig('imufilter','OutputFcn',@tunerPlotPose)
```

```
tc = 
  tunerconfig with properties:

               Filter: "imufilter"
    TunableParameters: ["AccelerometerNoise"    "GyroscopeNoise"    "GyroscopeDriftNoise"    "Li
          StepForward: 1.1000
         StepBackward: 0.5000
        MaxIterations: 20
       ObjectiveLimit: 0.1000
    FunctionTolerance: 0
              Display: iter
                 Cost: RMS
            OutputFcn: @tunerPlotPose
```

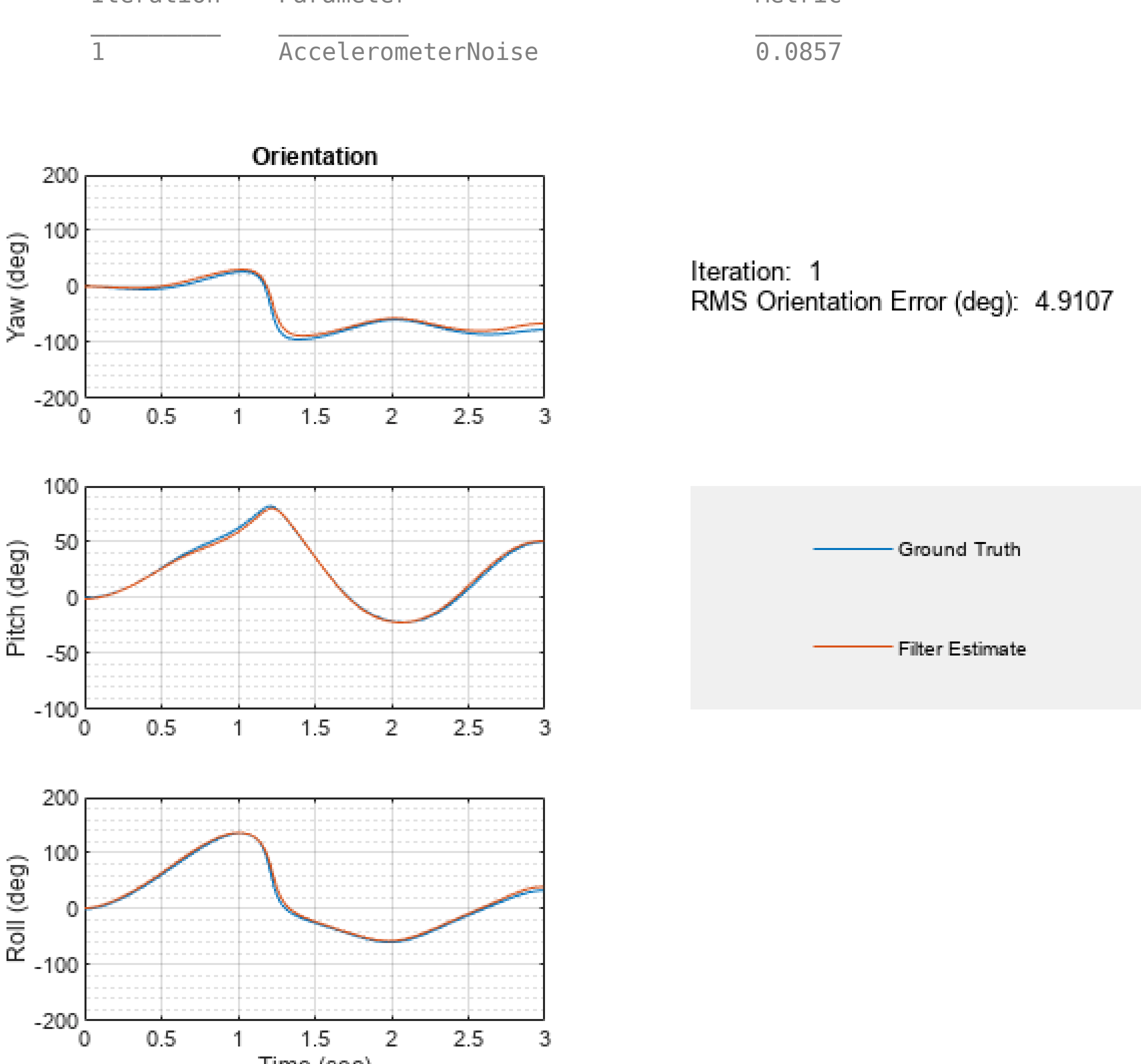
Load prerecorded sensor data.

```
ld = load('imufilterTuneData.mat');
```

Tune an `imufilter` object using the sensor data. The truth data and the estimates are shown in a figure.

```
tune(imufilter,ld.sensorData,ld.groundTruth,tc)
```

| Iteration | Parameter | Metric |
| --- | --- | --- |
| 1 | AccelerometerNoise | 0.0857 |




## Input Arguments

**`params` — Estimates of filter parameters**
structure

Estimates of filter parameters during the current iteration of the tuning process, specified as a structure. The structure contains one field for every public property of the filter and additional fields for any required measurement noise. The exact field names vary depending on the filter being tuned.

**`tunerValues` — Tuner values**
structure

Tuner values, specified as a structure. The structure has these fields:

| Field Name | Description |
| --- | --- |
| Iteration | Iteration count of the tuner, specified as a positive integer |
| SensorData | Sensor data input to the tune function |
| GroundTruth | Ground truth input to the tune function |
| Configuration | tunerconfig object used for tuning |
| Cost | Tuning cost at the end of the current iteration |

## Output Arguments

**stopTuning — Stop tuning process**
false

Stop the tuning process, returned as false. As a result, using the tunerPlotPose function as the output function of a tunerconfig object never terminates the tuning process of a fusion filter.

# Version History

**Introduced in R2021a**

## See Also

tunerconfig | tunernoise | imufilter | ahrsfilter | ahrs10filter | insfilterMARG | insfilterAsync | insfilterErrorState | insfilterNonholonomic

# velocityCommand

Retrieve velocity command from time series of velocity commands

## Syntax

`velout = velocityCommand(velcmds,timestamps,timeq)`

## Description

`velout = velocityCommand(velcmds,timestamps,timeq)` retrieves the velocity command `velout`, at the queried time instant `timeq`, from a series of velocity commands, `velcmds`, and corresponding timestamps, `timestamps`.

## Examples

### Retrieve Velocity from Time Series of Velocity Commands

Specify a set of velocity commands and corresponding timestamps.

```
velcmds = [0 0.5 1.0 1.2 1.4 1.5; ...
           0 0.2 0.5 0.2 0 0]';
timestamps = [0; 0.11; 0.2; 0.32; 0.45; 0.7];
```

Specify the query time.

```
timeq = 0.55;
```

Retrieve the velocity command at the queried time instant.

```
velout = velocityCommand(velcmds,timestamps,timeq);
disp("Set linear velocity to " + velout(1) + ...
    " and angular velocity to " + velout(2) + ".")
```

```
Set linear velocity to 1.4 and angular velocity to 0.
```

## Input Arguments

**`velcmds` — Series of velocity commands**
*N*-by-2 matrix

Series of velocity commands, specified as an *N*-by-2 matrix, where the first column is the linear velocity and the second column is the angular velocity.

Data Types: `double`

**`timestamps` — Timestamps of velocity commands**
*N*-element column vector

Timestamps of velocity commands, specified as an *N*-element column vector. Each element is the timestamp for the corresponding row in the `velcmds` input.

Data Types: `double`

**`timeq` — Query time**
positive numeric scalar

Query time, specified as a positive numeric scalar.

Data Types: `double`

### Output Arguments

**`velout` — Velocity command**
two-element row vector

Velocity command, returned as a two-element row vector containing the linear and angular velocity at the queried time `timeq`.

## Version History

**Introduced in R2023a**

### Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

### See Also

**Functions**
`headingFromXY`

**Objects**
`controllerTEB` | `plannerAStarGrid` | `mobileRobotPRM`

# writeBinaryOccupancyGrid

Write values from grid to ROS message

## Syntax

`writeBinaryOccupancyGrid(msg,map)`

## Description

`writeBinaryOccupancyGrid(msg,map)` writes occupancy values and other information to the ROS message, `msg`, from the binary occupancy grid, `map`.

## Input Arguments

**`map` — Binary occupancy grid**
`binaryOccupancyMap` object handle

Binary occupancy grid, specified as a `binaryOccupancyMap` object handle. `map` is converted to a `'nav_msgs/OccupancyGrid'` message on the ROS network. `map` is an object with a grid of binary values, where `1` indicates an occupied location and `0` indications an unoccupied location.

**`msg` — `'nav_msgs/OccupancyGrid'` ROS message**
`OccupancyGrid` object handle

`'nav_msgs/OccupancyGrid'` ROS message, specified as a `OccupancyGrid` object handle.

# Version History

**Introduced in R2015a**

## See Also

**Functions**
`rosReadBinaryOccupancyGrid` | `rosReadOccupancyMap3D` | `rosReadOccupancyGrid` | `rosWriteOccupancyGrid`

# writeBytes

Write raw commands to the GPS receiver

## Syntax

`writeBytes(gps,cmdArray)`

## Description

`writeBytes(gps,cmdArray)` writes raw commands specified by `cmdArray` to configure the GPS module.

## Examples

### Write Configuration Commands to GPS Receiver

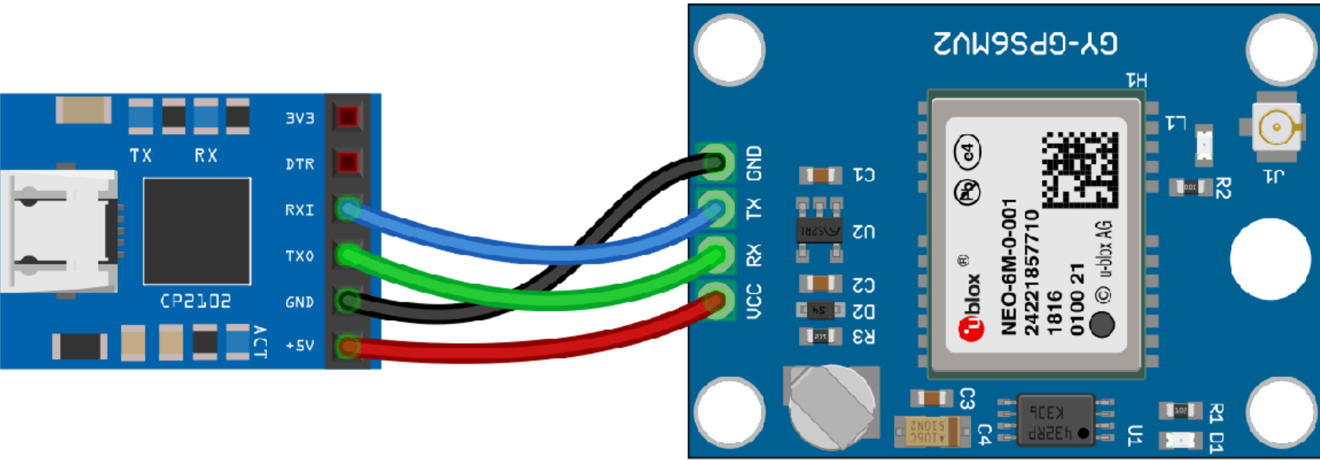
Write configuration commands to the GPS receiver connected to the host computer using `serialport` object.

**Required Hardware**

To run this example, you need:

- UBlox Neo-6M GPS module
- GPS antenna
- USB to UART module
- USB cable
- Connecting wires

**Hardware Connection**



Connect the pins on the UBlox Neo-6M GPS module to the pins on your USB to UART module. The connections are:

- VCC - +5V
- RX - TXO
- TX - RXI
- GND - GND

Connect the GPS antenna to the GPS module. Connect the USB to UART module to the host computer with a USB cable. GPS Fix can be easily acquired in locations that have a clear view of the sky. Wait for the GPS module to acquire satelite signals (Fix).This can be verified by checking the Fix LED (D1) of your GPS module.

**Create GPS Object**

Connect to the GPS receiver using `serialport` object. Specify the port name and the baud rate.

```
s = serialport('COM4',9600)
```

```
s =
  Serialport with properties:

                 Port: "COM4"
             BaudRate: 9600
    NumBytesAvailable: 0

  Show all properties, functions
```

```
gps = gpsdev(s)
```

```
gps =
  gpsdev with properties:

                         SerialPort: COM4
                           BaudRate: 9600 (bits/s)

                     SamplesPerRead: 1
                           ReadMode: "latest"
                        SamplesRead: 0
Show all properties all functions
```

**Write Configuration Commands**

In the default configuration the GPS receiver returns the following NMEA messages: GPRMC, GPVTG, GPGGA, GPGSA, GPGSV, and GPGLL. The receiver can be configured to have a user defined set of output messages.

Read few lines of default messages from the serial port the GPS receiver is connected.

```
for i = 1:10
data = readline(s);
disp(data);
end
```

```
$GPRMC,,V,,,,,,,,,,N*53
$GPVTG,,,,,,,,,N*30
```

```
$GPGGA,,,,,,0,00,99.99,,,,,,*48
$GPGSA,A,1,,,,,,,,,,,,,99.99,99.99,99.99*30
$GPGSV,2,1,08,01,,,18,08,,,12,09,,,12,15,,,19*77
$GPGSV,2,2,08,23,,,13,24,,,09,25,,,10,27,,,25*79
$GPGLL,,,,,,V,N*64
$GPRMC,,V,,,,,,,,,,N*53
$GPVTG,,,,,,,,,N*30
$GPGGA,,,,,,0,00,99.99,,,,,,*48
```

Write the version monitor command to the GPS receiver to return the software and hardware version of the GPS receiver.

```
configCMD = [0xB5 0x62 0x0A 0x04 0x00 0x00 0x0E 0x34];
% writeBytes(gps,cfg)
write(s,configCMD,'uint8')
```

Read few lines of messages again to verify the version message.

```
for i = 1:10
data = readline(s);
disp(data);
end
```

```
$GPGSA,A,1,,,,,,,,,,,,,99.99,99.99,99.99*30
$GPGSV,2,1,05,01,,,13,09,,,11,15,,,16,23,,,12*74
$GPGSV,2,2,05,25,,,10*7A
$GPGLL,,,,,,V,N*64
µb
( 7.03 (45969)                  00040007  °$GPRMC,,V,,,,,,,,,,N*53
$GPVTG,,,,,,,,,N*30
$GPGGA,,,,,,0,00,99.99,,,,,,*48
$GPGSA,A,1,,,,,,,,,,,,,99.99,99.99,99.99*30
$GPGSV,2,1,06,01,,,11,09,,,11,23,,,14,24,,,21*75
```

It can be observed from the output, `7.03 (45969)` is the software version and `00040007` is the hardware version.

### Clean Up

When the connection is no longer needed, clear the associated object.

```
delete(gps);
clear gps;
clear s;
```

## Input Arguments

**gps — GPS sensor**
`gpsdev` object

The GPS sensor, specified as a `gpsdev` object.

**`cmdArray` — Raw command to configure GPS module**
hexadecimal array

Raw command to configure the GPS module, specified as an hexadecimal array.

Example: [0xB5 0x62 0x06 0x01 0x08 0x00 0xF0 0x08 0x00 0x01 0x00 0x00 0x00 0x00 0x08 0x60]

Data Types: uint8

## Version History

**Introduced in R2020b**

### See Also

**Objects**
gpsdev

**Functions**
flush | release | read | info

# writeOccupancyGrid

Write values from grid to ROS message

## Syntax

`writeOccupancyGrid(msg,map)`

## Description

`writeOccupancyGrid(msg,map)` writes occupancy values and other information to the ROS message, `msg`, from the occupancy grid, `map`.

## Input Arguments

**`msg` — `'nav_msgs/OccupancyGrid'` ROS message**
`OccupancyGrid` object handle

`'nav_msgs/OccupancyGrid'` ROS message, specified as an `OccupancyGrid` ROS message object handle.

**`map` — Occupancy map**
`occupancyMap` object handle

Occupancy map, specified as an `occupancyMap` object handle.

# Version History

**Introduced in R2016b**

## See Also

**Functions**
`rosReadBinaryOccupancyGrid` | `rosReadOccupancyMap3D` | `rosReadOccupancyGrid` | `rosWriteOccupancyGrid`

# insCreateMotionModelTemplate

Create template file for motion model

## Syntax

`insCreateMotionModelTemplate(name)`

## Description

`insCreateMotionModelTemplate(name)` creates a template class file of a motion model to be used with the `insEKF` filter object. The function opens the file in the MATLAB editor. The `name` argument specifies the name of the class. Modify the class definition based on your application.

## Examples

### Create Motion Model Template for `insEKF`

Create a motion model template using the `insCreateMotionModel` object function. Specify the name of the class as `newMotionModel`.

```
insCreateMotionModelTemplate("newMotionModel")
```

In the MATLAB editor, an untitled file opens with its class definition. After modifying the class definition, save the class file and use an object of the class with the `insEKF` object.

```
classdef newMotionModel < positioning.INSMotionModel
    %newMotionModel Template for motion model using insEKF
    %   Customize this motion model and use it with the insEKF to fuse
    %   data.
    %
    %   Example:
    %       filt = insEKF(newMotionModel);
    %
    %   See also insEKF, positioning.INSMotionModel.

    %   Generated on 13-Mar-2022 11:25:13

    properties (Constant)
        State1Length = 1 % Length of motion model state State1
        State2Length = 2 % Length of motion model state State2
    end

    methods
        function s = modelstates(motion, opts)
            %modelstates Define the tracked states for this motion model
            %   MODELSTATES returns a struct which describes the
            %   states used by this motion model and tracked by the insEKF
            %   filter object. The field names describe the individual state
            %   quantities, and you can access the estimates of those
            %   quantities through the statesparts function. The values of
            %   the struct determine the size and default values of the
```

```
    %   state vector. The input OPTS is the insOptions object used
    %   to build the filter.
    %
    %   See also insEKF, positioning.INSMotionModel.

    % Preallocate a struct with fields State1 and State2.
    % Overwrite the fields with different default values if
    % needed.
    s = struct("State1", zeros(1, motion.State1Length, opts.Datatype), ...
        "State2", zeros(1, motion.State2Length, opts.Datatype));
end

function statesdot = stateTransition(motion, filt, dt, varargin)
    %stateTransition State transition for motion states
    %   STATETRANSITION returns a struct with identical fields
    %   as the output of the modelstates function. The
    %   returned struct describes the per-state transition function
    %   for the motion model states.
    %
    %   This function is called by the insEKF object FILT when the
    %   PREDICT method of the FILT function is called. The DT and
    %   varargin inputs are the corresponding inputs to the
    %   predict method of the insEKF object.
    %
    %   *** THIS METHOD IS OPTIONAL ***
    %   If you delete this method, the model states will be
    %   constant. In this case, also delete the
    %   stateTransitionJacobian method.
    %
    %   See also insEKF, positioning.INSMotionModel.

    % Set statesdot.State1 to the derivative of State1 with
    % respect to time. If State1 is constant overtime, leave the
    % following line unchanged.
    statesdot.State1 = zeros(1, motion.State1Length, "like", filt.State);

    % Set statesdot.State2 to the derivative of State2 with
    % respect to time. If State2 is constant overtime, leave the
    % following line unchanged.
    statesdot.State2 = zeros(1, motion.State2Length, "like", filt.State);
end

function dfdx = stateTransitionJacobian(motion, filt, dt, varargin)
    %stateTransitionJacobian Jacobian of the stateTransition function
    %   STATETRANSITIONJACOBIAN returns a struct with identical
    %   fields as modelstates and describes the Jacobian of the
    %   per-state transition function relative to the State
    %   property of FILT. Each field value of STATESDOT should be a
    %   M-by-numel(FILT.State) row vector, representing the partial
    %   derivatives of that field's state transition function
    %   relative to the state vector.
    %
    %   This function is called by the insEKF object FILT when the
    %   PREDICT method of the FILT function is called. The DT and
    %   varargin inputs are the corresponding inputs to the
    %   predict method.
    %
    %   *** THIS METHOD IS OPTIONAL ***
```

```
            %   If this method is not implemented, a numerical Jacobian
            %   will be used instead.
            %
            %   See also insEKF, positioning.INSMotionModel.

            N = numel(filt.State);

            dfdx.State1 = zeros(motion.State1Length, N, "like", filt.State);
            dfdx.State2 = zeros(motion.State2Length, N, "like", filt.State);

            % Create indexing
            s1idx = stateinfo(filt, "State1");
            s2idx = stateinfo(filt, "State2");

            % Uncomment the line below, and set dfdx.State1 to the
            % Jacobian of the stateTransition function with respect to
            % the State property of the filter object filt. Use s1idx to
            % index the columns of dfdx.State1.

            % % dfdx.State1(:,s1idx) =

            % Uncomment the line below, and set dfdx.State2 to the
            % Jacobian of the stateTransition function with respect to
            % the State property of the filter object filt. Use s2idx to
            % index the columns of dfdx.State2.

            % % dfdx.State2(:,s2idx) =
        end
    end
end

% [EOF]
```

## Input Arguments

**name — Motion model class name**
string scalar | character vector

Motion model class name, specified as a string scalar or a character vector.

Example: "myClass"

Data Types: char | string

# Version History

**Introduced in R2022b**

## See Also

insCreateSensorModelTemplate | insEKF

# insCreateSensorModelTemplate

Create template file for sensor model

## Syntax

`insCreateSensorModelTemplate(name)`

## Description

`insCreateSensorModelTemplate(name)` creates a template class file of a sensor model to be used with the `insEKF` filter object. The function opens the file in the MATLAB editor. The `name` argument specifies the name of the class. Modify the class definition based on your application.

## Examples

### Create Sensor Model Template for insEKF

Create a sensor model template using the `insCreateMotionModel` object function. Specify the name of the class as `newSensorModel`.

```
insCreateMotionModelTemplate("newSensorModel")
```

In the MATLAB editor, an untitled file opens with its class definition. After modifying the class definition, save the class file and use an object of the class with the `insEKF` object.

```
classdef newSensorModel < positioning.INSMotionModel
    %newSensorModel Template for motion model using insEKF
    %   Customize this motion model and use it with the insEKF to fuse
    %   data.
    %
    %   Example:
    %       filt = insEKF(newSensorModel);
    %
    %   See also insEKF, positioning.INSMotionModel.

    %   Generated on 13-Mar-2022 11:37:21

    properties (Constant)
        State1Length = 1 % Length of motion model state State1
        State2Length = 2 % Length of motion model state State2
    end

    methods
        function s = modelstates(motion, opts)
            %modelstates Define the tracked states for this motion model
            %   MODELSTATES returns a struct which describes the
            %   states used by this motion model and tracked by the insEKF
            %   filter object. The field names describe the individual state
            %   quantities, and you can access the estimates of those
            %   quantities through the statesparts function. The values of
            %   the struct determine the size and default values of the
```

```
    %   state vector. The input OPTS is the insOptions object used
    %   to build the filter.
    %
    %   See also insEKF, positioning.INSMotionModel.

    % Preallocate a struct with fields State1 and State2.
    % Overwrite the fields with different default values if
    % needed.
    s = struct("State1", zeros(1, motion.State1Length, opts.Datatype), ...
        "State2", zeros(1, motion.State2Length, opts.Datatype));
end

function statesdot = stateTransition(motion, filt, dt, varargin)
    %stateTransition State transition for motion states
    %   STATETRANSITION returns a struct with identical fields
    %   as the output of the modelstates function. The
    %   returned struct describes the per-state transition function
    %   for the motion model states.
    %
    %   This function is called by the insEKF object FILT when the
    %   PREDICT method of the FILT function is called. The DT and
    %   varargin inputs are the corresponding inputs to the
    %   predict method of the insEKF object.
    %
    %   *** THIS METHOD IS OPTIONAL ***
    %   If you delete this method, the model states will be
    %   constant. In this case, also delete the
    %   stateTransitionJacobian method.
    %
    %   See also insEKF, positioning.INSMotionModel.

    % Set statesdot.State1 to the derivative of State1 with
    % respect to time. If State1 is constant overtime, leave the
    % following line unchanged.
    statesdot.State1 = zeros(1, motion.State1Length, "like", filt.State);

    % Set statesdot.State2 to the derivative of State2 with
    % respect to time. If State2 is constant overtime, leave the
    % following line unchanged.
    statesdot.State2 = zeros(1, motion.State2Length, "like", filt.State);
end

function dfdx = stateTransitionJacobian(motion, filt, dt, varargin)
    %stateTransitionJacobian Jacobian of the stateTransition function
    %   STATETRANSITIONJACOBIAN returns a struct with identical
    %   fields as modelstates and describes the Jacobian of the
    %   per-state transition function relative to the State
    %   property of FILT. Each field value of STATESDOT should be a
    %   M-by-numel(FILT.State) row vector, representing the partial
    %   derivatives of that field's state transition function
    %   relative to the state vector.
    %
    %   This function is called by the insEKF object FILT when the
    %   PREDICT method of the FILT function is called. The DT and
    %   varargin inputs are the corresponding inputs to the
    %   predict method.
    %
    %   *** THIS METHOD IS OPTIONAL ***
```

```
            %   If this method is not implemented, a numerical Jacobian
            %   will be used instead.
            %
            %   See also insEKF, positioning.INSMotionModel.

            N = numel(filt.State);

            dfdx.State1 = zeros(motion.State1Length, N, "like", filt.State);
            dfdx.State2 = zeros(motion.State2Length, N, "like", filt.State);

            % Create indexing
            s1idx = stateinfo(filt, "State1");
            s2idx = stateinfo(filt, "State2");

            % Uncomment the line below, and set dfdx.State1 to the
            % Jacobian of the stateTransition function with respect to
            % the State property of the filter object filt. Use s1idx to
            % index the columns of dfdx.State1.

            % % dfdx.State1(:,s1idx) =

            % Uncomment the line below, and set dfdx.State2 to the
            % Jacobian of the stateTransition function with respect to
            % the State property of the filter object filt. Use s2idx to
            % index the columns of dfdx.State2.

            % % dfdx.State2(:,s2idx) =
        end
    end
end

% [EOF]
```

## Input Arguments

**name — Sensor model class name**
string scalar | character vector

Sensor model class name, specified as a string scalar or a character vector.

Example: `"myClass"`

Data Types: `char` | `string`

# Version History

**Introduced in R2022b**

## See Also

`insCreateMotionModelTemplate` | `insEKF`

# yumaread

Read data from YUMA almanac file

## Syntax

```
data = yumaread(filename)
data = yumaread(filename,GPSWeekEpoch=refdate)
```

## Description

`data = yumaread(filename)` reads data from the YUMA almanac file specified by `filename`, and returns the parameters of each associated satellite as a timetable.

`data = yumaread(filename,GPSWeekEpoch=refdate)` specifies the reference date from which the YUMA almanac file counts the Global Positioning System (GPS) week number.

## Examples

### Read GPS Navigation Message Data from YUMA Almanac File

Download the YUMA almanac file from the NAVCEN website and parse it. Specify the date for which to download the file.

```
d = datetime("today") - 2;
```

Create the URL.

```
baseURL = "https://www.navcen.uscg.gov/sites/default/files/gps/almanac/";
almanacType = "/yuma/";
almanacExtension = ".alm";
url = baseURL + d.Year + almanacType + num2str(day(d,"dayofyear"),'%03d') + ...
      almanacExtension;
```

Specify a filename for the saved almanac file.

```
filename = "yumaAlmanac" + "_" + d.Year + "-" + ...
           d.Month + "-" + d.Day + ".alm";
```

Save the file.

```
websave(filename,url);
```

Get the orbital parameters from the downloaded YUMA almanac file.

```
data = yumaread(filename)
```

```
data=31×13 timetable
            Time            PRN    Health    Eccentricity    TimeOfApplicability    OrbitalInclin
    ____________________    ___    ______    ____________    ___________________    _____________

    27-Jan-2023 19:56:30     1       0         0.012259           5.0381e+05              0.98919
```

```
    27-Jan-2023 19:56:30     2        0          0.020082          5.0381e+05               0.96693
    27-Jan-2023 19:56:30     3        0          0.004446          5.0381e+05                0.9773
    27-Jan-2023 19:56:30     4        0         0.0022964          5.0381e+05               0.96264
    27-Jan-2023 19:56:30     5        0         0.0057855          5.0381e+05                0.9643
    27-Jan-2023 19:56:30     6        0         0.0028877          5.0381e+05               0.98846
    27-Jan-2023 19:56:30     7        0          0.016655          5.0381e+05               0.95017
    27-Jan-2023 19:56:30     8        0         0.0082297          5.0381e+05               0.96065
    27-Jan-2023 19:56:30     9        0         0.0025482          5.0381e+05               0.95586
    27-Jan-2023 19:56:30    10        0         0.0084252          5.0381e+05               0.97706
    27-Jan-2023 19:56:30    11        0        0.00078106          5.0381e+05               0.96453
    27-Jan-2023 19:56:30    12        0         0.0088811          5.0381e+05               0.96648
    27-Jan-2023 19:56:30    13        0         0.0067534          5.0381e+05               0.96972
    27-Jan-2023 19:56:30    14        0          0.002604          5.0381e+05               0.94981
    27-Jan-2023 19:56:30    15        0          0.014733          5.0381e+05               0.93207
    27-Jan-2023 19:56:30    16        0          0.013348          5.0381e+05               0.96625
      ⋮
```

**View Satellite Positions Visible from Receiver Position Using YUMA Almanac File**

Read GPS and QZSS navigation message data from a YUMA almanac file.

```
gpsQzssData = yumaread("qg2022309.alm");
```

Get the satellite positions, velocities, and IDs at the specified time.

```
t = datetime(2022,11,10,8,12,00);
[satPos,satVel,satID] = gnssconstellation(t,gpsQzssData,GNSSFileType="YUMA");
```

Specify a GNSS receiver position in geodetic coordinates (latitude, longitude, and altitude).

```
recPos = [35.67 139.73 50]; % Tokyo
```

Get the azimuth and elevation look angles of the satellite positions for the specified receiver position. The `isVis` output indicates which satellites are visible. Find the total number of visible satellites by using `nnz`.

```
[az,el,isVis] = lookangles(recPos,satPos);
fprintf('%d satellites visible at %s.\n',nnz(isVis),t);
```

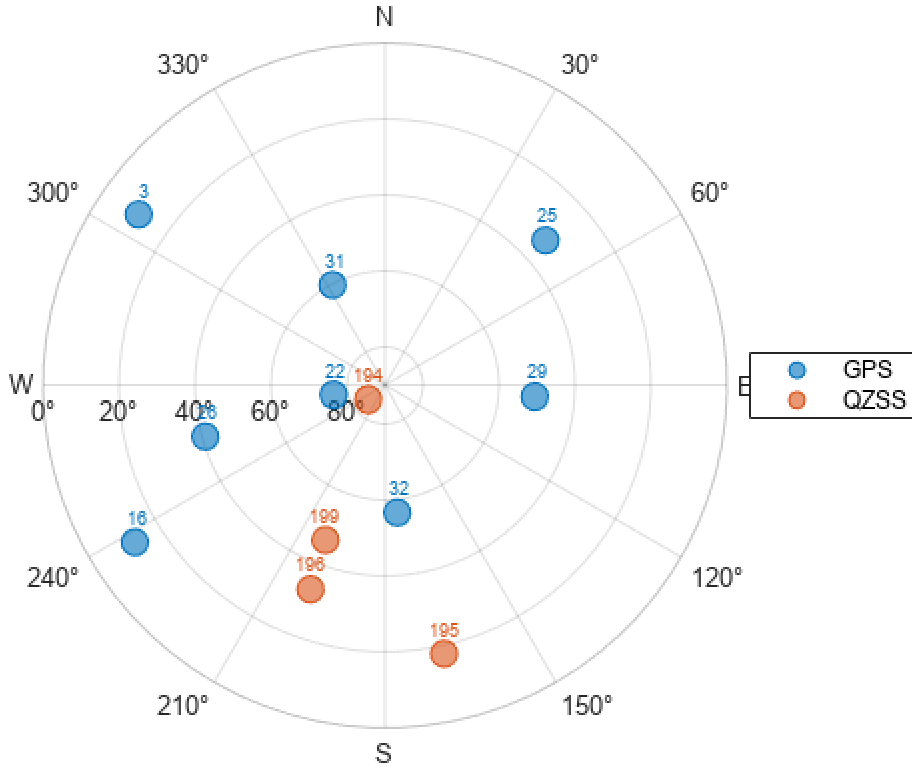
```
12 satellites visible at 10-Nov-2022 08:12:00.
```

Specify the PRN as the label for each point. Specify the categorical groups.

```
prn = gpsQzssData.PRN;
GPSPrn = (prn <= 32);
group = categorical(GPSPrn,[true false],["GPS" "QZSS"]);
```

Visualize the visible satellites. Show the legend.

```
skyplot(az(isVis),el(isVis),satID(isVis),GroupData=group(isVis))
legend("GPS","QZSS")
```




**Extract GPS and QZSS Data from YUMA Almanac File**

Read a YUMA almanac file containing GPS and QZSS data, downloaded from the QZSS website.

```
filenameQG = "qg2022309.alm";
dataQG = yumaread(filenameQG)
```

*dataQG=35×13 timetable*

| Time | PRN | Health | Eccentricity | TimeOfApplicability | OrbitalIncli |
|---|---|---|---|---|---|
| 08-Nov-2022 16:50:54 | 1 | 0 | 0.01204 | 2.3347e+05 | 0.98919 |
| 08-Nov-2022 16:50:54 | 2 | 0 | 0.02012 | 2.3347e+05 | 0.96699 |
| 08-Nov-2022 16:50:54 | 3 | 0 | 0.0044513 | 2.3347e+05 | 0.97615 |
| 08-Nov-2022 16:50:54 | 4 | 0 | 0.0021377 | 2.3347e+05 | 0.96147 |
| 08-Nov-2022 16:50:54 | 5 | 0 | 0.0059276 | 2.3347e+05 | 0.9632 |
| 08-Nov-2022 16:50:54 | 6 | 0 | 0.0026011 | 2.3347e+05 | 0.98847 |
| 08-Nov-2022 16:50:54 | 7 | 0 | 0.016459 | 2.3347e+05 | 0.95087 |
| 08-Nov-2022 16:50:54 | 8 | 0 | 0.0077338 | 2.3347e+05 | 0.96113 |
| 08-Nov-2022 16:50:54 | 9 | 0 | 0.0026331 | 2.3347e+05 | 0.95461 |
| 08-Nov-2022 16:50:54 | 10 | 0 | 0.0081372 | 2.3347e+05 | 0.97593 |
| 08-Nov-2022 16:50:54 | 11 | 0 | 0.00080109 | 2.3347e+05 | 0.9645 |
| 08-Nov-2022 16:50:54 | 12 | 0 | 0.0085993 | 2.3347e+05 | 0.96761 |
| 08-Nov-2022 16:50:54 | 13 | 0 | 0.0066509 | 2.3347e+05 | 0.96872 |
| 08-Nov-2022 16:50:54 | 14 | 0 | 0.0023918 | 2.3347e+05 | 0.95102 |

```
    08-Nov-2022 16:50:54    15       0          0.014719         2.3347e+05               0.9307
    08-Nov-2022 16:50:54    16       0          0.012957         2.3347e+05               0.9674
      ⋮
```

Extract GPS data from the timetable based on valid GPS PRNs between 1 and 32.

```
GPSdata = dataQG((dataQG.PRN >= 1 & dataQG.PRN <= 32),:)
```

```
GPSdata=31×13 timetable
            Time            PRN    Health    Eccentricity    TimeOfApplicability    OrbitalIncli
    ____________________    ___    ______    ____________    ___________________    ____________

    08-Nov-2022 16:50:54     1       0            0.01204        2.3347e+05              0.98919
    08-Nov-2022 16:50:54     2       0            0.02012        2.3347e+05              0.96699
    08-Nov-2022 16:50:54     3       0          0.0044513        2.3347e+05              0.97615
    08-Nov-2022 16:50:54     4       0          0.0021377        2.3347e+05              0.96147
    08-Nov-2022 16:50:54     5       0          0.0059276        2.3347e+05               0.9632
    08-Nov-2022 16:50:54     6       0          0.0026011        2.3347e+05              0.98847
    08-Nov-2022 16:50:54     7       0           0.016459        2.3347e+05              0.95087
    08-Nov-2022 16:50:54     8       0          0.0077338        2.3347e+05              0.96113
    08-Nov-2022 16:50:54     9       0          0.0026331        2.3347e+05              0.95461
    08-Nov-2022 16:50:54    10       0          0.0081372        2.3347e+05              0.97593
    08-Nov-2022 16:50:54    11       0         0.00080109        2.3347e+05               0.9645
    08-Nov-2022 16:50:54    12       0          0.0085993        2.3347e+05              0.96761
    08-Nov-2022 16:50:54    13       0          0.0066509        2.3347e+05              0.96872
    08-Nov-2022 16:50:54    14       0          0.0023918        2.3347e+05              0.95102
    08-Nov-2022 16:50:54    15       0           0.014719        2.3347e+05               0.9307
    08-Nov-2022 16:50:54    16       0           0.012957        2.3347e+05               0.9674
      ⋮
```

Extract QZSS data from the timetable based on valid QZSS PRNs between 193 and 202.

```
QZSSData = dataQG((dataQG.PRN >= 193 & dataQG.PRN <= 202),:)
```

```
QZSSData=4×13 timetable
            Time            PRN    Health    Eccentricity    TimeOfApplicability    OrbitalIncli
    ____________________    ___    ______    ____________    ___________________    ____________

    08-Nov-2022 08:53:02    194      0           0.076374         2.048e+05               0.7254
    08-Nov-2022 08:53:02    195      0           0.074928         2.048e+05               0.7109
    08-Nov-2022 08:53:02    196      0           0.074762         2.048e+05               0.6059
    08-Nov-2022 08:53:02    199      0         0.00022411         2.048e+05             0.001192
```

### Plot Trajectories of Satellites over Time from YUMA Almanac File

Read GPS navigation message data from a YUMA almanac file.

```
gpsData = yumaread("yumaAlmanac_2022-9-27.alm");
```

Use the initial GPS timestamp from the almanac data to determine the absolute GPS times for each 60 second time step across 12 hours.

```
startTime = gpsData.Time(1);
numHours = 12;
```

```
secondsPerHour = 3600;
dt = 60;
timeElapsed = 0:dt:(numHours*secondsPerHour);
t = startTime + seconds(timeElapsed);
```

Specify a GNSS receiver position in geodetic coordinates (latitude, longitude, and altitude).

```
recPos = [42 -71 50]; % Natick, MA
```

Get the azimuth and elevation look angles for the positions of all satellites for the specified receiver position.

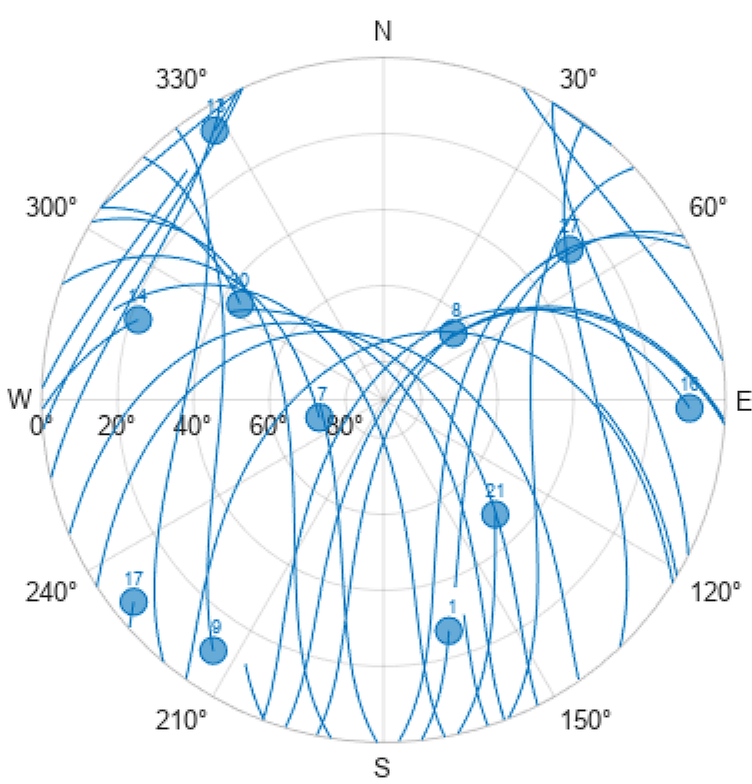
```
numSats = numel(gpsData.PRN); % Number of satellites
[allAz,allEl] = deal(NaN(numel(t),numSats));
for i = 1:numel(t)
    [satPos,~,satID] = gnssconstellation(t(i),gpsData,GNSSFileType="YUMA");
    [az,el,vis] = lookangles(recPos,satPos);
    allAz(i,:) = az;
    allEl(i,:) = el;
end
```

Mark all satellites below the horizon as `NaN` for no visibility.

```
allEl(allEl < 0) = NaN;
```

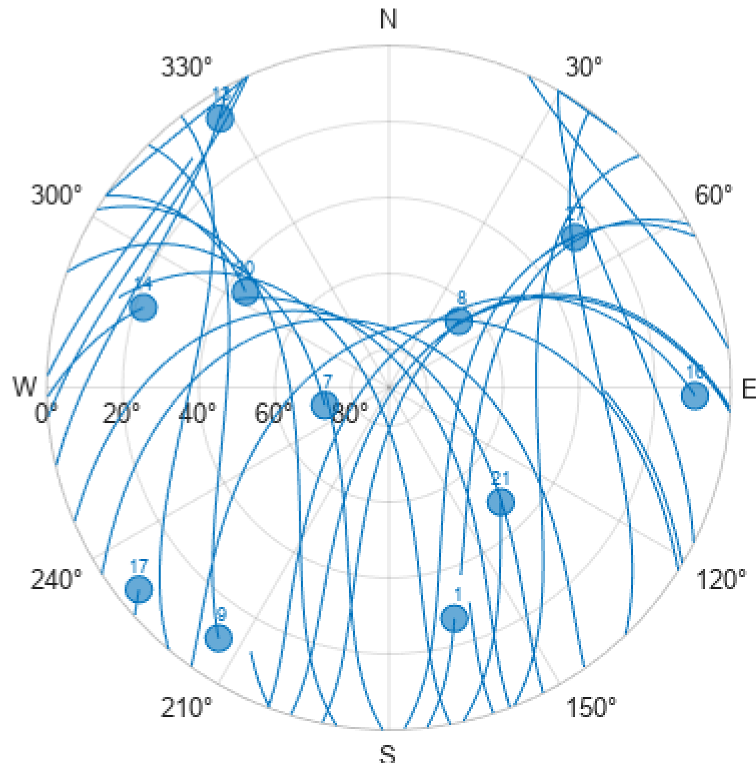
Visualize the trajectories of the satellites.

```
figure
skyplot(allAz,allEl,satID)
```



Animate the trajectories of the satellites.

```
figure
sp = skyplot(allAz(1,:),allEl(1,:),satID);
for i = 1:size(allAz,1)
    set(sp,AzimuthData=allAz(1:i,:),ElevationData=allEl(1:i,:))
    drawnow
end
```




## Input Arguments

**`filename` — YUMA almanac filename**
string scalar | character vector

YUMA almanac filename, specified as a string scalar or character vector. You can specify a relative or an absolute path, but if you specify only the filename itself, the function saves the file in the current working directory. The filename can also include a file extension.

Example: `"yumaAlmanac_2022-4-20.alm"`

Example: `"mydir/yumaAlmanac_2022-4-20.alm"`

Example: `"C:/mydir/yumaAlmanac_2022-4-20.alm"`

Data Types: `char` | `string`

**refdate — Reference date**
"06-Jan-1980" | "21-Aug-1999" | "06-Apr-2019"

Reference date, specified as one of these valid datetime strings that coincide with the GPS week number rollover dates:

- "06-Jan-1980"
- "21-Aug-1999"
- "06-Apr-2019"

These dates occur every 1024 weeks, starting from January 6, 1980 at 00:00 (UTC). The default value is a datetime string that coincides with the most recent GPS week number rollover date before the current day.

Example: GPSWeekEpoch="21-Aug-1999"

Data Types: char | string

## Output Arguments

**data — Parameters of each satellite**
timetable

Parameters of each satellite, returned as a timetable with a row for each record and a column for each parameter in that record.

| Parameter | Data Type | Description |
|---|---|---|
| Time | datetime | GPS Time, calculated using Week and TimeOfApplicability. |
| PRN | double | Satellite pseudorandom noise number. |
| Health | double | Satellite vehicle health data code. |
| Eccentricity | double | Eccentricity of the satellite. |
| TimeOfApplicability | double | Number of seconds since beginning of GPS week number. |
| OrbitalInclination | double | Inclination angle at reference time, in radians. |
| RateOfRightAscen | double | Rate of change in measurement of angle of right ascension, in radians per second. |
| SQRTA | double | Square root of semimajor axis, in meters$^{1/2}$. |
| RightAscenAtWeek | double | Geographic longitude of orbital plane at weekly epoch, in radians. |

| Parameter | Data Type | Description |
| --- | --- | --- |
| `ArgumentOfPerigee` | `double` | Angle from equator to perigee, in radians. |
| `MeanAnom` | `double` | Angle from position of satellite in its orbit relative to perigee, in radians. |
| `Af0` | `double` | Satellite almanac zeroth-order clock correction term, in seconds. |
| `Af1` | `double` | Satellite almanac first order clock correction term, in seconds per second. |
| `Week` | `double` | GPS week number, continuous, not `mod(1024)`. |

## Tips

- To download YUMA almanac files from the NAVCEN website for the current date, you must specify a date two days before the current date because the GPS time of applicability is approximately 70 hours later than the transmission time of the almanac data set. See the “Read GPS Navigation Message Data from YUMA Almanac File” on page 1-341 example for more details.

# Version History

**Introduced in R2023a**

## References

[1] Science Applications International Corporation. NAVSTAR GPS Space Segment/Navigation User Interfaces. IS-GPS-200M. Los Angeles, CA: United States Space Force Space Systems Command, approved May 21, 2021. https://www.navcen.uscg.gov/sites/default/files/pdf/gps/IS_GPS_200M.pdf.

[2] Science Applications International Corporation. NAVSTAR GPS Space Segment/Navigation User Interfaces. ICD-GPS-240D. Los Angeles, CA: United States Space Force Space Systems Command, approved May 21, 2021. https://www.navcen.uscg.gov/sites/default/files/pdf/gps/ICD_GPS_240D.pdf.

[3] United States Coast Guard. "GPS Almanacs, NANUs, and OPS Advisories Archives." US Coast Guard Navigation Center. Accessed May 6, 2022. https://www.navcen.uscg.gov/archives.

[4] Quasi-Zenith Satellite System(QZSS). "Satellite Positioning, Navigation and Timing Service." Accessed September 20, 2022. https://qzss.go.jp/en/technical/download/pdf/ps-is-qzss/is-qzss-pnt-004.pdf.

[5] QZSS almanac archives, Quasi-Zenith Satellite System(QZSS). "QZSS (Quasi-Zenith Satellite System) - Cabinet Office (Japan)" Accessed September 20, 2022. https://sys.qzss.go.jp/dod/en/archives/pnt.html.

## See Also

`semread` | `rinexread` | `gnssconstellation` | `skyplot`

2

# Classes

# accelparams

Accelerometer sensor parameters

## Description

The accelparams class creates an accelerometer sensor parameters object. You can use this object to model an accelerometer when simulating an IMU with imuSensor. See the “Algorithms” on page 2-545 section of imuSensor for details of accelparams modeling.

## Creation

### Syntax

```
params = accelparams
params = accelparams(Name,Value)
```

#### Description

params = accelparams returns an ideal accelerometer sensor parameters object with default values.

params = accelparams(Name,Value) configures an accelerometer sensor parameters object properties using one or more Name-Value pair arguments. Name is a property name and Value is the corresponding value. Name must appear inside single quotes (''). You can specify several name-value pair arguments in any order as (Name1,Value1,...,NameN,ValueN). Any unspecified properties take default values.

## Properties

**MeasurementRange — Maximum sensor reading (m/s$^2$)**
inf (default) | real positive scalar

Maximum sensor reading in m/s$^2$, specified as a real positive scalar.

Data Types: single | double

**Resolution — Resolution of sensor measurements ((m/s$^2$)/LSB)**
0 (default) | real nonnegative scalar

Resolution of sensor measurements in (m/s$^2$)/LSB, specified as a real nonnegative scalar. Here, LSB is the acronym for least significant bit. Resolution is often referred to as Scale Factor for accelerometer.

Data Types: single | double

**ConstantBias — Constant sensor offset bias (m/s$^2$)**
[0 0 0] (default) | real scalar | real 3-element row vector

Constant sensor offset bias in m/s$^2$, specified as a real scalar or 3-element row vector. Any scalar input is converted into a real 3-element row vector where each element has the input scalar value.

Data Types: `single` | `double`

**`AxesMisalignment` — Sensor axes skew (%)**
`diag([100 100 100])` (default) | scalar in the range [0,100] | 3-element row vector in the range [0,100] | 3-by-3 matrix in the range [0,100]

Sensor axes skew in percentage, specified as a scalar, a 3-element row vector, or a 3-by-3 matrix with values ranging from `0` to `100`. The diagonal elements of the matrix account for the misalignment effects for each axes. The off-diagonal elements account for the cross-axes misalignment effects. The measured state $v_{measure}$ is obtained from the true state $v_{true}$ via the misalignment matrix as:

$$v_{measure} = \frac{1}{100} M v_{true} = \frac{1}{100} \begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{bmatrix} v_{true}$$

- If you specify the property as a scalar, then all the off-diagonal elements of the matrix take the value of the specified scalar and all the diagonal elements are 100.
- If you specify the property as a vector [$a$ $b$ $c$], then $m_{21} = m_{31} = a$, $m_{12} = m_{32} = b$, and $m_{13} = m_{23} = c$. All the diagonal elements are 100.

Data Types: `single` | `double`

**`NoiseDensity` — Power spectral density of sensor noise (m/s²/√Hz)**
`[0 0 0]` (default) | real scalar | real 3-element row vector

Power spectral density of sensor noise in (m/s$^2$/√Hz), specified as a real scalar or 3-element row vector. This property corresponds to the velocity random walk (VRW). Any scalar input is converted into a real 3-element row vector where each element has the input scalar value.

Data Types: `single` | `double`

**`BiasInstability` — Instability of the bias offset (m/s²)**
`[0 0 0]` (default) | real scalar | real 3-element row vector

Instability of the bias offset in m/s$^2$, specified as a real scalar or 3-element row vector. Any scalar input is converted into a real 3-element row vector where each element has the input scalar value.

Data Types: `single` | `double`

**`RandomWalk` — Integrated white noise of sensor ((m/s²)*(√Hz))**
`[0 0 0]` (default) | real scalar | real 3-element row vector

Integrated white noise of sensor in (m/s$^2$)*(√Hz), specified as a real scalar or 3-element row vector. Any scalar input is converted into a real 3-element row vector where each element has the input scalar value.

Data Types: `single` | `double`

**`TemperatureBias` — Sensor bias from temperature ((m/s²)/°C)**
`[0 0 0]` (default) | real scalar | real 3-element row vector

Sensor bias from temperature in (m/s$^2$)/℃, specified as a real scalar or 3-element row vector. Any scalar input is converted into a real 3-element row vector where each element has the input scalar value.

Data Types: `single` | `double`

**`TemperatureScaleFactor` — Scale factor error from temperature (%/°C)**
`[0 0 0]` (default) | real scalar in the range [0,100] | real 3-element row vector in the range [0,100]

Scale factor error from temperature in %/℃, specified as a real scalar or real 3-element row vector with values ranging from 0 to 100. Any scalar input is converted into a real 3-element row vector where each element has the input scalar value.

Data Types: `single` | `double`

## Examples

### Generate Accelerometer Data from Stationary Inputs

Generate accelerometer data for an imuSensor object from stationary inputs.

Generate an accelerometer parameter object with a maximum sensor reading of 19.6 $\text{m/s}^2$ and a resolution of 0.598 $\left(\text{mm/s}^2\right)/\text{LSB}$. The constant offset bias is 0.49 $\text{m/s}^2$. The sensor has a power spectral density of 3920 $\left(\mu\text{m/s}^2\right)/\sqrt{\text{Hz}}$. The bias from temperature is 0.294 $\left(\text{m/s}^2\right)/{}^0\text{C}$. The scale factor error from temperature is 0.02%/${}^0$C. The sensor axes are skewed by 2%.

```
params = accelparams('MeasurementRange',19.6,'Resolution',0.598e-3,'ConstantBias',0.49,'NoiseDens
```

Use a sample rate of 100 Hz spaced out over 1000 samples. Create the imuSensor object using the accelerometer parameter object.

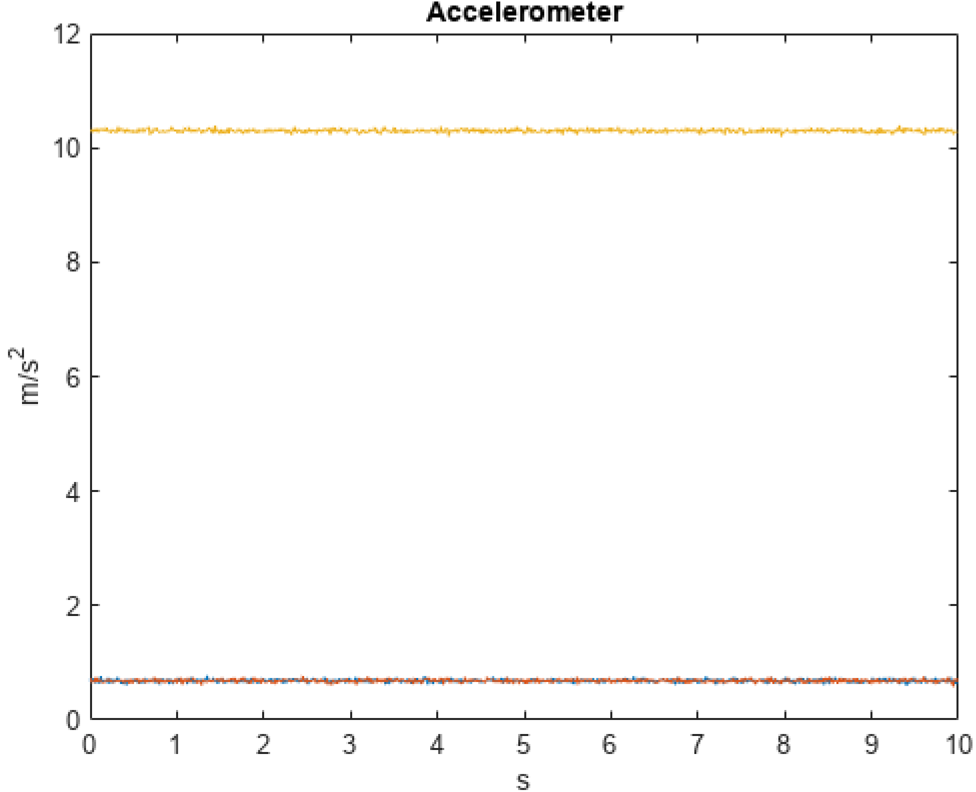
```
Fs = 100;
numSamples = 1000;
t = 0:1/Fs:(numSamples-1)/Fs;

imu = imuSensor('SampleRate', Fs, 'Accelerometer', params);
```

Generate accelerometer data from the imuSensor object.

```
orient = quaternion.ones(numSamples, 1);
acc = zeros(numSamples, 3);
angvel = zeros(numSamples, 3);

accelData = imu(acc, angvel, orient);
```

Plot the resultant accelerometer data.

```
plot(t, accelData)
title('Accelerometer')
xlabel('s')
ylabel('m/s^2')
```




# Version History
**Introduced in R2018b**

## Extended Capabilities

### C/C++ Code Generation
Generate C and C++ code using MATLAB® Coder™.

## See Also
`imuSensor` | `gyroparams` | `magparams`

# ahrs10filter

Height and orientation from MARG and altimeter readings

## Description

The `ahrs10filter` object fuses MARG and altimeter sensor data to estimate device height and orientation. MARG (magnetic, angular rate, gravity) data is typically derived from magnetometer, gyroscope, and accelerometer sensors. The filter uses an 18-element state vector to track the orientation quaternion, vertical velocity, vertical position, MARG sensor biases, and geomagnetic vector. The `ahrs10filter` object uses an extended Kalman filter to estimate these quantities.

## Creation

### Syntax

```
FUSE = ahrs10filter
FUSE = ahrs10filter('ReferenceFrame',RF)
FUSE = ahrs10filter(___,Name,Value)
```

#### Description

`FUSE = ahrs10filter` returns an extended Kalman filter object, `FUSE`, for sensor fusion of MARG and altimeter readings to estimate device height and orientation.

`FUSE = ahrs10filter('ReferenceFrame',RF)` returns an extended Kalman filter object that estimates device height and orientation relative to the reference frame `RF`. Specify RF as `'NED'` (North-East-Down) or `'ENU'` (East-North-Up). The default value is `'NED'`.

`FUSE = ahrs10filter(___,Name,Value)` sets each property `Name` to the specified `Value`. Unspecified properties have default values.

## Properties

**`IMUSampleRate` — Sample rate of the IMU (Hz)**
`100` (default) | positive scalar

Sample rate of the IMU in Hz, specified as a positive scalar.

Data Types: `single` | `double`

**`GyroscopeNoise` — Multiplicative process noise variance from gyroscope ((rad/s)$^2$)**
`[1e-9,1e-9,1e-9]` (default) | scalar | three-element row vector

Multiplicative process noise variance from the gyroscope in (rad/s)$^2$, specified as positive real finite numbers.

Data Types: `single` | `double`

**`AccelerometerNoise` — Multiplicative process noise variance from accelerometer ($(m/s^2)^2$)**
`[1e-4,1e-4,1e-4]` (default) | scalar | three-element row vector

Multiplicative process noise variance from the accelerometer in $(m/s^2)^2$, specified as positive real finite numbers.

Data Types: `single` | `double`

**`GyroscopeBiasNoise` — Multiplicative process noise variance from gyroscope bias ($(rad/s^2)^2$)**
`[1e-10,1e-10,1e-10]` (default) | scalar | three-element row vector

Multiplicative process noise variance from the gyroscope bias in $(rad/s^2)^2$, specified as positive real finite numbers.

Data Types: `single` | `double`

**`AccelerometerBiasNoise` — Multiplicative process noise variance from accelerometer bias ($(m/s^2)^2$)**
`[1e-4,1e-4,1e-4]` (default) | scalar | three-element row vector

Multiplicative process noise variance from the accelerometer bias in $(m/s^2)^2$, specified as positive real finite numbers.

Data Types: `single` | `double`

**`GeomagneticVectorNoise` — Additive process noise for geomagnetic vector ($\mu T^2$)**
`[1e-6,1e-6,1e-6]` (default) | scalar | three-element row vector

Additive process noise for geomagnetic vector in $\mu T^2$, specified as positive real finite numbers.

Data Types: `single` | `double`

**`MagnetometerBiasNoise` — Additive process noise for magnetometer bias ($\mu T^2$)**
`[0.1,0.1,0.1]` (default) | scalar | three-element row vector

Additive process noise for magnetometer bias in $\mu T^2$, specified as positive real finite numbers.

Data Types: `single` | `double`

**`State` — State vector of extended Kalman filter**
18-element column vector

State vector of the extended Kalman filter. The state values represent:

| State | Units | Index |
|---|---|---|
| Orientation (quaternion parts) | N/A | 1:4 |
| Altitude (NED or ENU) | m | 5 |
| Vertical Velocity (NED or ENU) | m/s | 6 |
| Delta Angle Bias (XYZ) | rad/s | 7:9 |
| Delta Velocity Bias (XYZ) | m/s | 10:12 |
| Geomagnetic Field Vector (NED or ENU) | μT | 13:15 |
| Magnetometer Bias (XYZ) | μT | 16:18 |

The default initial state corresponds to an object at rest located at `[0 0 0]` in geodetic LLA coordinates.

Data Types: `single` | `double`

**`StateCovariance` — State error covariance for extended Kalman filter**
`eye(18)*1e-6` (default) | 18-by-18 matrix

State error covariance for the Kalman filter, specified as an 18-by-18-element matrix of real numbers.

Data Types: `single` | `double`

## Object Functions

| | |
|---|---|
| predict | Update states using accelerometer and gyroscope data for ahrs10filter |
| fusemag | Correct states using magnetometer data for ahrs10filter |
| fusealtimeter | Correct states using altimeter data for ahrs10filter |
| correct | Correct states using direct state measurements for ahrs10filter |
| residual | Residuals and residual covariances from direct state measurements for ahrs10filter |
| residualmag | Residuals and residual covariance from magnetometer measurements for ahrs10filter |
| residualaltimeter | Residuals and residual covariance from altimeter measurements for ahrs10filter |
| pose | Current orientation and position estimate for ahrs10filter |
| reset | Reset internal states for ahrs10filter |
| stateinfo | Display state vector information for ahrs10filter |
| tune | Tune ahrs10filter parameters to reduce estimation error |
| copy | Create copy of ahrs10filter |

## Examples

### Estimate Pose of UAV

Load logged sensor data, ground truth pose, and initial state and initial state covariance. Calculate the number of IMU samples per altimeter sample and the number of IMU samples per magnetometer sample.

```
load('fuse10exampledata.mat', ...
     'imuFs','accelData','gyroData', ...
     'magnetometerFs','magData', ...
     'altimeterFs','altData', ...
     'expectedHeight','expectedOrient', ...
     'initstate','initcov');

imuSamplesPerAlt = fix(imuFs/altimeterFs);
imuSamplesPerMag = fix(imuFs/magnetometerFs);
```

Create an AHRS filter that fuses MARG and altimeter readings to estimate height and orientation. Set the sampling rate and measurement noises of the sensors. The values were determined from datasheets and experimentation.

```
filt = ahrs10filter('IMUSampleRate',imuFs, ...
                    'AccelerometerNoise',0.1, ...
                    'State',initstate, ...
                    'StateCovariance',initcov);
```

```
Ralt = 0.24;
Rmag = 0.9;
```

Preallocate variables to log height and orientation.

```
numIMUSamples = size(accelData,1);
estHeight = zeros(numIMUSamples,1);
estOrient = zeros(numIMUSamples,1,'quaternion');
```

Fuse accelerometer, gyroscope, magnetometer and altimeter data. The outer loop predicts the filter forward at the fastest sample rate (the IMU sample rate).

```
for ii = 1:numIMUSamples

    % Use predict to estimate the filter state based on the accelometer and
    % gyroscope data.
    predict(filt,accelData(ii,:),gyroData(ii,:));

    % Magnetometer data is collected at a lower rate than IMU data. Fuse
    % magnetometer data at the lower rate.
    if ~mod(ii,imuSamplesPerMag)
        fusemag(filt,magData(ii,:),Rmag);
    end

    % Altimeter data is collected at a lower rate than IMU data. Fuse
    % altimeter data at the lower rate.
    if ~mod(ii, imuSamplesPerAlt)
        fusealtimeter(filt,altData(ii),Ralt);
    end

    % Log the current height and orientation estimate.
    [estHeight(ii),estOrient(ii)] = pose(filt);
end
```

Calculate the RMS errors between the known true height and orientation and the output from the AHRS filter.

```
pErr = expectedHeight - estHeight;
qErr = rad2deg(dist(expectedOrient,estOrient));

pRMS = sqrt(mean(pErr.^2));
qRMS = sqrt(mean(qErr.^2));

fprintf('Altitude RMS Error\n');
```

```
Altitude RMS Error
```

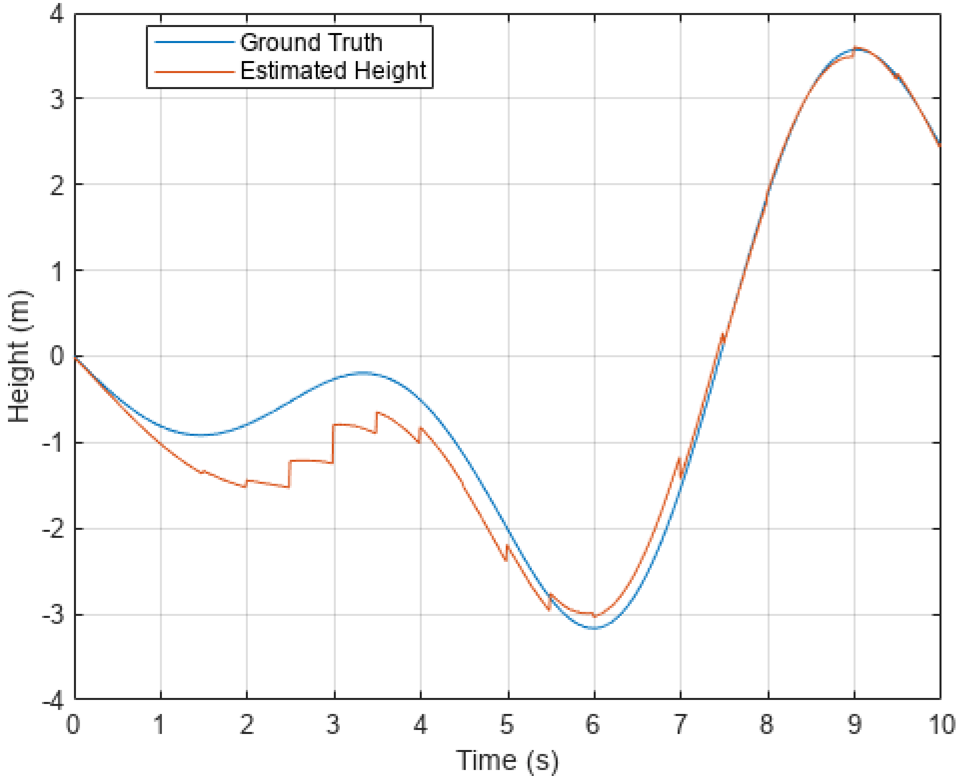
```
fprintf('\t%.2f (meters)\n\n',pRMS);
```

```
    0.38 (meters)
```

Visualize the true and estimated height over time.

```
t = (0:(numIMUSamples-1))/imuFs;
plot(t,expectedHeight);hold on
plot(t,estHeight);hold off
legend('Ground Truth','Estimated Height','location','best')
ylabel('Height (m)')
```

```
xlabel('Time (s)')
grid on
```




```
fprintf('Quaternion Distance RMS Error\n');

Quaternion Distance RMS Error

fprintf('\t%.2f (degrees)\n\n',qRMS);

    2.93 (degrees)
```

# Version History

**Introduced in R2019a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

ahrsfilter | insfilter

# correct

Correct states using direct state measurements for `ahrs10filter`

## Syntax

`correct(FUSE,idx,measurement,measurementCovariance)`

## Description

`correct(FUSE,idx,measurement,measurementCovariance)` corrects the state and state estimation error covariance based on the measurement and measurement covariance. The measurement maps directly to the state specified by the indices `idx`.

## Input Arguments

**`FUSE` — `ahrs10filter` object**
object

Object of `ahrs10filter`.

**`idx` — State vector index of measurement to correct**
*N*-element vector of increasing integers in the range [1,18]

State vector index of measurement to correct, specified as an *N*-element vector of increasing integers in the range [1,18].

The state values represent:

| State | Units | Index |
| --- | --- | --- |
| Orientation (quaternion parts) | N/A | 1:4 |
| Altitude (NED) | m | 5 |
| Vertical Velocity (NED) | m/s | 6 |
| Delta Angle Bias (XYZ) | rad/s | 7:9 |
| Delta Velocity Bias (XYZ) | m/s | 10:12 |
| Geomagnetic Field Vector (NED) | µT | 13:15 |
| Magnetometer Bias (XYZ) | µT | 16:18 |

Data Types: `single` | `double`

**`measurement` — Direct measurement of state**
*N*-element vector

Direct measurement of state, specified as a *N*-element vector. *N* is the number of elements of the index argument, `idx`.

Data Types: `single` | `double`

**`measurementCovariance` — Covariance of measurement**
scalar | *N*-element vector | *N*-by-*N* matrix

Covariance of measurement, specified as a scalar, *N*-element vector, or *N*-by-*N* matrix. *N* is the number of elements of the index argument, `idx`.

Data Types: `single` | `double`

# Version History

**Introduced in R2019a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`ahrs10filter` | `insfilter`

# copy

Create copy of `ahrs10filter`

## Syntax

`newFilter = copy(filter)`

## Description

`newFilter = copy(filter)` returns a copy of the `ahrs10filter`, `filter`, with the exactly same property values.

## Input Arguments

**`filter` — Filter to be copied**
`ahrs10filter`

Filter to be copied, specified as an `ahrs10filter` object.

## Output Arguments

**`newFilter` — New copied filter**
`ahrs10filter`

New copied filter, returned as an `ahrs10filter` object.

# Version History

**Introduced in R2020b**

## See Also

`ahrs10filter`

# fusealtimeter

Correct states using altimeter data for `ahrs10filter`

## Syntax

```
[res,resCov] = fusealtimeter(FUSE,altimeterReadings,
altimeterReadingsCovariance)
```

## Description

`[res,resCov] = fusealtimeter(FUSE,altimeterReadings, altimeterReadingsCovariance)` fuses altimeter data to correct the state estimate.

## Input Arguments

**`FUSE` — `ahrs10filter` object**
object

Object of `ahrs10filter`.

**`altimeterReadings` — Altimeter readings (m)**
real scalar

Altimeter readings in meters, specified as a real scalar.

Data Types: `single` | `double`

**`altimeterReadingsCovariance` — Altimeter readings error covariance ($m^2$)**
real scalar

Altimeter readings error covariance in $m^2$, specified as a real scalar.

Data Types: `single` | `double`

## Output Arguments

**`res` — Measurement residual**
scalar

Measurement residual, returned as a scalar in meters.

**`resCov` — Residual covariance**
nonnegative scalar

Residual covariance, returned as a nonnegative scalar in $m^2$.

# Version History

**Introduced in R2019a**

## Extended Capabilities

### C/C++ Code Generation
Generate C and C++ code using MATLAB® Coder™.

## See Also
`ahrs10filter` | `insfilter`

# fusemag

Correct states using magnetometer data for `ahrs10filter`

## Syntax

`[res,resCov] = fusemag(FUSE,magReadings,magReadingsCovariance)`

## Description

`[res,resCov] = fusemag(FUSE,magReadings,magReadingsCovariance)` fuses magnetometer data to correct the state estimate.

## Input Arguments

**`FUSE` — `ahrs10filter` object**
object

Object of `ahrs10filter`.

**`magReadings` — Magnetometer readings (µT)**
3-element row vector

Magnetometer readings in µT, specified as a 3-element row vector of finite real numbers.

Data Types: `single` | `double`

**`magReadingsCovariance` — Magnetometer readings error covariance (µT$^2$)**
scalar | 3-element row vector | 3-by-3 matrix

Magnetometer readings error covariance in µT$^2$, specified as a scalar, 3-element row vector, or 3-by-3 matrix.

Data Types: `single` | `double`

**`res` — Residual**
1-by-3 vector of real values

Residual, returned as a 1-by-3 vector of real values in µT.

Data Types: `single` | `double`

**`resCov` — Residual covariance**
3-by-3 matrix of real values

Residual covariance, returned a 3-by-3 matrix of real values in (µT)$^2$.

# Version History

**Introduced in R2019a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

`ahrs10filter` | `insfilter`

# pose

Current orientation and position estimate for `ahrs10filter`

## Syntax

```
[position, orientation, velocity] = pose(FUSE)
[position, orientation, velocity] = pose(FUSE,format)
```

## Description

`[position, orientation, velocity] = pose(FUSE)` returns the current estimate of the pose.

`[position, orientation, velocity] = pose(FUSE,format)` returns the current estimate of the pose with orientation in the specified orientation format.

## Input Arguments

**FUSE — `ahrs10filter` object**
object

Object of `ahrs10filter`.

**`format` — Output orientation format**
`'quaternion'` (default) | `'rotmat'`

Output orientation format, specified as either `'quaternion'` for a `quaternion` or `'rotmat'` for a rotation matrix.

Data Types: `char` | `string`

## Output Arguments

**`position` — Position estimate expressed in the local coordinate system (m)**
3-element row vector

Position estimate expressed in the local coordinate system of the filter in meters, returned as a 3-element row vector.

Data Types: `single` | `double`

**`orientation` — Orientation estimate expressed in the local coordinate system**
quaternion (default) | 3-by-3 rotation matrix

Orientation estimate expressed in the local coordinate system of the filter, returned as a scalar quaternion or 3-by-3 rotation matrix. The quaternion or rotation matrix represents a frame rotation from the local reference frame of the filter to the body reference frame.

Data Types: `single` | `double` | `quaternion`

**`velocity` — Velocity estimate expressed in local coordinate system (m/s)**
3-element row vector

Velocity estimate expressed in the local coordinate system of the filter in m/s, returned as a 3-element row vector.

Data Types: `single` | `double`

# Version History

**Introduced in R2019a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`ahrs10filter` | `insfilter`

# predict

Update states using accelerometer and gyroscope data for `ahrs10filter`

## Syntax

`predict(FUSE,accelReadings,gyroReadings)`

## Description

`predict(FUSE,accelReadings,gyroReadings)` fuses accelerometer and gyroscope data to update the state estimate.

## Input Arguments

**FUSE — `ahrs10Filter` object**
object

Object of `ahrs10filter`.

**`accelReadings` — Accelerometer readings in the sensor body coordinate system (m/s$^2$)**
*N*-by-3 matrix

Accelerometer readings in local sensor body coordinate system in m/s$^2$, specified as an *N*-by-3 matrix. *N* is the number of samples, and the three columns of `accelReadings` represent the [*x y z*] measurements. Accelerometer readings are assumed to correspond to the sample rate specified by the `IMUSampleRate` property.

Data Types: `single` | `double`

**`gyroReadings` — Gyroscope readings in the sensor body coordinate system (rad/s)**
*N*-by-3 matrix

Gyroscope readings in the sensor body coordinate system in rad/s, specified as an *N*-by-3 matrix. *N* is the number of samples, and the three columns of `gyroReadings` represent the [*x y z*] measurements. Gyroscope readings are assumed to correspond to the sample rate specified by the `IMUSampleRate` property.

Data Types: `single` | `double`

# Version History

**Introduced in R2019a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

`ahrs10filter` | `insfilter`

# reset

Reset internal states for `ahrs10filter`

## Syntax

`reset(FUSE)`

## Description

`reset(FUSE)` resets the `State`, `StateCovariance`, and internal integrators to their default values.

## Input Arguments

**FUSE — `ahrs10filter` object**
object

Object of `ahrs10filter`.

# Version History

**Introduced in R2019a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

`ahrs10filter` | `insfilter`

# residual

Residuals and residual covariances from direct state measurements for `ahrs10filter`

## Syntax

```
[res, resCov]= residual(FUSE,idx,measurement,measurementCovariance)
```

## Description

`[res, resCov]= residual(FUSE,idx,measurement,measurementCovariance)` computes the residual, `res`, and the residual covariance, `resCov`, based on the direct state measurement and measurement covariance. The `measurement` maps directly to the states specified by indices, `idx`.

## Input Arguments

**`FUSE` — `ahrs10filter`**
`ahrs10filter` | object

`ahrs10filter`, specified as an object.

**`idx` — State vector index of measurement to correct**
*N*-element vector of increasing integers in the range [1,18]

State vector index of measurement to correct, specified as an *N*-element vector of increasing integers in the range [1,18].

The state values represent:

| State | Units | Index |
| --- | --- | --- |
| Orientation (quaternion parts) | N/A | 1:4 |
| Altitude (NED) | m | 5 |
| Vertical Velocity (NED) | m/s | 6 |
| Delta Angle Bias (XYZ) | rad/s | 7:9 |
| Delta Velocity Bias (XYZ) | m/s | 10:12 |
| Geomagnetic Field Vector (NED) | µT | 13:15 |
| Magnetometer Bias (XYZ) | µT | 16:18 |

**`measurement` — Direct measurement of state**
*N*-element vector

Direct measurement of state, specified as a *N*-element vector. *N* is the number of elements of the index argument, `idx`.

**`measurementCovariance` — Covariance of measurement**
*N*-by-*N* matrix

Covariance of measurement, specified as an *N*-by-*N* matrix. *N* is the number of elements of the index argument, `idx`.

## Output Arguments

**`res` — Measurement residual**
1-by-*N* vector of real values

Measurement residual, returned as a 1-by-*N* vector of real values.

**`resCov` — Residual covariance**
*N*-by-*N* matrix of real values

Residual covariance, returned as a *N*-by-*N* matrix of real values.

# Version History

**Introduced in R2020a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

`ahrs10filter`

# residualaltimeter

Residuals and residual covariance from altimeter measurements for `ahrs10filter`

## Syntax

```
[res,resCov] = residualaltimeter(FUSE,altimeterReadings,
altimeterReadingsCovariance)
```

## Description

`[res,resCov] = residualaltimeter(FUSE,altimeterReadings, altimeterReadingsCovariance)` computes the residual, `res`, and the innovation covariance, `resCov`, based on the magnetometer readings and the corresponding covariance.

## Input Arguments

**`FUSE` — `ahrs10filter`**
`ahrs10filter` | object

`ahrs10filter`, specified as an object.

**`altimeterReadings` — Altimeter readings (m)**
real scalar

Altimeter readings in meters, specified as a real scalar.

Data Types: `single` | `double`

**`altimeterReadingsCovariance` — Altimeter readings error covariance (m$^2$)**
real scalar

Altimeter readings error covariance in m$^2$, specified as a real scalar.

Data Types: `single` | `double`

## Output Arguments

**`res` — Measurement residual**
scalar

Measurement residual, returned as a scalar in meters.

**`resCov` — Residual covariance**
nonnegative scalar

Residual covariance, returned as a nonnegative scalar in $m^2$.

# Version History

**Introduced in R2020a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

`ahrs10filter` | `insfilter`

# residualmag

Residuals and residual covariance from magnetometer measurements for `ahrs10filter`

## Syntax

```
[res,resCov] = residualmag(FUSE,magReadings,magReadingsCovariance)
```

## Description

`[res,resCov] = residualmag(FUSE,magReadings,magReadingsCovariance)` computes the residual, `residual`, and the residual covariance, `resCov`, based on the magnetometer readings and the corresponding covariance.

## Input Arguments

**FUSE — `ahrs10filter`**
`ahrs10filter` | object

`ahrs10filter`, specified as an object.

**`magReadings` — Magnetometer readings (µT)**
3-element row vector

Magnetometer readings in µT, specified as a 3-element row vector of finite real numbers.

Data Types: `single` | `double`

**`magReadingsCovariance` — Magnetometer readings error covariance ($\mu T^2$)**
scalar | 3-element row vector | 3-by-3 matrix

Magnetometer readings error covariance in $\mu T^2$, specified as a scalar, 3-element row vector, or 3-by-3 matrix.

Data Types: `single` | `double`

## Output Arguments

**`res` — Residual**
1-by-3 vector of real values

Residual, returned as a 1-by-3 vector of real values in µT.

Data Types: `single` | `double`

**`resCov` — Residual covariance**
3-by-3 matrix of real values

Residual covariance, returned a 3-by-3 matrix of real values in $(\mu T)^2$.

# Version History

**Introduced in R2020a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`ahrs10filter`

# stateinfo

Display state vector information for `ahrs10filter`

## Syntax

```
stateinfo(FUSE)
info = stateinfo(FUSE)
```

## Description

`stateinfo(FUSE)` displays the meaning of each index of the `State` property and the associated units.

`info = stateinfo(FUSE)` returns a structure with fields containing descriptions of the elements of the state vector of the filter, `FUSE`.

## Examples

### State information of ahrs10filter

Create an `ahrs10filter` object.

```
filter = ahrs10filter;
```

Display the state information of the created filter.

```
stateinfo(filter)
```

```
States                            Units    Index
Orientation (quaternion parts)             1:4
Altitude (NAV)                    m        5
Vertical Velocity (NAV)           m/s      6
Delta Angle Bias (XYZ)            rad      7:9
Delta Velocity Bias (XYZ)         m/s      10:12
Geomagnetic Field Vector (NAV)    μT       13:15
Magnetometer Bias (XYZ)           μT       16:18
```

Output the state information of the filter as a structure.

```
info = stateinfo(filter)
```

```
info = struct with fields:
               Orientation: [1 2 3 4]
                  Altitude: 5
          VerticalVelocity: 6
            DeltaAngleBias: [7 8 9]
         DeltaVelocityBias: [10 11 12]
    GeomagneticFieldVector: [13 14 15]
          MagnetometerBias: [16 17 18]
```

## Input Arguments

**`FUSE` — `ahrs10filter` object**
object

Object of `ahrs10filter`.

## Output Arguments

**`info` — State information**
structure

State information, returned as a structure. The field names of the structure are names of the elements of the state vector in the filter. The values of each field are the corresponding indices of the state vector.

# Version History

**Introduced in R2019a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

`ahrs10filter` | `insfilter`

# tune

Tune `ahrs10filter` parameters to reduce estimation error

## Syntax

```
tunedMeasureNoise = tune(filter,measureNoise,sensorData,groundTruth)
tunedMeasureNoise = tune( ___ ,config)
```

## Description

`tunedMeasureNoise = tune(filter,measureNoise,sensorData,groundTruth)` adjusts the properties of the `ahrs10filter` filter object, `filter`, and measurement noises to reduce the root-mean-squared (RMS) state estimation error between the fused sensor data and the ground truth. The function also returns the tuned measurement noise, `tunedMeasureNoise`. The function uses the property values in the filter and the measurement noise provided in the `measureNoise` structure as the initial estimate for the optimization algorithm.

`tunedMeasureNoise = tune( ___ ,config)` specifies the tuning configuration based on a `tunerconfig` object, `config`.

## Examples

### Tune ahrs10filter to Optimize Pose Estimate

Load the recorded sensor data and ground truth data.

```
load('ahrs10filterTuneData.mat');
```

Create tables for the sensor data and the truth data.

```
sensorData = table(Accelerometer,Gyroscope,...
    Magnetometer,Altimeter);
groundTruth = table(Orientation, Altitude);
```

Create an `ahrs10filter` filter object.

```
filter = ahrs10filter('State', initialState, ...
    'StateCovariance', initialStateCovariance);
```

Create a tuner configuration object for the filter. Set the maximum iterations to ten and set the objective limit to 0.001.

```
cfg = tunerconfig('ahrs10filter','MaxIterations',10,...
          'ObjectiveLimit',1e-3);
```

Use the tuner noise function to obtain a set of initial sensor noises used in the filter.

```
measNoise = tunernoise('ahrs10filter')
```

```
measNoise = struct with fields:
    MagnetometerNoise: 1
```

```
    AltimeterNoise: 1
```

Tune the filter and obtain the tuned parameters.

```
tunedNoise = tune(filter, measNoise, sensorData, ...
    groundTruth, cfg);

    Iteration    Parameter                 Metric
    _________    _________                 ______
    1            AccelerometerNoise        0.0526
    1            GyroscopeNoise            0.0526
    1            MagnetometerNoise         0.0523
    1            AltimeterNoise            0.0515
    1            AccelerometerBiasNoise    0.0510
    1            GyroscopeBiasNoise        0.0510
    1            GeomagneticVectorNoise    0.0510
    1            MagnetometerBiasNoise     0.0508
    2            AccelerometerNoise        0.0508
    2            GyroscopeNoise            0.0508
    2            MagnetometerNoise         0.0504
    2            AltimeterNoise            0.0494
    2            AccelerometerBiasNoise    0.0490
    2            GyroscopeBiasNoise        0.0490
    2            GeomagneticVectorNoise    0.0490
    2            MagnetometerBiasNoise     0.0487
    3            AccelerometerNoise        0.0487
    3            GyroscopeNoise            0.0487
    3            MagnetometerNoise         0.0482
    3            AltimeterNoise            0.0472
    3            AccelerometerBiasNoise    0.0467
    3            GyroscopeBiasNoise        0.0467
    3            GeomagneticVectorNoise    0.0467
    3            MagnetometerBiasNoise     0.0463
    4            AccelerometerNoise        0.0463
    4            GyroscopeNoise            0.0463
    4            MagnetometerNoise         0.0456
    4            AltimeterNoise            0.0446
    4            AccelerometerBiasNoise    0.0442
    4            GyroscopeBiasNoise        0.0442
    4            GeomagneticVectorNoise    0.0442
    4            MagnetometerBiasNoise     0.0437
    5            AccelerometerNoise        0.0437
    5            GyroscopeNoise            0.0437
    5            MagnetometerNoise         0.0428
    5            AltimeterNoise            0.0417
    5            AccelerometerBiasNoise    0.0413
    5            GyroscopeBiasNoise        0.0413
    5            GeomagneticVectorNoise    0.0413
    5            MagnetometerBiasNoise     0.0408
    6            AccelerometerNoise        0.0408
    6            GyroscopeNoise            0.0408
    6            MagnetometerNoise         0.0397
    6            AltimeterNoise            0.0385
    6            AccelerometerBiasNoise    0.0381
    6            GyroscopeBiasNoise        0.0381
    6            GeomagneticVectorNoise    0.0381
    6            MagnetometerBiasNoise     0.0375
```

```
    7           AccelerometerNoise        0.0375
    7           GyroscopeNoise            0.0375
    7           MagnetometerNoise         0.0363
    7           AltimeterNoise            0.0351
    7           AccelerometerBiasNoise    0.0347
    7           GyroscopeBiasNoise        0.0347
    7           GeomagneticVectorNoise    0.0347
    7           MagnetometerBiasNoise     0.0342
    8           AccelerometerNoise        0.0342
    8           GyroscopeNoise            0.0342
    8           MagnetometerNoise         0.0331
    8           AltimeterNoise            0.0319
    8           AccelerometerBiasNoise    0.0316
    8           GyroscopeBiasNoise        0.0316
    8           GeomagneticVectorNoise    0.0316
    8           MagnetometerBiasNoise     0.0313
    9           AccelerometerNoise        0.0313
    9           GyroscopeNoise            0.0313
    9           MagnetometerNoise         0.0313
    9           AltimeterNoise            0.0301
    9           AccelerometerBiasNoise    0.0298
    9           GyroscopeBiasNoise        0.0298
    9           GeomagneticVectorNoise    0.0298
    9           MagnetometerBiasNoise     0.0296
    10          AccelerometerNoise        0.0296
    10          GyroscopeNoise            0.0296
    10          MagnetometerNoise         0.0296
    10          AltimeterNoise            0.0285
    10          AccelerometerBiasNoise    0.0283
    10          GyroscopeBiasNoise        0.0283
    10          GeomagneticVectorNoise    0.0283
    10          MagnetometerBiasNoise     0.0282
```

Fuse the sensor data using the tuned filter.

```
N = size(sensorData,1);
qEstTuned = quaternion.zeros(N,1);
altEstTuned = zeros(N,1);
for ii=1:N
    predict(filter,Accelerometer(ii,:),Gyroscope(ii,:));
    if all(~isnan(Magnetometer(ii,1)))
        fusemag(filter, Magnetometer(ii,:),tunedNoise.MagnetometerNoise);
    end
    if ~isnan(Altimeter(ii))
        fusealtimeter(filter, Altimeter(ii),tunedNoise.AltimeterNoise);
    end
    [altEstTuned(ii), qEstTuned(ii)] = pose(filter);
end
```

Compute the RMS errors.

```
orientationErrorTuned = rad2deg(dist(qEstTuned, Orientation));
rmsOrientationErrorTuned = sqrt(mean(orientationErrorTuned.^2))
```

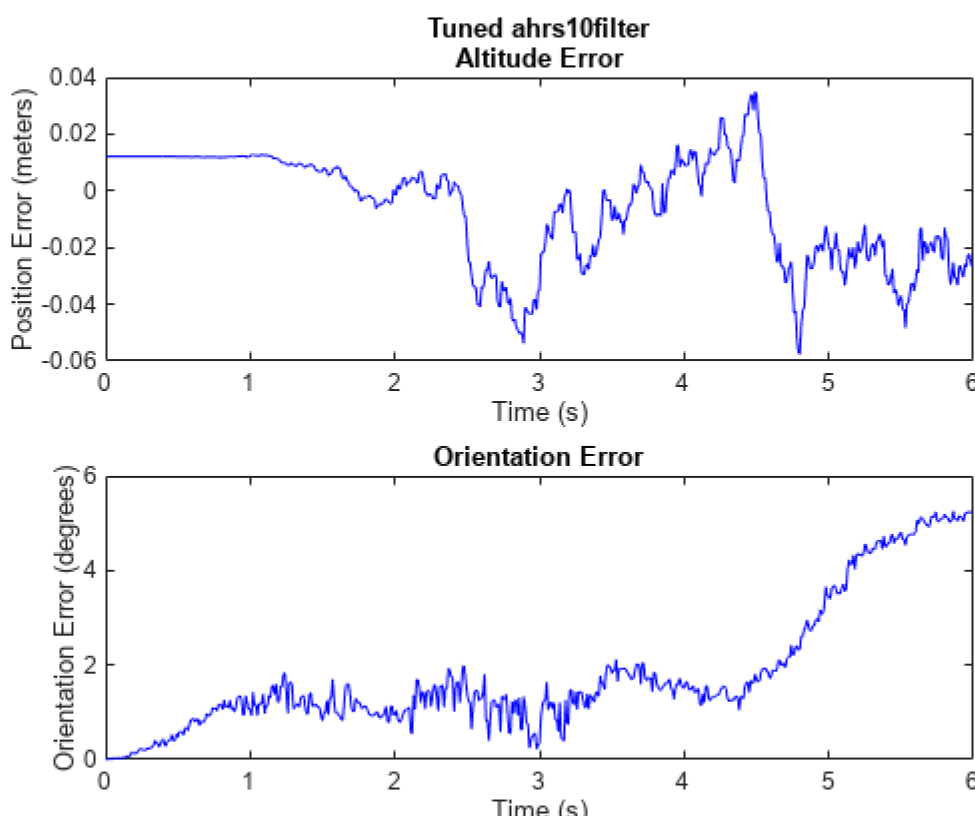
```
rmsOrientationErrorTuned = 2.2899
```

```
positionErrorTuned = altEstTuned - Altitude;
rmsPositionErrorTuned = sqrt(mean( positionErrorTuned.^2))
```

```
rmsPositionErrorTuned = 0.0199
```

Visualize the results.

```
figure;
t = (0:N-1)./ filter.IMUSampleRate;
subplot(2,1,1)
plot(t, positionErrorTuned, 'b');
title("Tuned ahrs10filter" + newline + ...
    "Altitude Error")
xlabel('Time (s)');
ylabel('Position Error (meters)')
subplot(2,1,2)
plot(t, orientationErrorTuned, 'b');
title("Orientation Error")
xlabel('Time (s)');
ylabel('Orientation Error (degrees)');
```




## Input Arguments

**filter — Filter object**
ahrs10filter object

Filter object, specified as an `ahrs10filter` object.

**measureNoise — Measurement noise**
structure

Measurement noise, specified as a structure. The function uses the measurement noise input as the initial guess for tuning the measurement noise. The structure must contain these fields:

| Field name | Description |
| --- | --- |
| MagnetometerNoise | Variance of magnetometer noise, specified as a scalar in $(\mu T)^2$ |
| AltimeterNoise | Variance of altimeter noise, specified as a scalar in $m^2$ |

**sensorData — Sensor data**
table

Sensor data, specified as a table. In each row, the sensor data is specified as:

- Accelerometer — Accelerometer data, specified as a 1-by-3 vector of scalars in $m^2/s$.
- Gyroscope— Gyroscope data, specified as a 1-by-3 vector of scalars in rad/s.
- Magnetometer — Magnetometer data, specified as a 1-by-3 vector of scalars in μT.
- Altimeter — Altimeter data, specified as a scalar in meters.

If the magnetometer does not produce measurements, specify the corresponding entry as NaN. If you set the Cost property of the tuner configuration input, config, to Custom, then you can use other data types for the sensorData input based on your choice.

**groundTruth — Ground truth data**
table

Ground truth data, specified as a table. In each row, the table can optionally contain any of these variables:

- Orientation — Orientation from the navigation frame to the body frame, specified as a quaternion or a 3-by-3 rotation matrix.
- Altitude — Altitude, specified as a scalar in meters.
- VertialVelocity — Velocity in the vertical direction, specified as a scalar in m/s.
- DeltaAngleBias — Delta angle bias, specified as a 1-by-3 vector of scalars in radians.
- DeltaVelocityBias — Delta velocity bias, specified as a 1-by-3 vector of scalars in m/s.
- GeomagneticFieldVector — Geomagnetic field vector in navigation frame, specified as a 1-by-3 vector of scalars.
- MagnetometerBias — Magnetometer bias in body frame, specified as a 1-by-3 vector of scalars in μT.

The function processes each row of the sensorData and groundTruth tables sequentially to calculate the state estimate and RMS error from the ground truth. State variables not present in groundTruth input are ignored for the comparison. The sensorData and the groundTruth tables must have the same number of rows.

If you set the Cost property of the tuner configuration input, config, to Custom, then you can use other data types for the groundTruth input based on your choice.

**config — Tuner configuration**
tunerconfig object

Tuner configuration, specified as a tunerconfig object.

## Output Arguments

**tunedMeasureNoise — Tuned measurement noise**
structure

Tuned measurement noise, returned as a structure. The structure contains these fields.

| Field name | Description |
| --- | --- |
| MagnetometerNoise | Variance of magnetometer noise, specified as a scalar in $(\mu T)^2$ |
| AltimeterNoise | Variance of altimeter noise, specified as a scalar in $m^2$ |

# Version History

**Introduced in R2021a**

## References

[1] Abbeel, P., Coates, A., Montemerlo, M., Ng, A.Y. and Thrun, S. Discriminative Training of Kalman Filters. In *Robotics: Science and systems*, Vol. 2, pp. 1, 2005.

## See Also

tunerconfig | tunernoise

# ahrsfilter

Orientation from accelerometer, gyroscope, and magnetometer readings

## Description

The `ahrsfilter` System object™ fuses accelerometer, magnetometer, and gyroscope sensor data to estimate device orientation.

To estimate device orientation:

1. Create the `ahrsfilter` object and set its properties.
2. Call the object with arguments, as if it were a function.

To learn more about how System objects work, see What Are System Objects?

# Creation

## Syntax

```
FUSE = ahrsfilter
FUSE = ahrsfilter('ReferenceFrame',RF)
FUSE = ahrsfilter(___,Name,Value)
```

### Description

`FUSE = ahrsfilter` returns an indirect Kalman filter System object, `FUSE`, for sensor fusion of accelerometer, gyroscope, and magnetometer data to estimate device orientation and angular velocity. The filter uses a 12-element state vector to track the estimation error for the orientation, the gyroscope bias, the linear acceleration, and the magnetic disturbance.

`FUSE = ahrsfilter('ReferenceFrame',RF)` returns an ahrsfilter System object that fuses accelerometer, gyroscope, and magnetometer data to estimate device orientation relative to the reference frame `RF`. Specify `RF` as `'NED'` (North-East-Down) or `'ENU'` (East-North-Up). The default value is 'NED'.

`FUSE = ahrsfilter(___,Name,Value)` sets each property `Name` to the specified `Value`. Unspecified properties have default values.

## Properties

Unless otherwise indicated, properties are *nontunable*, which means you cannot change their values after calling the object. Objects lock when you call them, and the `release` function unlocks them.

If a property is *tunable*, you can change its value at any time.

For more information on changing property values, see System Design in MATLAB Using System Objects.

**`SampleRate` — Input sample rate of sensor data (Hz)**
`100` (default) | positive scalar

Input sample rate of the sensor data in Hz, specified as a positive scalar.

**Tunable:** No

Data Types: `single` | `double`

**`DecimationFactor` — Decimation factor**
`1` (default) | positive integer

Decimation factor by which to reduce the input sensor data rate as part of the fusion algorithm, specified as a positive integer.

The number of rows of the inputs –– `accelReadings`, `gyroReadings`, and `magReadings` –– must be a multiple of the decimation factor.

Data Types: `single` | `double`

**`AccelerometerNoise` — Variance of accelerometer signal noise ($(m/s^2)^2$)**
`0.00019247` (default) | positive real scalar

Variance of accelerometer signal noise in $(m/s^2)^2$, specified as a positive real scalar.

**Tunable:** Yes

Data Types: `single` | `double`

**`MagnetometerNoise` — Variance of magnetometer signal noise ($\mu T^2$)**
`0.1` (default) | positive real scalar

Variance of magnetometer signal noise in $\mu T^2$, specified as a positive real scalar.

**Tunable:** Yes

Data Types: `single` | `double`

**`GyroscopeNoise` — Variance of gyroscope signal noise ($(rad/s)^2$)**
`9.1385e-5` (default) | positive real scalar

Variance of gyroscope signal noise in $(rad/s)^2$, specified as a positive real scalar.

**Tunable:** Yes

Data Types: `single` | `double`

**`GyroscopeDriftNoise` — Variance of gyroscope offset drift ($(rad/s)^2$)**
`3.0462e-13` (default) | positive real scalar

Variance of gyroscope offset drift in $(rad/s)^2$, specified as a positive real scalar.

**Tunable:** Yes

Data Types: `single` | `double`

**`LinearAccelerationNoise` — Variance of linear acceleration noise $(m/s^2)^2$**
`0.0096236` (default) | positive real scalar

Variance of linear acceleration noise in $(m/s^2)^2$, specified as a positive real scalar. Linear acceleration is modeled as a lowpass-filtered white noise process.

**Tunable:** Yes

Data Types: `single` | `double`

### `LinearAccelerationDecayFactor` — Decay factor for linear acceleration drift

`0.5` (default) | scalar in the range [0,1)

Decay factor for linear acceleration drift, specified as a scalar in the range [0,1). If linear acceleration is changing quickly, set `LinearAcclerationDecayFactor` to a lower value. If linear acceleration changes slowly, set `LinearAcclerationDecayFactor` to a higher value. Linear acceleration drift is modeled as a lowpass-filtered white noise process.

**Tunable:** Yes

Data Types: `single` | `double`

### `MagneticDisturbanceNoise` — Variance of magnetic disturbance noise ($\mu T^2$)

`0.5` (default) | real finite positive scalar

Variance of magnetic disturbance noise in $\mu T^2$, specified as a real finite positive scalar.

**Tunable:** Yes

Data Types: `single` | `double`

### `MagneticDisturbanceDecayFactor` — Decay factor for magnetic disturbance

`0.5` (default) | positive scalar in the range [0,1]

Decay factor for magnetic disturbance, specified as a positive scalar in the range [0,1]. Magnetic disturbance is modeled as a first order Markov process.

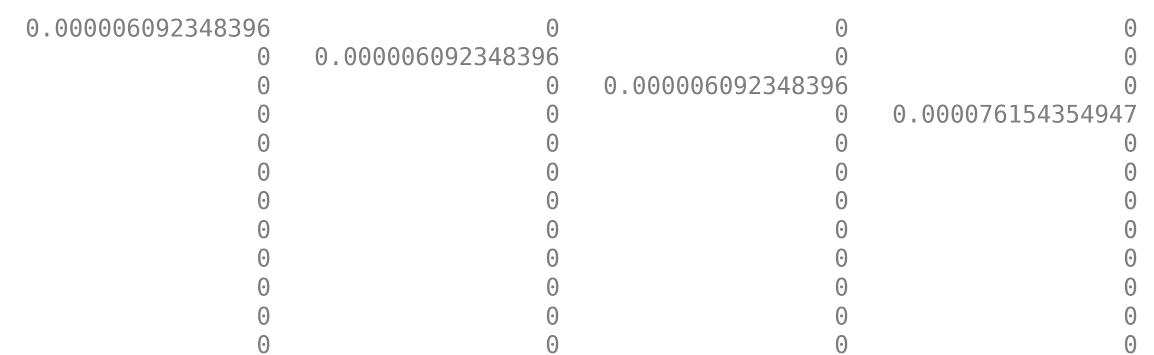
**Tunable:** Yes

Data Types: `single` | `double`

### `InitialProcessNoise` — Covariance matrix for process noise

12-by-12 matrix

Covariance matrix for process noise, specified as a 12-by-12 matrix. The default is:



```
  Columns 1 through 6

  0.000006092348396                  0                  0                  0
                  0  0.000006092348396                  0                  0
                  0                  0  0.000006092348396                  0
                  0                  0                  0  0.000076154354947
                  0                  0                  0                  0  0.00007615435
                  0                  0                  0                  0
                  0                  0                  0                  0
                  0                  0                  0                  0
                  0                  0                  0                  0
                  0                  0                  0                  0
                  0                  0                  0                  0
                  0                  0                  0                  0
```

```
  Columns 7 through 12

                 0                  0                  0                  0
                 0                  0                  0                  0
                 0                  0                  0                  0
                 0                  0                  0                  0
                 0                  0                  0                  0
                 0                  0                  0                  0
 0.009623610000000                  0                  0                  0
                 0  0.009623610000000                  0                  0
                 0                  0  0.009623610000000                  0
                 0                  0                  0  0.600000000000000
                 0                  0                  0                  0  0.60000000000
                 0                  0                  0                  0
```

The initial process covariance matrix accounts for the error in the process model.

Data Types: `single` | `double`

**`ExpectedMagneticFieldStrength` — Expected estimate of magnetic field strength (µT)**
`50` (default) | real positive scalar

Expected estimate of magnetic field strength in µT, specified as a real positive scalar. The expected magnetic field strength is an estimate of the magnetic field strength of the Earth at the current location.

**Tunable:** Yes

Data Types: `single` | `double`

**`OrientationFormat` — Output orientation format**
`'quaternion'` (default) | `'Rotation matrix'`

Output orientation format, specified as `'quaternion'` or `'Rotation matrix'`. The size of the output depends on the input size, *N*, and the output orientation format:

- `'quaternion'` -– Output is an *N*-by-1 `quaternion`.
- `'Rotation matrix'` -– Output is a 3-by-3-by-*N* rotation matrix.

Data Types: `char` | `string`

## Usage

## Syntax

`[orientation,angularVelocity] = FUSE(accelReadings,gyroReadings,magReadings)`

### Description

`[orientation,angularVelocity] = FUSE(accelReadings,gyroReadings,magReadings)` fuses accelerometer, gyroscope, and magnetometer data to compute orientation and angular velocity measurements. The algorithm assumes that the device is stationary before the first call.

### Input Arguments

**`accelReadings` — Accelerometer readings in sensor body coordinate system (m/s²)**
*N*-by-3 matrix

Accelerometer readings in the sensor body coordinate system in m/s$^2$, specified as an *N*-by-3 matrix. *N* is the number of samples, and the three columns of `accelReadings` represent the [*x y z*] measurements. Accelerometer readings are assumed to correspond to the sample rate specified by the SampleRate property.

Data Types: `single` | `double`

**`gyroReadings` — Gyroscope readings in sensor body coordinate system (rad/s)**
*N*-by-3 matrix

Gyroscope readings in the sensor body coordinate system in rad/s, specified as an *N*-by-3 matrix. *N* is the number of samples, and the three columns of `gyroReadings` represent the [*x y z*] measurements. Gyroscope readings are assumed to correspond to the sample rate specified by the SampleRate property.

Data Types: `single` | `double`

**`magReadings` — Magnetometer readings in sensor body coordinate system (µT)**
*N*-by-3 matrix

Magnetometer readings in the sensor body coordinate system in µT, specified as an *N*-by-3 matrix. *N* is the number of samples, and the three columns of `magReadings` represent the [*x y z*] measurements. Magnetometer readings are assumed to correspond to the sample rate specified by the SampleRate property.

Data Types: `single` | `double`

### Output Arguments

**`orientation` — Orientation that rotates quantities from local navigation coordinate system to sensor body coordinate system**
*M*-by-1 array of quaternions (default) | 3-by-3-by-*M* array

Orientation that can rotate quantities from the local navigation coordinate system to a body coordinate system, returned as quaternions or an array. The size and type of `orientation` depends on whether the OrienationFormat property is set to `'quaternion'` or `'Rotation matrix'`:

- `'quaternion'` –– the output is an *M*-by-1 vector of quaternions, with the same underlying data type as the inputs
- `'Rotation matrix'` –– the output is a 3-by-3-by-*M* array of rotation matrices the same data type as the inputs

The number of input samples, *N*, and the DecimationFactor property determine *M*.

You can use `orientation` in a `rotateframe` function to rotate quantities from a local navigation system to a sensor body coordinate system.

Data Types: `quaternion` | `single` | `double`

**`angularVelocity` — Angular velocity in sensor body coordinate system (rad/s)**
*M*-by-3 array (default)

Angular velocity with gyroscope bias removed in the sensor body coordinate system in rad/s, returned as an *M*-by-3 array. The number of input samples, *N*, and the `DecimationFactor` property determine *M*.

Data Types: `single` | `double`

## Object Functions

To use an object function, specify the System object as the first input argument. For example, to release system resources of a System object named `obj`, use this syntax:

```
release(obj)
```

### Specific to `ahrsfilter`

tune Tune ahrsfilter parameters to reduce estimation error

### Common to All System Objects

step Run System object algorithm
release Release resources and allow changes to System object property values and input characteristics
reset Reset internal states of System object

## Examples

### Estimate Orientation Using `ahrsfilter`

Load the `rpy_9axis` file, which contains recorded accelerometer, gyroscope, and magnetometer sensor data from a device oscillating in pitch (around *y*-axis), then yaw (around *z*-axis), and then roll (around *x*-axis). The file also contains the sample rate of the recording.

```
load 'rpy_9axis' sensorData Fs
accelerometerReadings = sensorData.Acceleration;
gyroscopeReadings = sensorData.AngularVelocity;
magnetometerReadings = sensorData.MagneticField;
```

Create an `ahrsfilter` System object™ with `SampleRate` set to the sample rate of the sensor data. Specify a decimation factor of two to reduce the computational cost of the algorithm.

```
decim = 2;
fuse = ahrsfilter('SampleRate',Fs,'DecimationFactor',decim);
```

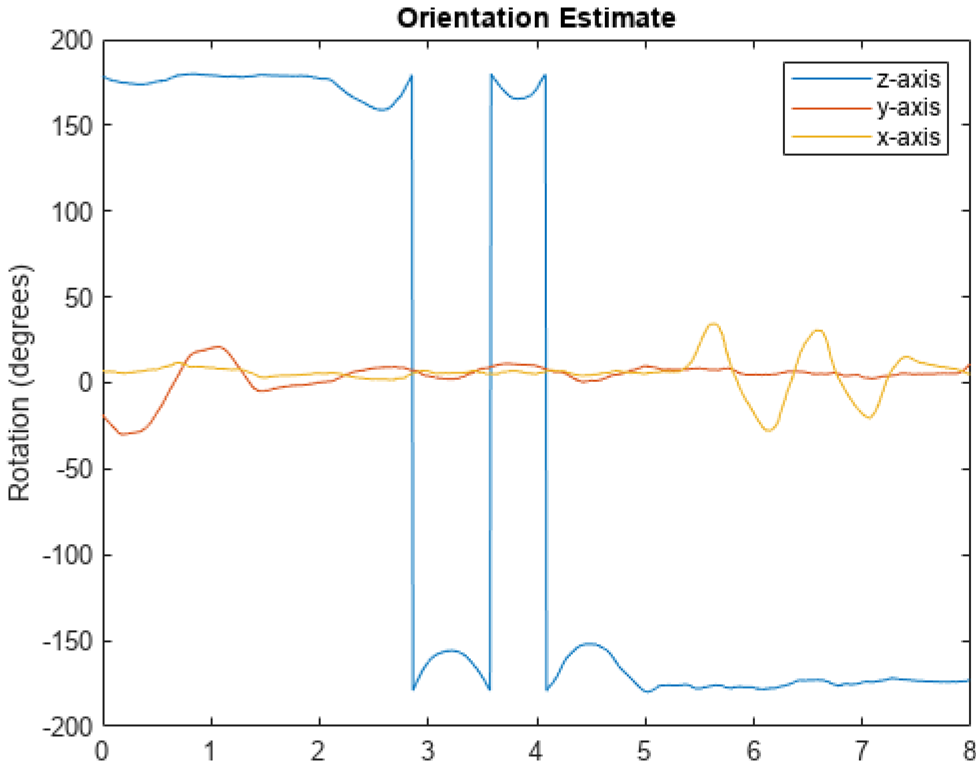
Pass the accelerometer readings, gyroscope readings, and magnetometer readings to the `ahrsfilter` object, `fuse`, to output an estimate of the sensor body orientation over time. By default, the orientation is output as a vector of quaternions.

```
q = fuse(accelerometerReadings,gyroscopeReadings,magnetometerReadings);
```

Orientation is defined by angular displacement required to rotate a parent coordinate system to a child coordinate system. Plot the orientation in Euler angles in degrees over time.

`ahrsfilter` correctly estimates the change in orientation over time, including the south-facing initial orientation.

```
time = (0:decim:size(accelerometerReadings,1)-1)/Fs;

plot(time,eulerd(q,'ZYX','frame'))
title('Orientation Estimate')
legend('z-axis', 'y-axis', 'x-axis')
ylabel('Rotation (degrees)')
```




### Simulate Magnetic Jamming on `ahrsFilter`

This example shows how performance of the `ahrsfilter` System object™ is affected by magnetic jamming.

Load `StationaryIMUReadings`, which contains accelerometer, magnetometer, and gyroscope readings from a stationary IMU.

```
load 'StationaryIMUReadings.mat' accelReadings magReadings gyroReadings SampleRate

numSamples = size(accelReadings,1);
```

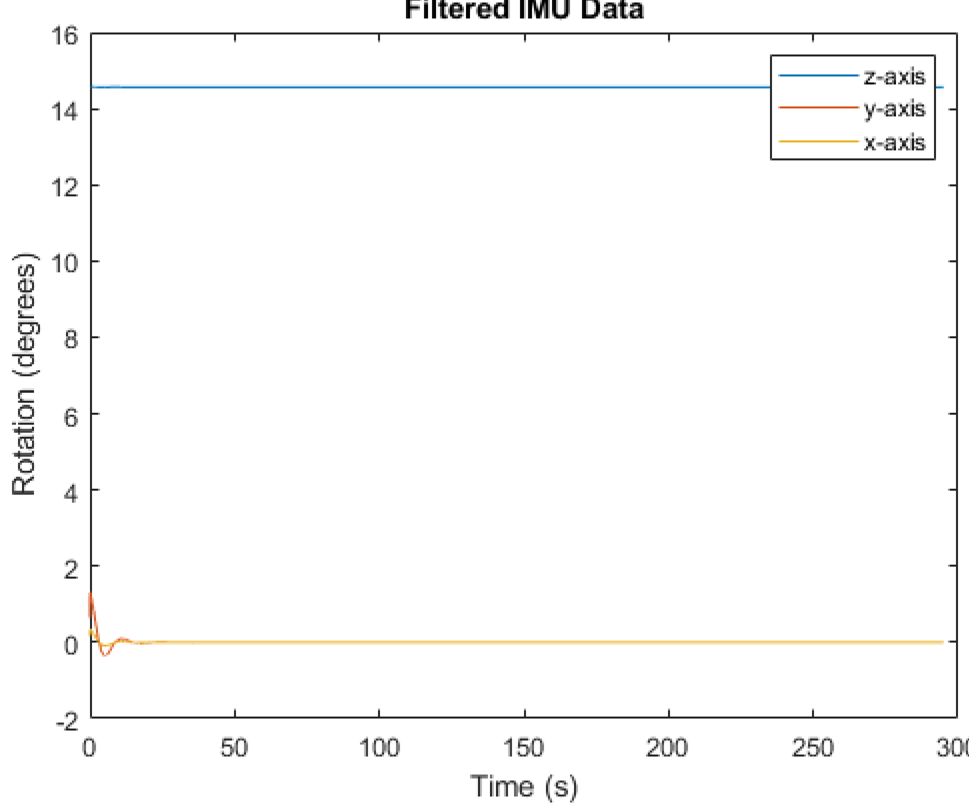
The `ahrsfilter` uses magnetic field strength to stabilize its orientation against the assumed constant magnetic field of the Earth. However, there are many natural and man-made objects which output magnetic fields and can confuse the algorithm. To account for the presence of transient magnetic fields, you can set the `MagneticDisturbanceNoise` property on the `ahrsfilter` object.

Create an `ahrsfilter` object with the decimation factor set to 2 and note the default expected magnetic field strength.

```
decim = 2;
FUSE = ahrsfilter('SampleRate',SampleRate,'DecimationFactor',decim);
```

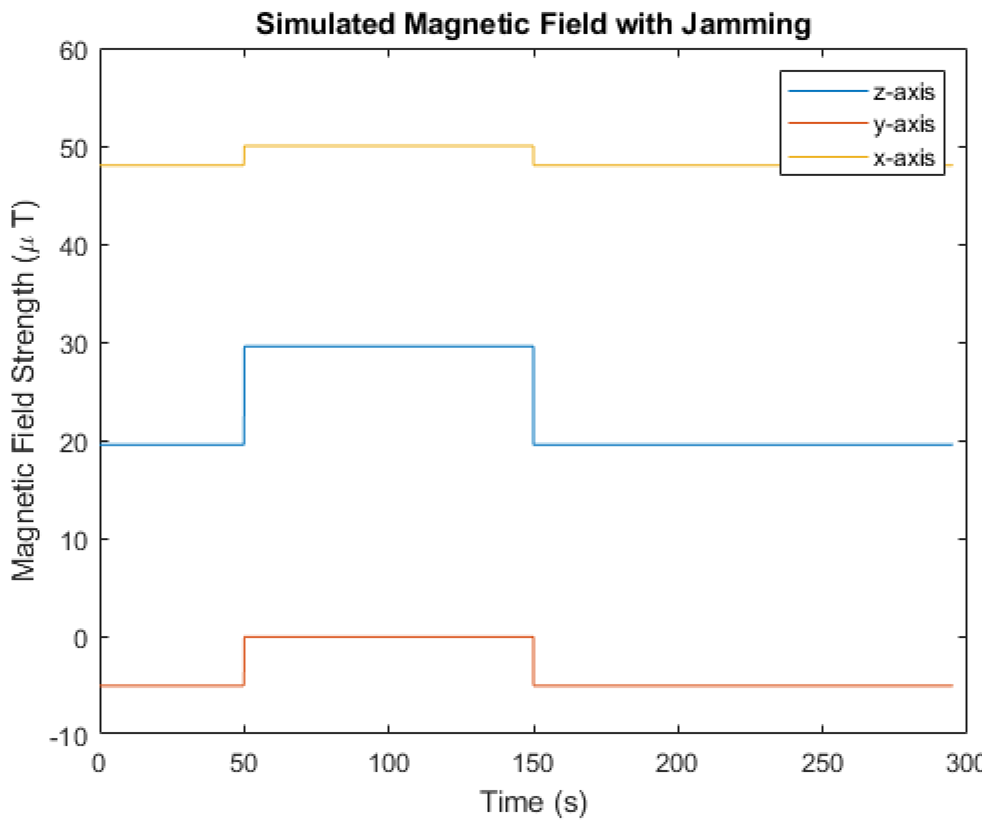
Fuse the IMU readings using the attitude and heading reference system (AHRS) filter, and then visualize the orientation of the sensor body over time. The orientation fluctuates at the beginning and stabilizes after approximately 60 seconds.

```
orientation = FUSE(accelReadings,gyroReadings,magReadings);

orientationEulerAngles = eulerd(orientation,'ZYX','frame');
time = (0:decim:(numSamples-1))'/SampleRate;

figure(1)
plot(time,orientationEulerAngles(:,1), ...
     time,orientationEulerAngles(:,2), ...
     time,orientationEulerAngles(:,3))
xlabel('Time (s)')
ylabel('Rotation (degrees)')
legend('z-axis','y-axis','x-axis')
title('Filtered IMU Data')
```




Mimic magnetic jamming by adding a transient, strong magnetic field to the magnetic field recorded in the `magReadings`. Visualize the magnetic field jamming.

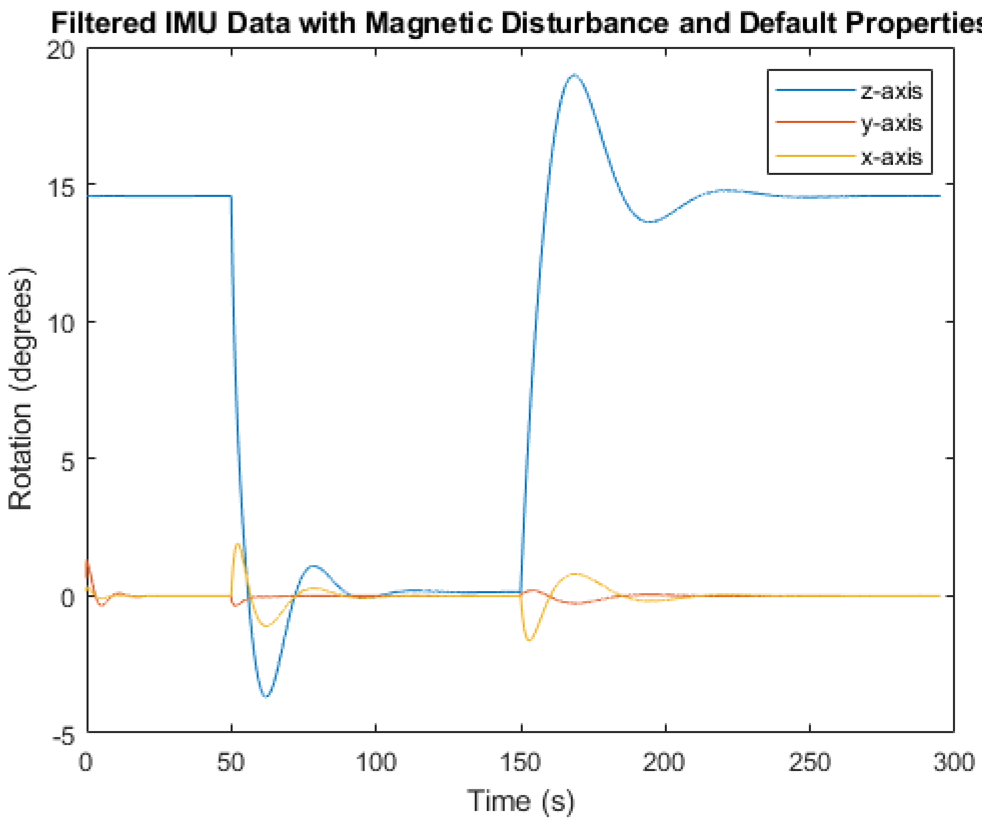
```
jamStrength = [10,5,2];
startStop = (50*SampleRate):(150*SampleRate);
jam = zeros(size(magReadings));
jam(startStop,:) = jamStrength.*ones(numel(startStop),3);

magReadings = magReadings + jam;

figure(2)
plot(time,magReadings(1:decim:end,:))
xlabel('Time (s)')
ylabel('Magnetic Field Strength (\mu T)')
title('Simulated Magnetic Field with Jamming')
legend('z-axis','y-axis','x-axis')
```




Run the simulation again using the `magReadings` with magnetic jamming. Plot the results and note the decreased performance in orientation estimation.

```
reset(FUSE)
orientation = FUSE(accelReadings,gyroReadings,magReadings);

orientationEulerAngles = eulerd(orientation,'ZYX','frame');

figure(3)
plot(time,orientationEulerAngles(:,1), ...
     time,orientationEulerAngles(:,2), ...
     time,orientationEulerAngles(:,3))
xlabel('Time (s)')
ylabel('Rotation (degrees)')
```

```
legend('z-axis','y-axis','x-axis')
title('Filtered IMU Data with Magnetic Disturbance and Default Properties')
```



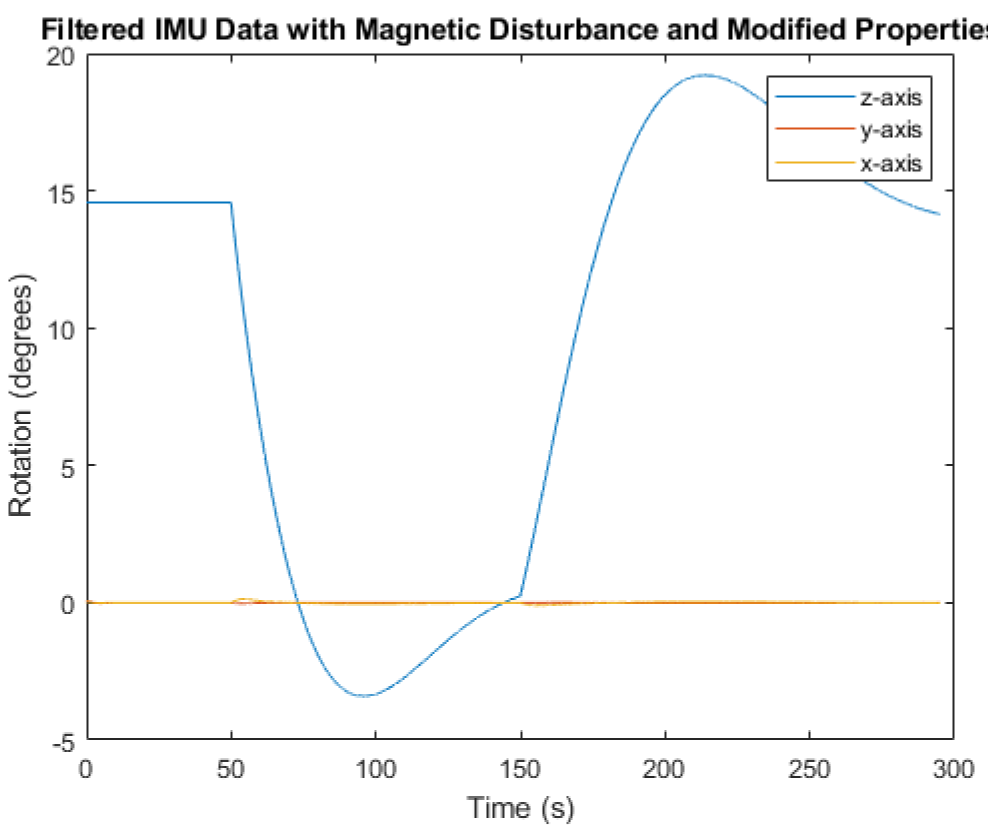

The magnetic jamming was misinterpreted by the AHRS filter, and the sensor body orientation was incorrectly estimated. You can compensate for jamming by increasing the `MagneticDisturbanceNoise` property. Increasing the `MagneticDisturbanceNoise` property increases the assumed noise range for magnetic disturbance, and the entire magnetometer signal is weighted less in the underlying fusion algorithm of `ahrsfilter`.

Set the `MagneticDisturbanceNoise` to `200` and run the simulation again.

The orientation estimation output from `ahrsfilter` is more accurate and less affected by the magnetic transient. However, because the magnetometer signal is weighted less in the underlying fusion algorithm, the algorithm may take more time to restabilize.

```
reset(FUSE)
FUSE.MagneticDisturbanceNoise = 20;

orientation = FUSE(accelReadings,gyroReadings,magReadings);

orientationEulerAngles = eulerd(orientation,'ZYX','frame');

figure(4)
plot(time,orientationEulerAngles(:,1), ...
     time,orientationEulerAngles(:,2), ...
     time,orientationEulerAngles(:,3))
xlabel('Time (s)')
```

```
ylabel('Rotation (degrees)')
legend('z-axis','y-axis','x-axis')
title('Filtered IMU Data with Magnetic Disturbance and Modified Properties')
```



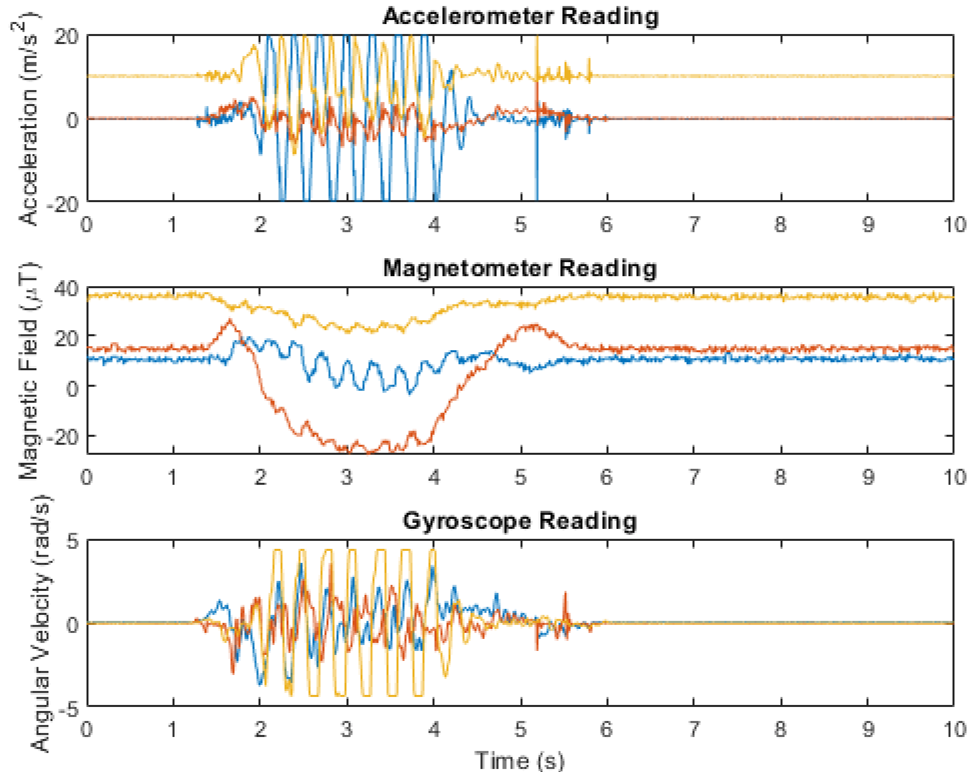

### Track Shaking 9-Axis IMU

This example uses the `ahrsfilter` System object™ to fuse 9-axis IMU data from a sensor body that is shaken. Plot the quaternion distance between the object and its final resting position to visualize performance and how quickly the filter converges to the correct resting position. Then tune parameters of the `ahrsfilter` so that the filter converges more quickly to the ground-truth resting position.

Load `IMUReadingsShaken` into your current workspace. This data was recorded from an IMU that was shaken then laid in a resting position. Visualize the acceleration, magnetic field, and angular velocity as recorded by the sensors.

```
load 'IMUReadingsShaken' accelReadings gyroReadings magReadings SampleRate
numSamples = size(accelReadings,1);
time = (0:(numSamples-1))'/SampleRate;

figure(1)
subplot(3,1,1)
plot(time,accelReadings)
title('Accelerometer Reading')
ylabel('Acceleration (m/s^2)')
```

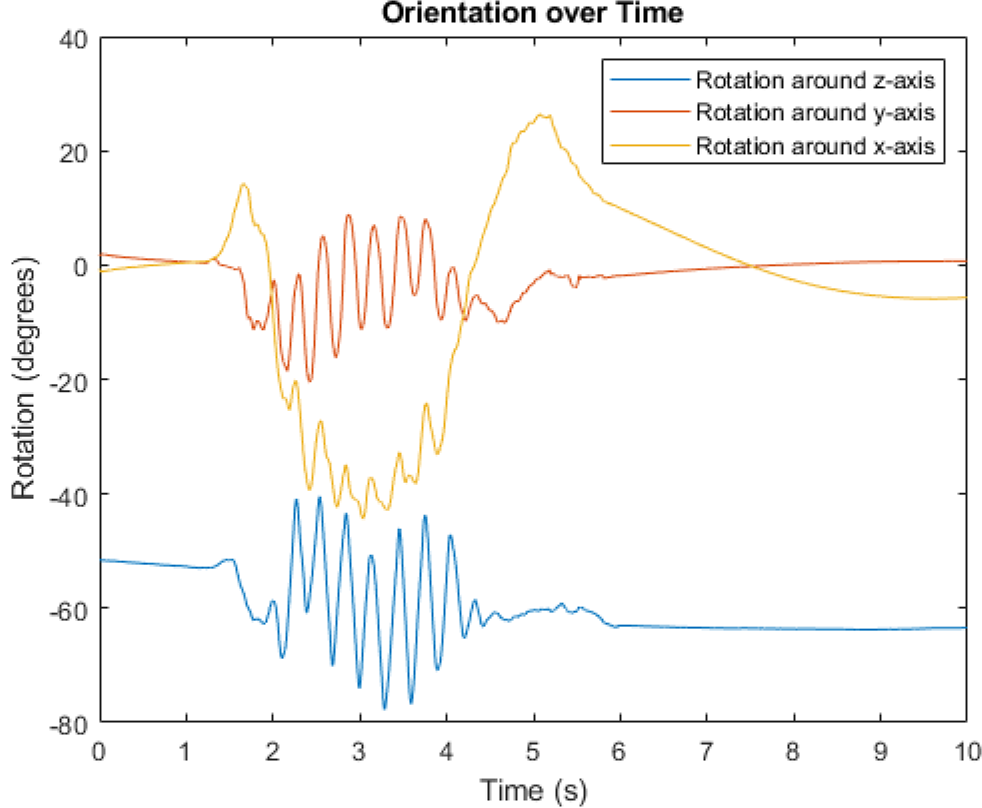
```
subplot(3,1,2)
plot(time,magReadings)
title('Magnetometer Reading')
ylabel('Magnetic Field (\muT)')

subplot(3,1,3)
plot(time,gyroReadings)
title('Gyroscope Reading')
ylabel('Angular Velocity (rad/s)')
xlabel('Time (s)')
```




Create an `ahrsfilter` and then fuse the IMU data to determine orientation. The orientation is returned as a vector of quaternions; convert the quaternions to Euler angles in degrees. Visualize the orientation of the sensor body over time by plotting the Euler angles required, at each time step, to rotate the global coordinate system to the sensor body coordinate system.

```
fuse = ahrsfilter('SampleRate',SampleRate);
orientation = fuse(accelReadings,gyroReadings,magReadings);

orientationEulerAngles = eulerd(orientation,'ZYX','frame');

figure(2)
plot(time,orientationEulerAngles(:,1), ...
     time,orientationEulerAngles(:,2), ...
     time,orientationEulerAngles(:,3))
xlabel('Time (s)')
```

```
ylabel('Rotation (degrees)')
title('Orientation over Time')
legend('Rotation around z-axis', ...
       'Rotation around y-axis', ...
       'Rotation around x-axis')
```

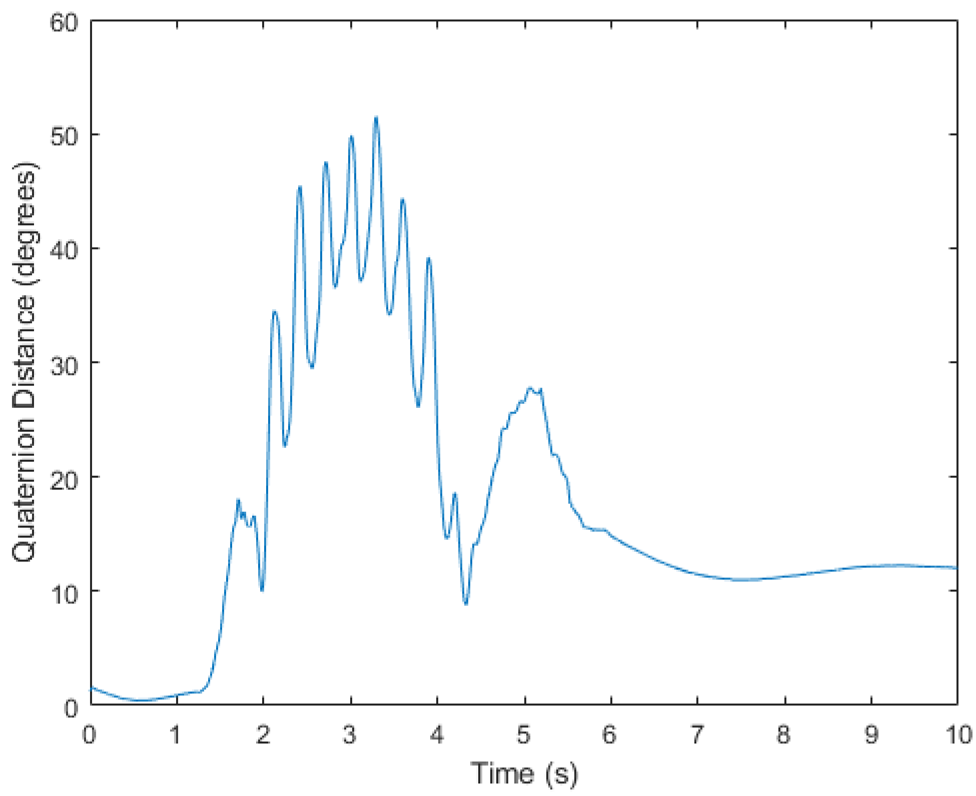



In the IMU recording, the shaking stops after approximately six seconds. Determine the resting orientation so that you can characterize how fast the `ahrsfilter` converges.

To determine the resting orientation, calculate the averages of the magnetic field and acceleration for the final four seconds and then use the `ecompass` function to fuse the data.

Visualize the quaternion distance from the resting position over time.

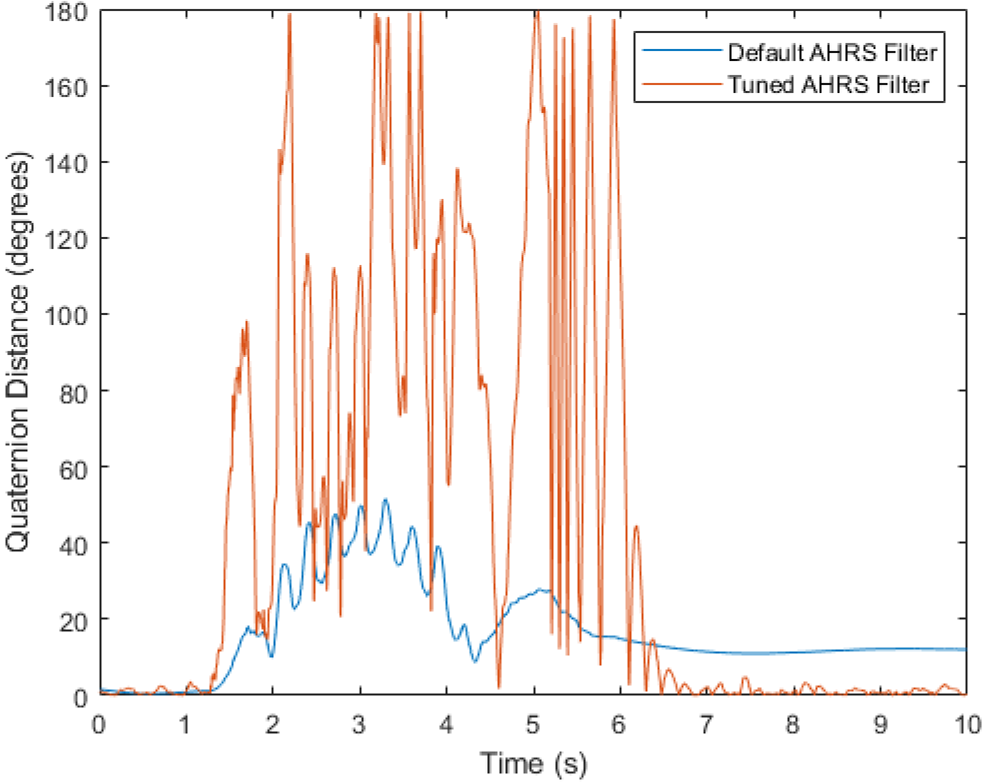
```
restingOrientation = ecompass(mean(accelReadings(6*SampleRate:end,:)), ...
                              mean(magReadings(6*SampleRate:end,:)));

figure(3)
plot(time,rad2deg(dist(restingOrientation,orientation)))
hold on
xlabel('Time (s)')
ylabel('Quaternion Distance (degrees)')
```




Modify the default `ahrsfilter` properties so that the filter converges to gravity more quickly. Increase the `GyroscopeDriftNoise` to `1e-2` and decrease the `LinearAccelerationNoise` to `1e-4`. This instructs the `ahrsfilter` algorithm to weigh gyroscope data less and accelerometer data more. Because the `accelerometer` data provides the stabilizing and consistent gravity vector, the resulting orientation converges more quickly.

Reset the filter, fuse the data, and plot the results.

```
fuse.LinearAccelerationNoise = 1e-4;
fuse.GyroscopeDriftNoise     = 1e-2;
reset(fuse)

orientation = fuse(accelReadings,gyroReadings,magReadings);

figure(3)
plot(time,rad2deg(dist(restingOrientation,orientation)))
legend('Default AHRS Filter','Tuned AHRS Filter')
```




## Algorithms

*Note: The following algorithm only applies to an NED reference frame.*

The `ahrsfilter` uses the nine-axis Kalman filter structure described in [1]. The algorithm attempts to track the errors in orientation, gyroscope offset, linear acceleration, and magnetic disturbance to output the final orientation and angular velocity. Instead of tracking the orientation directly, the indirect Kalman filter models the error process, $x$, with a recursive update:

$$x_k = \begin{bmatrix} \theta_k \\ b_k \\ a_k \\ d_k \end{bmatrix} = F_k \begin{bmatrix} \theta_{k-1} \\ b_{k-1} \\ a_{k-1} \\ d_{k-1} \end{bmatrix} + w_k$$

where $x_k$ is a 12-by-1 vector consisting of:

- $\theta_k$ -- 3-by-1 orientation error vector, in degrees, at time $k$
- $b_k$ -- 3-by-1 gyroscope zero angular rate bias vector, in deg/s, at time $k$
- $a_k$ -- 3-by-1 acceleration error vector measured in the sensor frame, in g, at time $k$
- $d_k$ -- 3-by-1 magnetic disturbance error vector measured in the sensor frame, in µT, at time $k$

and where $w_k$ is a 12-by-1 additive noise vector, and $F_k$ is the state transition model.

Because $x_k$ is defined as the error process, the *a priori* estimate is always zero, and therefore the state transition model, $F_k$, is zero. This insight results in the following reduction of the standard Kalman equations:

Standard Kalman equations:

$$x_k^- = F_k x_{k-1}^+$$

$$P_k^- = F_k P_{k-1}^+ F_k^T + Q_k$$

$$y_k = z_k - H_k x_k^-$$

$$S_k = R_k + H_k P_k^- H_k T$$

$$K_k = P_k^- H_k^T (S_k)^{-1}$$

$$x_k^+ = x_k^- + K_k y_k$$

$$P_k^+ = P_k - - K_k H_k P_k^-$$

Kalman equations used in this algorithm:

$$x_k^- = 0$$

$$P_k^- = Q_k$$

$$y_k = z_k$$

$$S_k = R_k + H_k P_k^- H_k T$$

$$K_k = P_k^- H_k^T (S_k)^{-1}$$

$$x_k^+ = K_k y_k$$

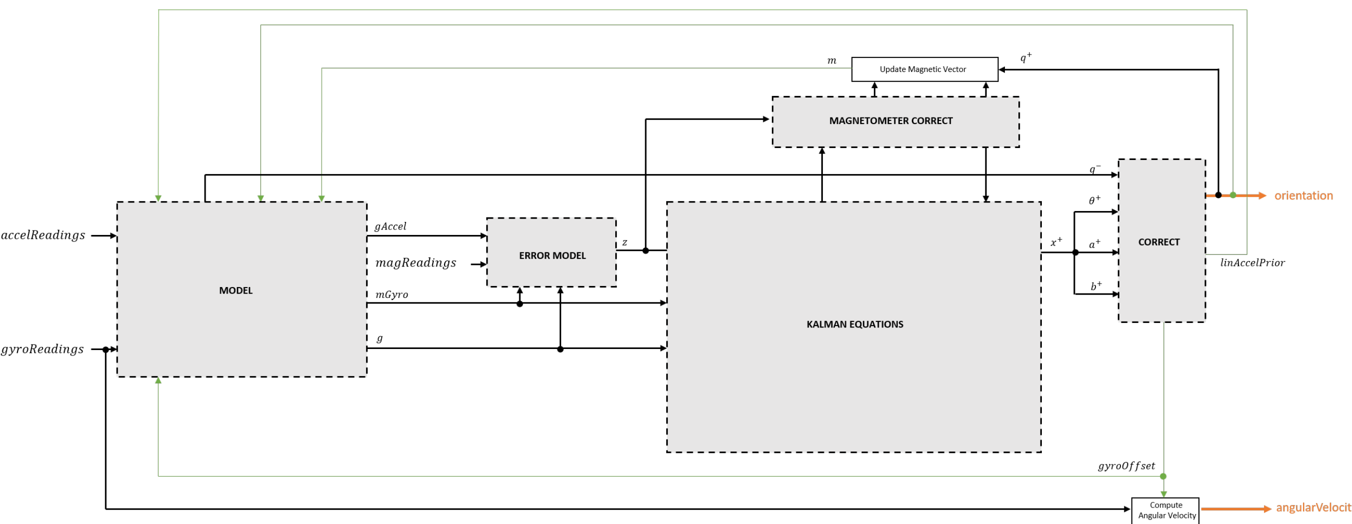
$$P_k^+ = P_k - - K_k H_k P_k^-$$

where:

- $x_k^-$ –– predicted (*a priori*) state estimate; the error process
- $P_k^-$ –– predicted (*a priori*) estimate covariance
- $y_k$ –– innovation
- $S_k$ –– innovation covariance
- $K_k$ –– Kalman gain
- $x_k^+$ –– updated (*a posteriori*) state estimate
- $P_k^+$ –– updated (*a posteriori*) estimate covariance

$k$ represents the iteration, the superscript $^+$ represents an *a posteriori* estimate, and the superscript $^-$ represents an *a priori* estimate.

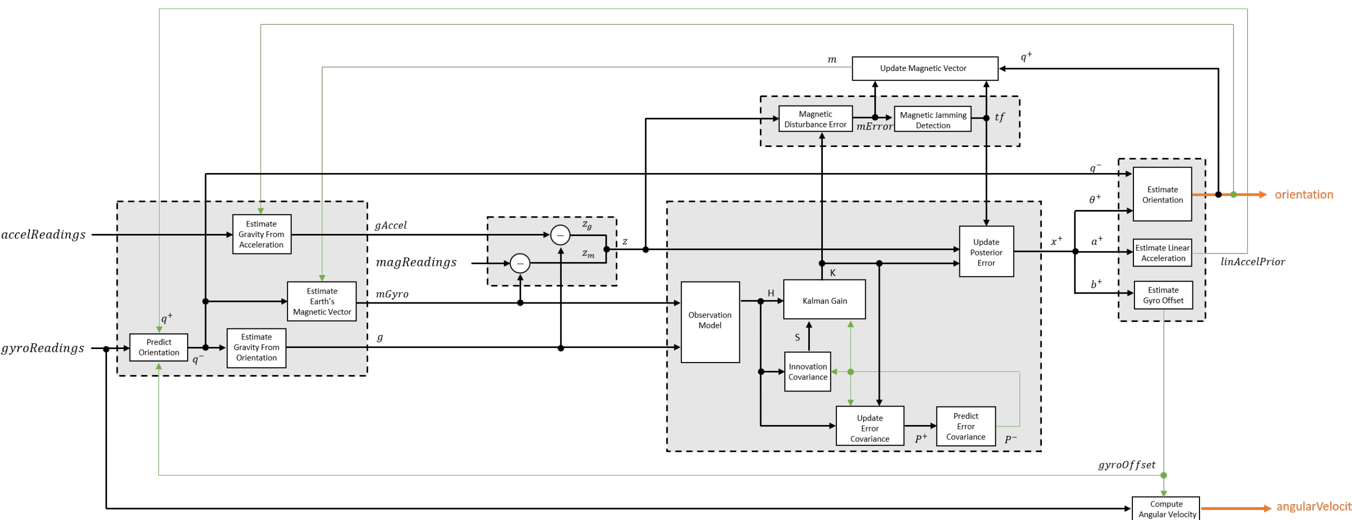
The graphic and following steps describe a single frame-based iteration through the algorithm.




Before the first iteration, the `accelReadings`, `gyroReadings`, and `magReadings` inputs are chunked into `DecimationFactor`-by-3 frames. For each chunk, the algorithm uses the most current accelerometer and magnetometer readings corresponding to the chunk of gyroscope readings.

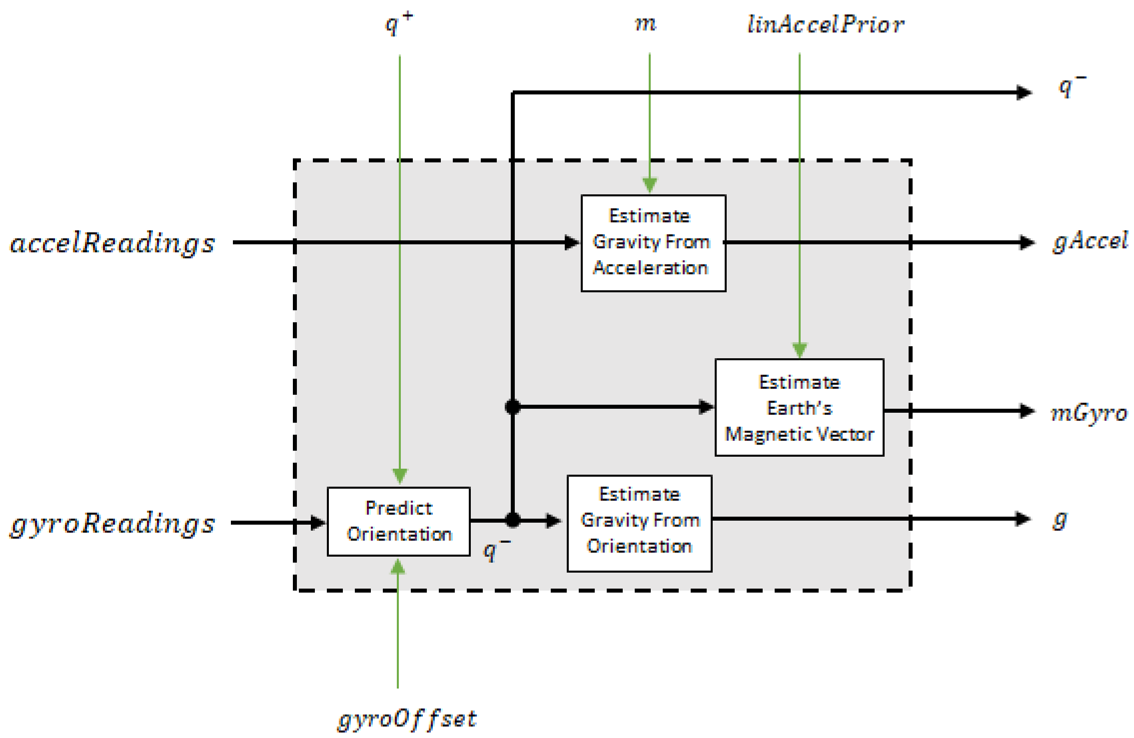
## Detailed Overview

Walk through the algorithm for an explanation of each stage of the detailed overview.




## Model

The algorithm models acceleration and angular change as linear processes.




**Predict Orientation**

The orientation for the current frame is predicted by first estimating the angular change from the previous frame:

$$\Delta\varphi_{N \times 3} = \frac{(gyroReadings_{N \times 3} - gyroOffset_{1 \times 3})}{fs}$$

where $N$ is the decimation factor specified by the DecimationFactor property and $fs$ is the sample rate specified by the SampleRate property.

The angular change is converted into quaternions using the `rotvec` `quaternion` construction syntax:

$$\Delta Q_{N \times 1} = \text{quaternion}(\Delta\varphi_{N \times 3}, 'rotvec')$$

The previous orientation estimate is updated by rotating it by $\Delta Q$:

$$q^-_{1 \times 1} = (q^+_{1 \times 1})\left(\prod_{n=1}^{N} \Delta Q_n\right)$$

During the first iteration, the orientation estimate, $q^-$, is initialized by `ecompass`.

**Estimate Gravity from Orientation**

The gravity vector is interpreted as the third column of the quaternion, $q^-$, in rotation matrix form:

$$g_{1 \times 3} = (rPrior(:,3))^T$$

See [1] for an explanation of why the third column of *rPrior* can be interpreted as the gravity vector.

#### Estimate Gravity from Acceleration

A second gravity vector estimation is made by subtracting the decayed linear acceleration estimate of the previous iteration from the accelerometer readings:

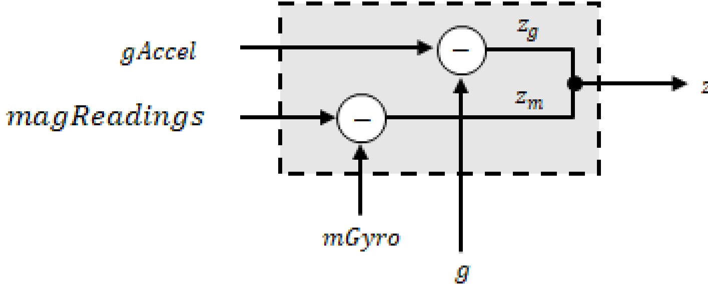
$$gAccel_{1 \times 3} = accelReadings_{1 \times 3} - linAccelprior_{1 \times 3}$$

#### Estimate Earth's Magnetic Vector

Earth's magnetic vector is estimated by rotating the magnetic vector estimate from the previous iteration by the *a priori* orientation estimate, in rotation matrix form:

$$mGyro_{1 \times 3} = \left((rPrior)\left(m^T\right)\right)^T$$

### Error Model

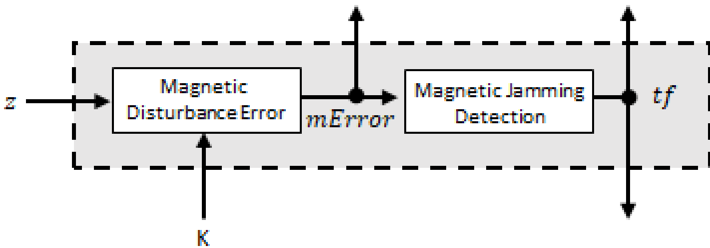



The error model combines two differences:

- The difference between the gravity estimate from the accelerometer readings and the gravity estimate from the gyroscope readings: $z_g = g - gAccel$
- The difference between the magnetic vector estimate from the gyroscope readings and the magnetic vector estimate from the magnetometer:$z_m = mGyro - magReadings$

### Magnetometer Correct

The magnetometer correct estimates the error in the magnetic vector estimate and detects magnetic jamming.




#### Magnetometer Disturbance Error

The magnetic disturbance error is calculated by matrix multiplication of the Kalman gain associated with the magnetic vector with the error signal:

$$mError_{3 \times 1} = \left((K(10{:}12, :)_{3 \times 6})(z_{1 \times 6})^T\right)^T$$

The Kalman gain, $K$, is the Kalman gain calculated in the current iteration.

**Magnetic Jamming Detection**

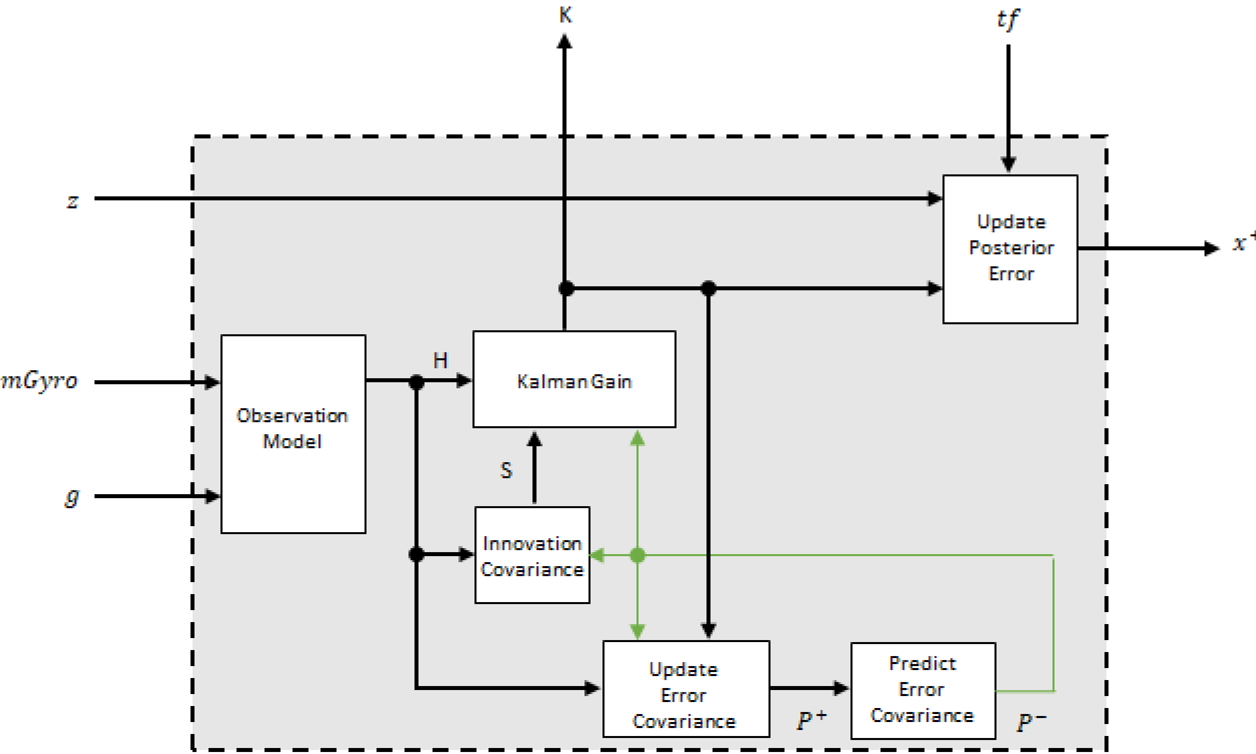
Magnetic jamming is determined by verifying that the power of the detected magnetic disturbance is less than or equal to four times the power of the expected magnetic field strength:

$$tf = \begin{cases} \text{true} & \text{if} \quad \sum |mError|^2 > (4)(\text{ExpectedMagneticFieldStrength})^2 \\ \text{false} & \text{else} \end{cases}$$

ExpectedMagneticFieldStrength is a property of `ahrsfilter`.

### Kalman Equations

The Kalman equations use the gravity estimate derived from the gyroscope readings, $g$, the magnetic vector estimate derived from the gyroscope readings, $mGyro$, and the observation of the error process, $z$, to update the Kalman gain and intermediary covariance matrices. The Kalman gain is applied to the error signal, $z$, to output an *a posteriori* error estimate, $x^+$.




**Observation Model**

The observation model maps the 1-by-3 observed states, $g$ and $mGyro$, into the 6-by-12 true state, $H$.

The observation model is constructed as:

$$H_{3\times 9} = \begin{bmatrix} 0 & g_z & -g_y & 0 & -\kappa g_z & \kappa g_y & 1 & 0 & 0 & 0 & 0 & 0 \\ -g_z & 0 & g_x & \kappa g_z & 0 & -\kappa g_x & 0 & 1 & 0 & 0 & 0 & 0 \\ g_y & -g_x & 0 & -\kappa g_y & \kappa g_x & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & m_z & -m_y & 0 & -\kappa m_z & -\kappa m_y & 0 & 0 & 0 & -1 & 0 & 0 \\ -m_z & 0 & m_x & \kappa m_z & 0 & -\kappa m_x & 0 & 0 & 0 & 0 & -1 & 0 \\ m_y & -m_x & 0 & -\kappa m_y & \kappa m_x & 0 & 0 & 0 & 0 & 0 & 0 & -1 \end{bmatrix}$$

where $g_x$, $g_y$, and $g_z$ are the *x*-, *y*-, and *z*-elements of the gravity vector estimated from the *a priori* orientation, respectively. $m_x$, $m_y$, and $m_z$ are the *x*-, *y*-, and *z*-elements of the magnetic vector estimated from the *a priori* orientation, respectively. $\kappa$ is a constant determined by the SampleRate and DecimationFactor properties: $\kappa$ = `DecimationFactor/SampleRate`.

See sections 7.3 and 7.4 of [1] for a derivation of the observation model.

#### Innovation Covariance

The innovation covariance is a 6-by-6 matrix used to track the variability in the measurements. The innovation covariance matrix is calculated as:

$$S_{6x6} = R_{6x6} + (H_{6x12})\left(P^{-}_{12x12}\right)(H_{6x12})^T$$

where

- $H$ is the observation model matrix
- $P^{-}$ is the predicted (*a priori*) estimate of the covariance of the observation model calculated in the previous iteration
- $R$ is the covariance of the observation model noise, calculated as:

$$R_{6\times 6} = \begin{bmatrix} accel_{\text{noise}} & 0 & 0 & 0 & 0 & 0 \\ 0 & accel_{\text{noise}} & 0 & 0 & 0 & 0 \\ 0 & 0 & accel_{\text{noise}} & 0 & 0 & 0 \\ 0 & 0 & 0 & mag_{\text{noise}} & 0 & 0 \\ 0 & 0 & 0 & 0 & mag_{\text{noise}} & 0 \\ 0 & 0 & 0 & 0 & 0 & mag_{\text{noise}} \end{bmatrix}$$

  where

  $accel_{\text{noise}}$ = AccelerometerNoise + LinearAccelerationNoise + $\kappa^2$ (GyroscopeDriftNoise + GyroscopeNoise)

  and

  $mag_{\text{noise}}$ = MagnetometerNoise + MagneticDisturbanceNoise + $\kappa^2$ (GyroscopeDriftNoise + GyroscopeNoise)

  The following properties define the observation model noise variance:

  - $\kappa$ –– DecimationFactor/SampleRate

- AccelerometerNoise
- LinearAccelerationNoise
- GyroscopeDriftNoise
- GyroscopeNoise
- MagneticDisturbanceNoise
- MagnetometerNoise

**Update Error Estimate Covariance**

The error estimate covariance is a 12-by-12 matrix used to track the variability in the state.

The error estimate covariance matrix is updated as:

$$P^{+}_{12 \times 12} = P^{-}_{12 \times 12} - (K_{12 \times 6})(H_{6 \times 12})\left(P^{-}_{12 \times 12}\right)$$

where $K$ is the Kalman gain, $H$ is the measurement matrix, and $P^{-}$ is the error estimate covariance calculated during the previous iteration.

**Predict Error Estimate Covariance**

The error estimate covariance is a 12-by-12 matrix used to track the variability in the state. The *a priori* error estimate covariance, $P^{-}$, is set to the process noise covariance, $Q$, determined during the previous iteration. $Q$ is calculated as a function of the *a posteriori* error estimate covariance, $P^{+}$. When calculating $Q$, it is assumed that the cross-correlation terms are negligible compared to the autocorrelation terms, and are set to zero:

$$Q =$$

$$\begin{bmatrix} P^+(1) + \kappa^2\left(P^+(40) + \beta + \eta\right) & 0 & 0 & -\kappa\left(P^+(40) + \beta\right) & 0 \\ 0 & P^+(14) + \kappa^2\left(P^+(53) + \beta + \eta\right) & 0 & 0 & -\kappa\left(P^+(5\right. \\ 0 & 0 & P^+(27) + \kappa^2\left(P^+(66) + \beta + \eta\right) & 0 & 0 \\ -\kappa\left(P^+(40) + \beta\right) & 0 & 0 & P^+(40) + \beta & 0 \\ 0 & -\kappa\left(P^+(53) + \beta\right) & 0 & 0 & P^+(53) \\ 0 & 0 & -\kappa\left(P^+(66) + \beta\right) & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

where

- $P^+$ -- is the updated (*a posteriori*) error estimate covariance
- $\kappa$ -- DecimationFactor/SampleRate
- $\beta$ -- GyroscopeDriftNoise
- $\eta$ -- GyroscopeNoise
- $\nu$ -- LinearAcclerationDecayFactor
- $\xi$ -- LinearAccelerationNoise
- $\sigma$ -- MagneticDisturbanceDecayFactor
- $\gamma$ -- MagneticDisturbanceNoise

See section 10.1 of [1] for a derivation of the terms of the process error matrix.

**Kalman Gain**

The Kalman gain matrix is a 12-by-6 matrix used to weight the innovation. In this algorithm, the innovation is interpreted as the error process, $z$.

The Kalman gain matrix is constructed as:

$$K_{12\times6} = \left(P^-_{12\times12}\right)\left(H_{6\times12}\right)^T\left(\left(S_{6\times6}\right)^T\right)^{-1}$$

where

- $P^-$ -- predicted error covariance
- $H$ -- observation model
- $S$ -- innovation covariance

**Update a Posteriori Error**

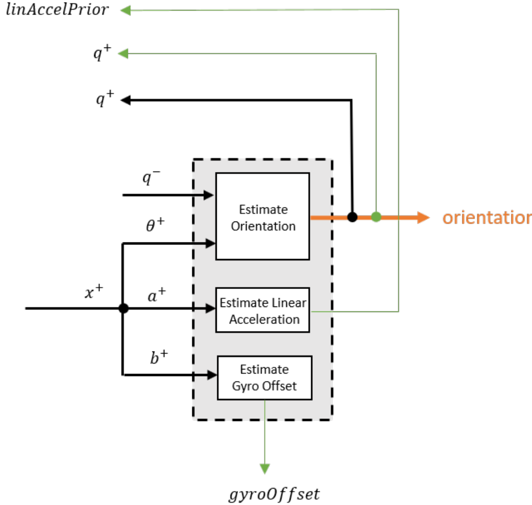
The *a posterior* error estimate is determined by combining the Kalman gain matrix with the error in the gravity vector and magnetic vector estimations:

$$x_{12\times1} = \left(K_{12\times6}\right)\left(z_{1\times6}\right)^T$$

If magnetic jamming is detected in the current iteration, the magnetic vector error signal is ignored, and the *a posterior* error estimate is calculated as:

$$x_{9\times1} = \left(K(1{:}9, 1{:}3)\right)\left(z_g\right)^T$$

### Correct




#### Estimate Orientation

The orientation estimate is updated by multiplying the previous estimation by the error:

$$q^{+} = (q^{-})\left(\theta^{+}\right)$$

#### Estimate Linear Acceleration

The linear acceleration estimation is updated by decaying the linear acceleration estimation from the previous iteration and subtracting the error:

$$linAccelPrior = (linAccelPrior_{k-1})\nu - b^{+}$$

where

- $\nu$ -- LinearAcclerationDecayFactor

#### Estimate Gyroscope Offset

The gyroscope offset estimation is updated by subtracting the gyroscope offset error from the gyroscope offset from the previous iteration:

$$gyroOffset = gyroOffset_{k-1} - a^{+}$$

### Compute Angular Velocity

To estimate angular velocity, the frame of `gyroReadings` are averaged and the gyroscope offset computed in the previous iteration is subtracted:

$$angularVelocity_{1\times3} = \frac{\sum gyroReadings_{N\times3}}{N} - gyroOffset_{1\times3}$$

where $N$ is the decimation factor specified by the `DecimationFactor` property.

The gyroscope offset estimation is initialized to zeros for the first iteration.

### Update Magnetic Vector

If magnetic jamming was not detected in the current iteration, the magnetic vector estimate, *m*, is updated using the *a posteriori* magnetic disturbance error and the *a posteriori* orientation.

The magnetic disturbance error is converted to the navigation frame:

$$mErrorNED_{1 \times 3} = \left((rPost_{3 \times 3})^T (mError_{1 \times 3})^T\right)^T$$

The magnetic disturbance error in the navigation frame is subtracted from the previous magnetic vector estimate and then interpreted as inclination:

$$M = m - mErrorNED$$

$$inclination = \text{atan2}(M(3), M(1))$$

The inclination is converted to a constrained magnetic vector estimate for the next iteration:

$$m(1) = (\text{ExpectedMagneticFieldStrength})(\cos(inclination))$$
$$m(2) = 0$$
$$m(3) = (\text{ExpectedMagneticFieldStrength})(\sin(inclination))$$

ExpectedMagneticFieldStrength is a property of `ahrsfilter`.

## Version History

**Introduced in R2018b**

## References

[1] Open Source Sensor Fusion. https://github.com/memsindustrygroup/Open-Source-Sensor-Fusion/tree/master/docs

[2] Roetenberg, D., H.J. Luinge, C.T.M. Baten, and P.H. Veltink. "Compensation of Magnetic Disturbances Improves Inertial and Magnetic Sensing of Human Body Segment Orientation." *IEEE Transactions on Neural Systems and Rehabilitation Engineering*. Vol. 13. Issue 3, 2005, pp. 395-405.

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

Usage notes and limitations:

See “System Objects in MATLAB Code Generation” (MATLAB Coder).

## See Also

`ecompass` | `gpsSensor` | `imufilter` | `imuSensor`

# tune

Tune `ahrsfilter` parameters to reduce estimation error

## Syntax

```
tune(filter,sensorData,groundTruth)
tune( ___ ,config)
```

## Description

`tune(filter,sensorData,groundTruth)` adjusts the properties of the `ahrsfilter` filter object, `filter`, to reduce the root-mean-squared (RMS) quaternion distance error between the fused sensor data and the ground truth. The function uses the property values in the filter as the initial estimate for the optimization algorithm.

`tune( ___ ,config)` specifies the tuning configuration based on a `tunerconfig` object, `config`.

## Examples

### Tune `ahrsfilter` to Improve Orientation Estimate

Load recorded sensor data and ground truth data.

```
ld = load('ahrsfilterTuneData.mat');
qTrue = ld.groundTruth.Orientation; % true orientation
```

Create an `arhsfitler` object.

```
fuse = ahrsfilter;
```

Fuse the sensor data using the default, untuned filter.

```
qEstUntuned = fuse(ld.sensorData.Accelerometer, ...
    ld.sensorData.Gyroscope, ld.sensorData.Magnetometer);
```

Create a `tunerconfig` object. Tune the `ahrsfilter` object to improve the orientation estimation based on the configuration.

```
config = tunerconfig('ahrsfilter');
tune(fuse,ld.sensorData,ld.groundTruth,config);
```

```
    Iteration    Parameter                         Metric
    _________    _________                         ______
    1            AccelerometerNoise                0.1345
    1            GyroscopeNoise                    0.1342
    1            MagnetometerNoise                 0.1341
    1            GyroscopeDriftNoise               0.1341
    1            LinearAccelerationNoise           0.1332
    1            MagneticDisturbanceNoise          0.1324
    1            LinearAccelerationDecayFactor     0.1317
    1            MagneticDisturbanceDecayFactor    0.1316
```

```
2            AccelerometerNoise                 0.1316
2            GyroscopeNoise                     0.1312
2            MagnetometerNoise                  0.1311
2            GyroscopeDriftNoise                0.1311
2            LinearAccelerationNoise            0.1300
2            MagneticDisturbanceNoise           0.1292
2            LinearAccelerationDecayFactor      0.1285
2            MagneticDisturbanceDecayFactor     0.1285
3            AccelerometerNoise                 0.1285
3            GyroscopeNoise                     0.1280
3            MagnetometerNoise                  0.1279
3            GyroscopeDriftNoise                0.1279
3            LinearAccelerationNoise            0.1267
3            MagneticDisturbanceNoise           0.1258
3            LinearAccelerationDecayFactor      0.1253
3            MagneticDisturbanceDecayFactor     0.1253
4            AccelerometerNoise                 0.1252
4            GyroscopeNoise                     0.1247
4            MagnetometerNoise                  0.1246
4            GyroscopeDriftNoise                0.1246
4            LinearAccelerationNoise            0.1233
4            MagneticDisturbanceNoise           0.1224
4            LinearAccelerationDecayFactor      0.1220
4            MagneticDisturbanceDecayFactor     0.1220
5            AccelerometerNoise                 0.1220
5            GyroscopeNoise                     0.1213
5            MagnetometerNoise                  0.1212
5            GyroscopeDriftNoise                0.1212
5            LinearAccelerationNoise            0.1200
5            MagneticDisturbanceNoise           0.1190
5            LinearAccelerationDecayFactor      0.1187
5            MagneticDisturbanceDecayFactor     0.1187
6            AccelerometerNoise                 0.1187
6            GyroscopeNoise                     0.1180
6            MagnetometerNoise                  0.1178
6            GyroscopeDriftNoise                0.1178
6            LinearAccelerationNoise            0.1167
6            MagneticDisturbanceNoise           0.1156
6            LinearAccelerationDecayFactor      0.1155
6            MagneticDisturbanceDecayFactor     0.1155
7            AccelerometerNoise                 0.1155
7            GyroscopeNoise                     0.1147
7            MagnetometerNoise                  0.1145
7            GyroscopeDriftNoise                0.1145
7            LinearAccelerationNoise            0.1137
7            MagneticDisturbanceNoise           0.1126
7            LinearAccelerationDecayFactor      0.1125
7            MagneticDisturbanceDecayFactor     0.1125
8            AccelerometerNoise                 0.1125
8            GyroscopeNoise                     0.1117
8            MagnetometerNoise                  0.1116
8            GyroscopeDriftNoise                0.1116
8            LinearAccelerationNoise            0.1112
8            MagneticDisturbanceNoise           0.1100
8            LinearAccelerationDecayFactor      0.1099
8            MagneticDisturbanceDecayFactor     0.1099
9            AccelerometerNoise                 0.1099
9            GyroscopeNoise                     0.1091
```

```
    9           MagnetometerNoise                0.1090
    9           GyroscopeDriftNoise              0.1090
    9           LinearAccelerationNoise          0.1090
    9           MagneticDisturbanceNoise         0.1076
    9           LinearAccelerationDecayFactor    0.1075
    9           MagneticDisturbanceDecayFactor   0.1075
    10          AccelerometerNoise               0.1075
    10          GyroscopeNoise                   0.1066
    10          MagnetometerNoise                0.1064
    10          GyroscopeDriftNoise              0.1064
    10          LinearAccelerationNoise          0.1064
    10          MagneticDisturbanceNoise         0.1049
    10          LinearAccelerationDecayFactor    0.1047
    10          MagneticDisturbanceDecayFactor   0.1047
    11          AccelerometerNoise               0.1047
    11          GyroscopeNoise                   0.1038
    11          MagnetometerNoise                0.1036
    11          GyroscopeDriftNoise              0.1036
    11          LinearAccelerationNoise          0.1036
    11          MagneticDisturbanceNoise         0.1016
    11          LinearAccelerationDecayFactor    0.1014
    11          MagneticDisturbanceDecayFactor   0.1014
    12          AccelerometerNoise               0.1014
    12          GyroscopeNoise                   0.1005
    12          MagnetometerNoise                0.1002
    12          GyroscopeDriftNoise              0.1002
    12          LinearAccelerationNoise          0.1002
    12          MagneticDisturbanceNoise         0.0978
```

Fuse the sensor data using the tuned filter.

```
qEstTuned = fuse(ld.sensorData.Accelerometer, ...
    ld.sensorData.Gyroscope, ld.sensorData.Magnetometer);
```

Compare the tuned and untuned RMS error performances.

```
dUntuned = rad2deg(dist(qEstUntuned, qTrue));
dTuned = rad2deg(dist(qEstTuned, qTrue));
rmsUntuned = sqrt(mean(dUntuned.^2))
```

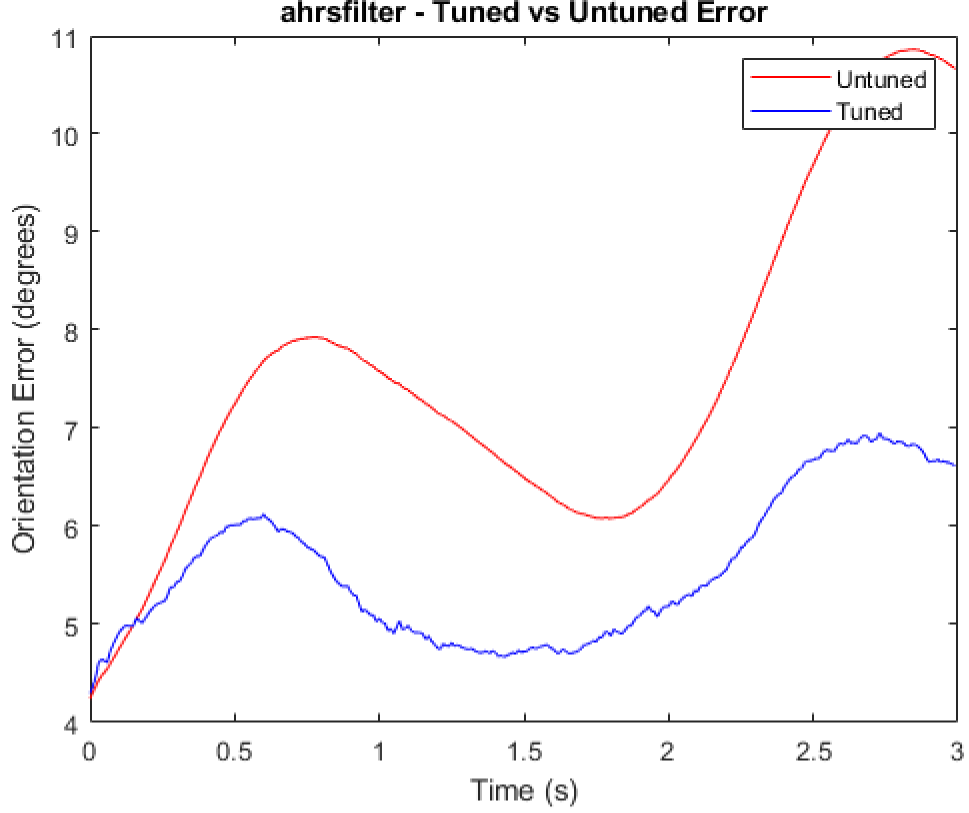
```
rmsUntuned = 7.7088
```

```
rmsTuned = sqrt(mean(dTuned.^2))
```

```
rmsTuned = 5.6033
```

Visualize the errors with respect to time.

```
N = numel(dUntuned);
t = (0:N-1)./ fuse.SampleRate;
plot(t, dUntuned, 'r', t, dTuned, 'b');
legend('Untuned', 'Tuned');
title('ahrsfilter - Tuned vs Untuned Error')
xlabel('Time (s)');
ylabel('Orientation Error (degrees)');
```




## Input Arguments

**`filter` — Filter object**
`ahrsfilter` object

Filter object, specified as an `ahrsfilter` object.

**`sensorData` — Sensor data**
`table`

Sensor data, specified as a `table`. In each row, the sensor data is specified as:

- `Accelerometer` — Accelerometer data, specified as a 1-by-3 vector of scalars in $m^2/s$.
- `Gyroscope` — Gyroscope data, specified as a 1-by-3 vector of scalars in rad/s.
- `Magnetometer` — Magnetometer data, specified as a 1-by-3 vector of scalars in μT.

If you set the `Cost` property of the tuner configuration input, `config`, to `Custom`, then you can use other data types for the `sensorData` input based on your choice.

**`groundTruth` — Ground truth data**
`timetable`

Ground truth data, specified as a `table`. The table has only one column of `Orientation` data. In each row, the orientation is specified as a `quaternion` object or a 3-by-3 rotation matrix.

The function processes each row of the `sensorData` and `groundTruth` tables sequentially to calculate the state estimate and RMS error from the ground truth. Each row of the `sensorData` and the `groundTruth` tables must correspond to each other.

If you set the `Cost` property of the tuner configuration input, `config`, to `Custom`, then you can use other data types for the `groundTruth` input based on your choice.

**`config` — Tuner configuration**
`tunerconfig` object

Tuner configuration, specified as a `tunerconfig` object.

# Version History

**Introduced in R2020b**

## References

[1] Abbeel, P., Coates, A., Montemerlo, M., Ng, A.Y. and Thrun, S. Discriminative Training of Kalman Filters. In *Robotics: Science and systems*, Vol. 2, pp. 1, 2005.

# altimeterSensor

Altimeter simulation model

## Description

The `altimeterSensor` System object models receiving data from an altimeter sensor.

To model an altimeter:

1. Create the `altimeterSensor` object and set its properties.
2. Call the object with arguments, as if it were a function.

To learn more about how System objects work, see What Are System Objects?

# Creation

## Syntax

```
altimeter = altimeterSensor
altimeter = altimeterSensor('ReferenceFrame',RF)
altimeter = altimeterSensor( ___ ,Name,Value)
```

### Description

`altimeter = altimeterSensor` returns an `altimeterSensor` System object that simulates altimeter readings.

`altimeter = altimeterSensor('ReferenceFrame',RF)` returns an `altimeterSensor` System object that simulates altimeter readings relative to the reference frame `RF`. Specify `RF` as `'NED'` (North-East-Down) or `'ENU'` (East-North-Up). The default value is `'NED'`.

`altimeter = altimeterSensor( ___ ,Name,Value)` sets each property `Name` to the specified `Value`. Unspecified properties have default values.

## Properties

Unless otherwise indicated, properties are *nontunable*, which means you cannot change their values after calling the object. Objects lock when you call them, and the `release` function unlocks them.

If a property is *tunable*, you can change its value at any time.

For more information on changing property values, see System Design in MATLAB Using System Objects.

**`SampleRate` — Update rate of sensor (Hz)**
`1` (default) | positive scalar

Update rate of sensor in Hz, specified as a positive scalar.

Data Types: `single` | `double`

**`ConstantBias` — Constant offset bias (m)**
`0` (default) | scalar

Constant offset bias in meters, specified as a scalar.

**Tunable:** Yes

Data Types: `single` | `double`

**`NoiseDensity` — Power spectral density of sensor noise (m/√Hz)**
`0` (default) | nonnegative scalar

Power spectral density of sensor noise in m/√Hz, specified as a nonnegative scalar.

**Tunable:** Yes

Data Types: `single` | `double`

**`BiasInstability` — Instability of bias offset (m)**
`0` (default) | nonnegative scalar

Instability of the bias offset in meters, specified as a nonnegative scalar.

**Tunable:** Yes

Data Types: `single` | `double`

**`DecayFactor` — Bias instability noise decay factor**
`0` (default) | scalar in the range [0,1]

Bias instability noise decay factor, specified as a scalar in the range [0,1]. A decay factor of `0` models the bias instability noise as a white noise process. A decay factor of `1` models the bias instability noise as a random walk process.

**Tunable:** Yes

Data Types: `single` | `double`

**`RandomStream` — Random number source**
`'Global stream'` (default) | `'mt19937ar with seed'`

Random number source, specified as a character vector or string:

- `'Global stream'` –– Random numbers are generated using the current global random number stream.
- `'mt19937ar with seed'` –– Random numbers are generated using the mt19937ar algorithm with the seed specified by the `Seed` property.

Data Types: `char` | `string`

**Seed — Initial seed**
`67` (default) | nonnegative integer scalar

Initial seed of an mt19937ar random number generator algorithm, specified as a nonnegative integer scalar.

#### Dependencies

To enable this property, set `RandomStream` to `'mt19937ar with seed'`.

Data Types: `single` | `double`

## Usage

## Syntax

`altimeterReadings = altimeter(position)`

### Description

`altimeterReadings = altimeter(position)` generates an altimeter sensor altitude reading from the `position` input.

### Input Arguments

**`position` — Position of sensor in local navigation coordinate system (m)**
*N*-by-3 matrix

Position of sensor in the local navigation coordinate system, specified as an *N*-by-3 matrix with elements measured in meters. *N* is the number of samples in the current frame.

Data Types: `single` | `double`

### Output Arguments

**`altimeterReadings` — Altitude of sensor relative to local navigation coordinate system (m)**
*N*-element column vector

Altitude of sensor relative to the local navigation coordinate system in meters, returned as an *N*-element column vector. *N* is the number of samples in the current frame.

Data Types: `single` | `double`

## Object Functions

To use an object function, specify the System object as the first input argument. For example, to release system resources of a System object named `obj`, use this syntax:

```
release(obj)
```

## Common to All System Objects

| | |
|---|---|
| step | Run System object algorithm |
| release | Release resources and allow changes to System object property values and input characteristics |
| reset | Reset internal states of System object |

## Examples

### Generate Noisy Altimeter Readings from Stationary Input

Create an altimeterSensor System object™ to model receiving altimeter sensor data. Assume a typical one Hz sample rate and a 10 minute simulation time. Set ConstantBias to 0.01, NoiseDensity to 0.05, BiasInstability to 0.05, and DecayFactor to 0.5.

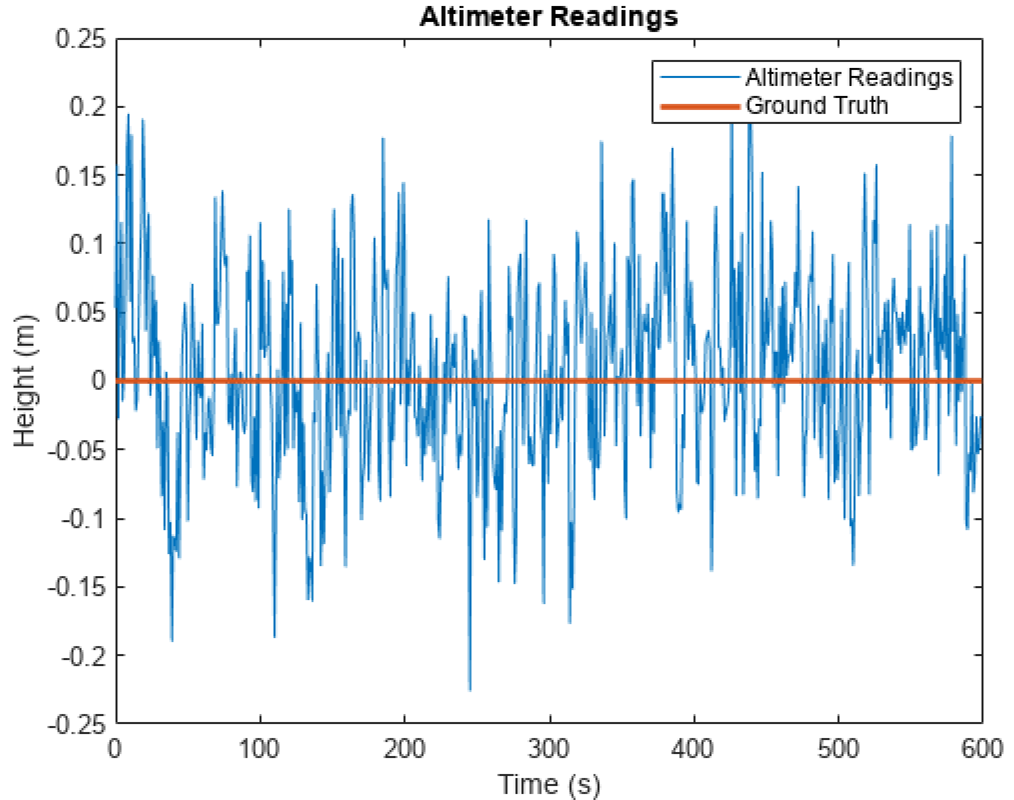
```
Fs = 1;
duration = 60*10;
numSamples = duration*Fs;


altimeter = altimeterSensor('SampleRate',Fs, ...
                            'ConstantBias',0.01, ...
                            'NoiseDensity',0.05, ...
                            'BiasInstability',0.05, ...
                            'DecayFactor',0.5);

truePosition = zeros(numSamples,3);
```

Call altimeter with the specified truePosition to model noisy altimeter readings from a stationary platform.

```
altimeterReadings = altimeter(truePosition);
```

Plot the true position and the altimeter sensor readings for height.

```
t = (0:(numSamples-1))/Fs;

plot(t,altimeterReadings)
hold on
plot(t,truePosition(:,3),'LineWidth',2)
hold off
title('Altimeter Readings')
xlabel('Time (s)')
ylabel('Height (m)')
legend('Altimeter Readings','Ground Truth')
```




# Version History

**Introduced in R2019a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

Usage notes and limitations:

See "System Objects in MATLAB Code Generation" (MATLAB Coder).

## See Also

`gpsSensor` | `imuSensor`

# complementaryFilter

Estimate orientation using complementary filter

## Description

The `complementaryFilter` System object fuses accelerometer, gyroscope, and magnetometer sensor data to estimate device orientation and angular velocity.

To estimate orientation using this object:

1. Create the `complementaryFilter` object and set its properties.
2. Call the object with arguments, as if it were a function.

To learn more about how System objects work, see What Are System Objects?

# Creation

## Syntax

```
FUSE = complementaryFilter
FUSE = complementaryFilter('ReferenceFrame',RF)
FUSE = complementaryFilter( ___ ,Name,Value)
```

### Description

`FUSE = complementaryFilter` returns a `complementaryFilter` System object, `FUSE`, for sensor fusion of accelerometer, gyroscope, and magnetometer data to estimate device orientation and angular velocity.

`FUSE = complementaryFilter('ReferenceFrame',RF)` returns a `complementaryFilter` System object that fuses accelerometer, gyroscope, and magnetometer data to estimate device orientation relative to the reference frame `RF`. Specify `RF` as `'NED'` (North-East-Down) or `'ENU'` (East-North-Up). The default value is `'NED'`.

`FUSE = complementaryFilter( ___ ,Name,Value)` sets each property `Name` to the specified `Value`. Unspecified properties have default values.

## Properties

Unless otherwise indicated, properties are *nontunable*, which means you cannot change their values after calling the object. Objects lock when you call them, and the `release` function unlocks them.

If a property is *tunable*, you can change its value at any time.

For more information on changing property values, see System Design in MATLAB Using System Objects.

**`SampleRate` — Input sample rate of sensor data (Hz)**
`100` (default) | positive scalar

Input sample rate of the sensor data in Hz, specified as a positive scalar.

**Tunable:** No

Data Types: `single` | `double`

**`AccelerometerGain` — Accelerometer gain**
`0.01` (default) | real scar in [0, 1]

Accelerometer gain, specified as a real scalar in the range of [0, 1]. The gain determines how much the accelerometer measurement is trusted over the gyroscope measurement for orientation estimation. This property is tunable.

Data Types: `single` | `double`

**`MagnetometerGain` — Magnetometer gain**
`0.01` (default) | real scar in [0, 1]

Magnetometer gain, specified as a real scalar in the range of [0, 1]. The gain determines how much the magnetometer measurement is trusted over the gyroscope measurement for orientation estimation. This property is tunable.

Data Types: `single` | `double`

**`HasMagnetometer` — Enable magnetometer input**
`true` (default) | `false`

Enable magnetometer input, specified as `true` or `false`.

Data Types: `logical`

**`OrientationFormat` — Output orientation format**
`'quaternion'` (default) | `'Rotation matrix'`

Output orientation format, specified as `'quaternion'` or `'Rotation matrix'`. The size of the output depends on the output orientation format:

- `'quaternion'` -– Output is an *N*-by-1 `quaternion`.
- `'Rotation matrix'` -– Output is a 3-by-3-by-*N* rotation matrix.

*N* is the number of samples.

Data Types: `char` | `string`

## Usage

## Syntax

```
[orientation,angularVelocity] = FUSE(accelReadings,gyroReadings,magReadings)
[orientation,angularVelocity] = FUSE(accelReadings,gyroReadings)
```

### Description

`[orientation,angularVelocity] = FUSE(accelReadings,gyroReadings,magReadings)` fuses accelerometer, gyroscope, and magnetometer data to compute orientation and angular velocity. To use this syntax, set the `HasMagnetometer` property as `true`.

`[orientation,angularVelocity] = FUSE(accelReadings,gyroReadings)` fuses accelerometer and gyroscope data to compute orientation and angular velocity. To use this syntax, set the `HasMagnetometer` property as `false`.

### Input Arguments

**`accelReadings` — Accelerometer readings in sensor body coordinate system (m/s²)**
*N*-by-3 matrix

Accelerometer readings in the sensor body coordinate system in $m/s^2$, specified as an *N*-by-3 matrix. *N* is the number of samples, and the three columns of `accelReadings` represent the [*x y z*] measurements. Accelerometer readings are assumed to correspond to the sample rate specified by the `SampleRate` property. In the filter, the gravity constant *g* is assumed to be `9.81` $m/s^2$.

Data Types: `single` | `double`

**`gyroReadings` — Gyroscope readings in sensor body coordinate system (rad/s)**
*N*-by-3 matrix

Gyroscope readings in the sensor body coordinate system in rad/s, specified as an *N*-by-3 matrix. *N* is the number of samples, and the three columns of `gyroReadings` represent the [*x y z*] measurements. Gyroscope readings are assumed to correspond to the sample rate specified by the `SampleRate` property.

Data Types: `single` | `double`

**`magReadings` — Magnetometer readings in sensor body coordinate system (µT)**
*N*-by-3 matrix

Magnetometer readings in the sensor body coordinate system in µT, specified as an *N*-by-3 matrix. *N* is the number of samples, and the three columns of `magReadings` represent the [*x y z*] measurements. Magnetometer readings are assumed to correspond to the sample rate specified by the `SampleRate` property.

Data Types: `single` | `double`

### Output Arguments

**`orientation` — Orientation that rotates quantities from local navigation coordinate system to sensor body coordinate system**
*N*-by-1 array of quaternions (default) | 3-by-3-by-*N* array

Orientation that rotates quantities from the local navigation coordinate system to the body coordinate system, returned as quaternions or an array. The size and type of `orientation` depends on whether the `OrienationFormat` property is set to `'quaternion'` or `'Rotation matrix'`:

- `'quaternion'` –– the output is an *N*-by-1 vector of quaternions, where *N* is the number of samples.
- `'Rotation matrix'` –– the output is a 3-by-3-by-*N* array of rotation matrices, where *N* is the number of samples.

Data Types: quaternion | single | double

**angularVelocity — Angular velocity in sensor body coordinate system (rad/s)**
*N*-by-3 array (default)

Angular velocity expressed in the sensor body coordinate system in rad/s, returned as an *N*-by-3 array, where *N* is the number of samples.

Data Types: single | double

## Object Functions

To use an object function, specify the System object as the first input argument. For example, to release system resources of a System object named obj, use this syntax:

```
release(obj)
```

## Common to All System Objects

| | |
|---|---|
| step | Run System object algorithm |
| release | Release resources and allow changes to System object property values and input characteristics |
| reset | Reset internal states of System object |
| clone | Create duplicate System object |
| isLocked | Determine if System object is in use |

## Examples

### Estimate Orientation from Recorded IMU Data

Load the rpy_9axis file, which contains recorded accelerometer, gyroscope, and magnetometer sensor data from a device oscillating in pitch (around *y*-axis), then yaw (around *z*-axis), and then roll (around *x*-axis). The file also contains the sample rate of the recording.

```
ld = load('rpy_9axis.mat');
accel = ld.sensorData.Acceleration;
gyro = ld.sensorData.AngularVelocity;
mag = ld.sensorData.MagneticField;
```

Create a complementary filter object with sample rate equal to the frequency of the data.

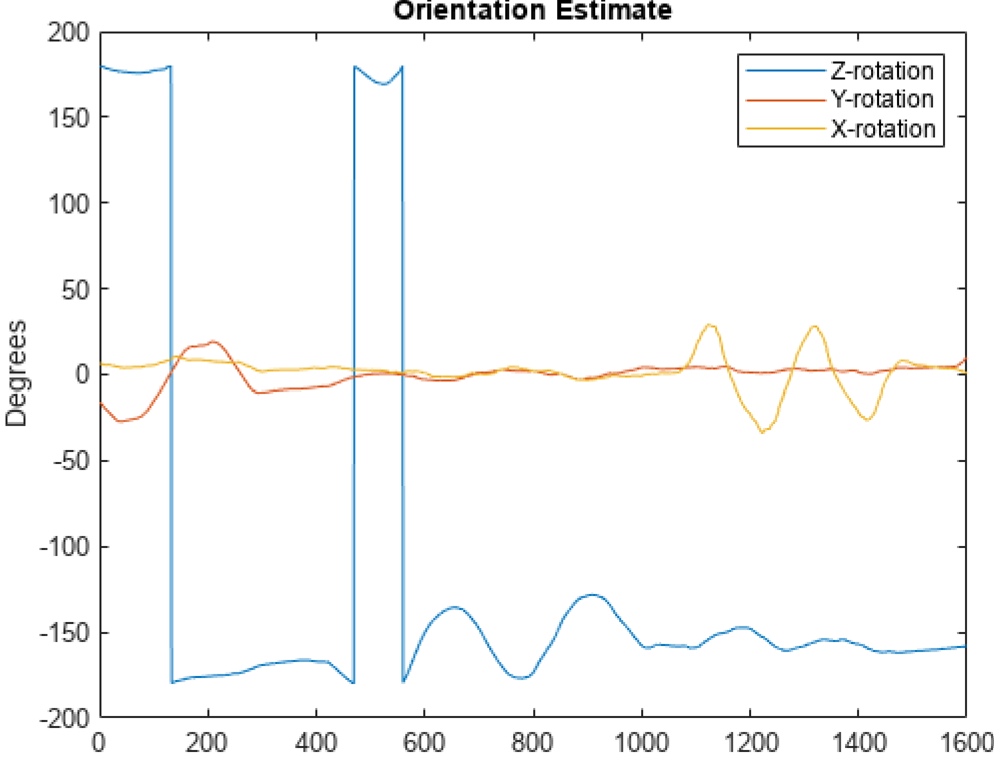
```
Fs  = ld.Fs;  % Hz
fuse = complementaryFilter('SampleRate', Fs);
```

Fuse accelerometer, gyroscope, and magnetometer data using the filter.

```
q = fuse(accel, gyro, mag);
```

Visualize the results.

```
plot(eulerd( q, 'ZYX', 'frame'));
title('Orientation Estimate');
legend('Z-rotation', 'Y-rotation', 'X-rotation');
ylabel('Degrees');
```




# Version History

**Introduced in R2019b**

## References

[1] Valenti, R., I. Dryanovski, and J. Xiao. "Keeping a good attitude: A quaternion-based orientation filter for IMUs and MARGs." *Sensors.* Vol. 15, Number 8, 2015, pp. 19302-19330.

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`ahrsfilter` | `imufilter`

# insfilterAsync

Estimate pose from asynchronous MARG and GPS data

## Description

The `insfilterAsync` object implements sensor fusion of MARG and GPS data to estimate pose in the NED (or ENU) reference frame. MARG (magnetic, angular rate, gravity) data is typically derived from magnetometer, gyroscope, and accelerometer data, respectively. The filter uses a 28-element state vector to track the orientation `quaternion`, velocity, position, MARG sensor biases, and geomagnetic vector. The `insfilterAsync` object uses a continuous-discrete extended Kalman filter to estimate these quantities.

## Creation

### Syntax

```
filter = insfilterAsync
filter = insfilterAsync('ReferenceFrame',RF)
filter = insfilterAsync( ___ ,Name,Value)
```

#### Description

`filter = insfilterAsync` creates an `insfilterAsync` object to fuse asynchronous MARG and GPS data with default property values.

`filter = insfilterAsync('ReferenceFrame',RF)` allows you to specify the reference frame, `RF`, of the `filter`. Specify `RF` as `'NED'` (North-East-Down) or `'ENU'` (East-North-Up). The default value is `'NED'`.

`filter = insfilterAsync( ___ ,Name,Value)` also allows you set properties of the created `filter` using one or more name-value pairs. Enclose each property name in single quotes.

## Properties

**`ReferenceLocation` — Reference location (deg, deg, meters)**
`[0 0 0]` (default) | three-element positive row vector

Reference location, specified as a three-element row vector in geodetic coordinates (latitude, longitude, and altitude). Altitude is the height above the reference ellipsoid model, WGS84. The reference location units are [degrees degrees meters].

Data Types: `single` | `double`

**`QuaternionNoise` — Additive quaternion process noise variance**
`[1e-6 1e-6 1e-6 1e-6]` (default) | scalar | four-element row vector

Additive quaternion process noise variance, specified as a scalar or four-element vector of quaternion parts.

Data Types: single | double

**AngularVelocityNoise — Additive angular velocity process noise in local navigation coordinate system ((rad/s)$^2$)**

[0.005 0.005 0.005] (default) | scalar | three-element row vector

Additive angular velocity process noise in the local navigation coordinate system in (rad/s)$^2$, specified as a scalar or three-element row vector of positive real finite numbers.

- If AngularVelocityNoise is a row vector, the elements correspond to the noise in the *x*, *y*, and *z* axes of the local navigation coordinate system, respectively.
- If AngularVelocityNoise is a scalar, the single element is applied to each axis.

Data Types: single | double

**PositionNoise — Additive position process noise variance in local navigation coordinate system (m$^2$)**

[1e-6 1e-6 1e-6] (default) | scalar | three-element row vector

Additive position process noise in the local navigation coordinate system in m$^2$, specified as a scalar or three-element row vector of positive real finite numbers.

- If PositionNoise is a row vector, the elements correspond to the noise in the *x*, *y*, and *z* axes of the local navigation coordinate system, respectively.
- If PositionNoise is a scalar, the single element is applied to each axis.

Data Types: single | double

**VelocityNoise — Additive velocity process noise variance in local navigation coordinate system ((m/s)$^2$)**

[1e-6 1e-6 1e-6] (default) | scalar | three-element row vector

Additive velocity process noise in the local navigation coordinate system in (m/s)$^2$, specified as a scalar or three-element row vector of positive real finite numbers.

- If VelocityNoise is a row vector, the elements correspond to the noise in the *x*, *y*, and *z* axes of the local navigation coordinate system, respectively.
- If VelocityNoise is a scalar, the single element is applied to each axis.

Data Types: single | double

**AccelerationNoise — Additive acceleration process noise variance in local navigation coordinate system ((m/s$^2$)$^2$)**

[50 50 50] (default) | scalar | three-element row vector

Additive acceleration process noise in (m/s$^2$)$^2$, specified as a scalar or three-element row vector of positive real finite numbers.

- If AccelerationNoise is a row vector, the elements correspond to the noise in the *x*, *y*, and *z* axes of the local navigation coordinate system, respectively.
- If AccelerationNoise is a scalar, the single element is applied to each axis.

Data Types: single | double

**GyroscopeBiasNoise — Additive process noise variance from gyroscope bias ((rad/s)$^2$)**
[1e-10 1e-10 1e-10] (default) | scalar | three-element row vector

Additive process noise variance from the gyroscope bias in (rad/s)$^2$, specified as a scalar or three-element row vector of positive real finite numbers.

- If GyroscopeBiasNoise is a row vector, the elements correspond to the noise in the *x*, *y*, and *z* axes of the gyroscope, respectively.
- If GyroscopeBiasNoise is a scalar, the single element is applied to each axis.

Data Types: single | double

**AccelerometerBiasNoise — Additive process noise variance from accelerometer bias ((m/s$^2$)$^2$)**
[1e-4 1e-4 1e-4] (default) | positive scalar | three-element row vector

Additive process noise variance from accelerometer bias in (m/s$^2$)$^2$, specified as a scalar or three-element row vector of positive real numbers.

- If AccelerometerBiasNoise is a row vector, the elements correspond to the noise in the *x*, *y*, and *z* axes of the accelerometer, respectively.
- If AccelerometerBiasNoise is a scalar, the single element is applied to each axis.

**GeomagneticVectorNoise — Additive process noise variance of geomagnetic vector in local navigation coordinate system (μT$^2$)**
[1e-6 1e-6 1e-6] (default) | positive scalar | three-element row vector

Additive process noise variance of geomagnetic vector in μT$^2$, specified as a scalar or three-element row vector of positive real numbers.

- If GeomagneticVectorNoise is a row vector, the elements correspond to the noise in the *x*, *y*, and *z* axes of the local navigation coordinate system, respectively.
- If GeomagneticVectorNoise is a scalar, the single element is applied to each axis.

**MagnetometerBiasNoise — Additive process noise variance from magnetometer bias (μT$^2$)**
[0.1 0.1 0.1] (default) | positive scalar | three-element row vector

Additive process noise variance from magnetometer bias in μT$^2$, specified as a scalar or three-element row vector of positive real numbers.

- If MagnetometerBiasNoise is a row vector, the elements correspond to the noise in the *x*, *y*, and *z* axes of the magnetometer, respectively.
- If MagnetometerBiasNoise is a scalar, the single element is applied to each axis.

**State — State vector of extended Kalman filter**
28-element column vector

State vector of the extended Kalman filter. The state values represent:

| State | Units | Index |
|---|---|---|
| Orientation (quaternion parts) | N/A | 1:4 |
| Angular Velocity (XYZ) | rad/s | 5:7 |

| State | Units | Index |
|---|---|---|
| Position (NED or ENU) | m | 8:10 |
| Velocity (NED or ENU) | m/s | 11:13 |
| Acceleration (NED or ENU) | m/s$^2$ | 14:16 |
| Accelerometer Bias (XYZ) | m/s$^2$ | 17:19 |
| Gyroscope Bias (XYZ) | rad/s | 20:22 |
| Geomagnetic Field Vector (NED or ENU) | μT | 23:25 |
| Magnetometer Bias (XYZ) | μT | 26:28 |

The default initial state corresponds to an object at rest located at `[0 0 0]` in geodetic LLA coordinates.

Data Types: `single` | `double`

**`StateCovariance` — State error covariance for extended Kalman filter**
`eye(28)` (default) | 28-by-28 matrix

State error covariance for the extended Kalman filter, specified as a 28-by-28-element matrix of real numbers.

Data Types: `single` | `double`

## Object Functions

| | |
|---|---|
| predict | Update states based on motion model for insfilterAsync |
| fuseaccel | Correct states using accelerometer data for insfilterAsync |
| fusegyro | Correct states using gyroscope data for insfilterAsync |
| fusemag | Correct states using magnetometer data for insfilterAsync |
| fusegps | Correct states using GPS data for insfilterAsync |
| correct | Correct states using direct state measurements for insfilterAsync |
| residual | Residuals and residual covariances from direct state measurements for insfilterAsync |
| residualaccel | Residuals and residual covariance from accelerometer measurements for insfilterAsync |
| residualgps | Residuals and residual covariance from GPS measurements for insfilterAsync |
| residualmag | Residuals and residual covariance from magnetometer measurements for insfilterAsync |
| residualgyro | Residuals and residual covariance from gyroscope measurements for insfilterAsync |
| pose | Current position, orientation, and velocity estimate for insfilterAsync |
| reset | Reset internal states for insfilterAsync |
| stateinfo | Display state vector information for insfilterAsync |
| copy | Create copy of insfilterAsync |
| tune | Tune insfilterAsync parameters to reduce estimation error |
| tunernoise | Noise structure of fusion filter |

## Examples

### Estimate Pose of UAV

Load logged sensor data and ground truth pose.

```
load('uavshort.mat','refloc','initstate','imuFs', ...
    'accel','gyro','mag','lla','gpsvel', ...
    'trueOrient','truePos')
```

Create an INS filter to fuse asynchronous MARG and GPS data to estimate pose.

```
filt = insfilterAsync;
filt.ReferenceLocation = refloc;
filt.State = [initstate(1:4);0;0;0;initstate(5:10);0;0;0;initstate(11:end)];
```

Define sensor measurement noises. The noises were determined from datasheets and experimentation.

```
Rmag  = 80;
Rvel  = 0.0464;
Racc  = 800;
Rgyro = 1e-4;
Rpos  = 34;
```

Preallocate variables for position and orientation. Allocate a variable for indexing into the GPS data.

```
N = size(accel,1);
p = zeros(N,3);
q = zeros(N,1,'quaternion');

gpsIdx = 1;
```

Fuse accelerometer, gyroscope, magnetometer, and GPS data. The outer loop predicts the filter forward one time step and fuses accelerometer and gyroscope data at the IMU sample rate.

```
for ii = 1:N

    % Predict the filter forward one time step
    predict(filt,1./imuFs);

    % Fuse accelerometer and gyroscope readings
    fuseaccel(filt,accel(ii,:),Racc);
    fusegyro(filt,gyro(ii,:),Rgyro);

    % Fuse magnetometer at 1/2 the IMU rate
    if ~mod(ii, fix(imuFs/2))
        fusemag(filt,mag(ii,:),Rmag);
    end

    % Fuse GPS once per second
    if ~mod(ii,imuFs)
        fusegps(filt,lla(gpsIdx,:),Rpos,gpsvel(gpsIdx,:),Rvel);
        gpsIdx = gpsIdx + 1;
    end

    % Log the current pose estimate
    [p(ii,:),q(ii)] = pose(filt);

end
```

Calculate the RMS errors between the known true position and orientation and the output from the asynchronous IMU filter.

```
posErr = truePos - p;
qErr = rad2deg(dist(trueOrient,q));

pRMS = sqrt(mean(posErr.^2));
qRMS = sqrt(mean(qErr.^2));

fprintf('Position RMS Error\n');
```

```
Position RMS Error
```

```
fprintf('\tX: %.2f, Y: %.2f, Z: %.2f (meters)\n\n',pRMS(1),pRMS(2),pRMS(3));
```

```
    X: 0.55, Y: 0.71, Z: 0.74 (meters)
```

```
fprintf('Quaternion Distance RMS Error\n');
```

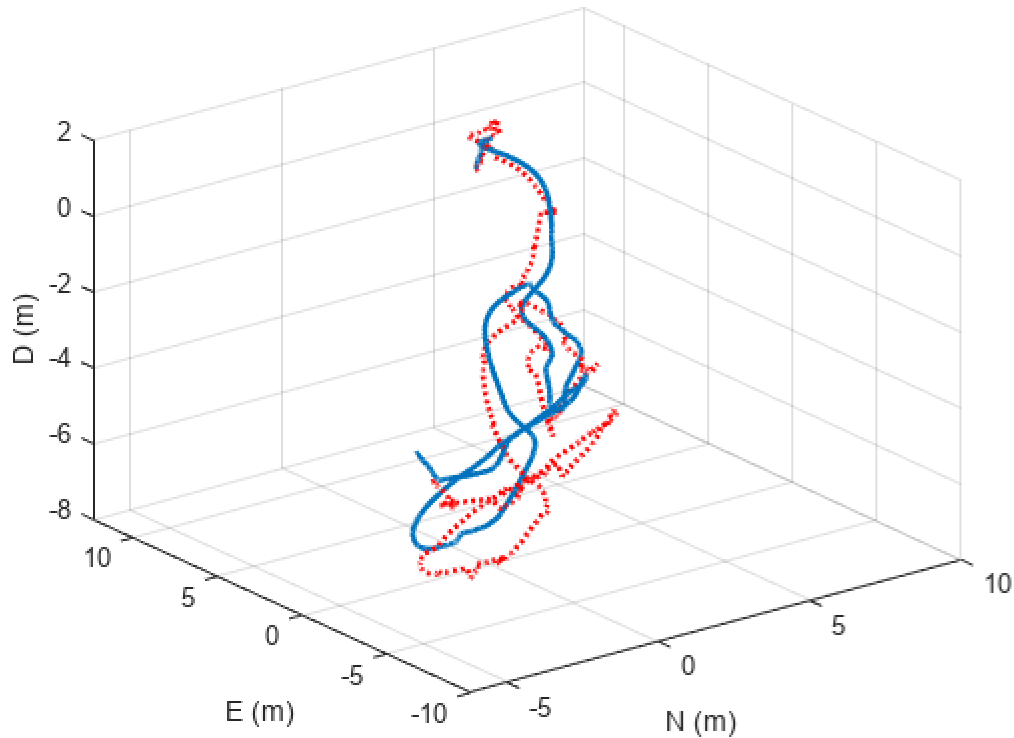
```
Quaternion Distance RMS Error
```

```
fprintf('\t%.2f (degrees)\n\n', qRMS);
```

```
    4.72 (degrees)
```

Visualize the true position and the estimated position.

```
plot3(truePos(:,1),truePos(:,2),truePos(:,3),'LineWidth',2)
hold on
plot3(p(:,1),p(:,2),p(:,3),'r:','LineWidth',2)
grid on
xlabel('N (m)')
ylabel('E (m)')
zlabel('D (m)')
```




## Algorithms

### Dynamic Model Used in `insfilterAsync`

*Note: The following algorithm only applies to an NED reference frame.*

`insfilterAsync` implements a 28-axis continuous-discrete extended Kalman filter using sequential fusion. The filter relies on the assumption that individual sensor measurements are uncorrelated. The filter uses an omnidirectional motion model and assumes constant angular velocity and constant acceleration. The state is defined as:

$$x = \begin{bmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \\ angVel_X \\ angVel_Y \\ angVel_Z \\ position_N \\ position_E \\ position_D \\ \nu_N \\ \nu_E \\ \nu_D \\ accel_N \\ accel_E \\ accel_D \\ accelbias_X \\ accelbias_Y \\ accelbias_Z \\ gyrobias_X \\ gyrobias_Y \\ gyrobias_Z \\ geomagneticFieldVector_N \\ geomagneticFieldVector_E \\ geomagneticFieldVector_D \\ magbias_X \\ magbias_Y \\ magbias_Z \end{bmatrix}$$

where

- $q_0$, $q_1$, $q_2$, $q_3$ –– Parts of orientation quaternion. The orientation quaternion represents a frame rotation from the platform's current orientation to the local NED coordinate system.
- $angVel_X$, $angVel_Y$, $angVel_Z$ –– Angular velocity relative to the platform's body frame.
- $position_N$, $position_E$, $position_D$ –– Position of the platform in the local NED coordinate system.
- $\nu_N$, $\nu_E$, $\nu_D$ –– Velocity of the platform in the local NED coordinate system.
- $accel_N$, $accel_E$, $accel_D$ –– Acceleration of the platform in the local NED coordinate system.
- $accelbias_X$, $accelbias_Y$, $accelbias_Z$ –– Bias in the accelerometer reading.
- $gyrobias_X$, $gyrobias_Y$, $gyrobias_Z$ –– Bias in the gyroscope reading.

- $geomagneticFieldVector_{\mathrm{N}}$, $geomagneticFieldVector_{\mathrm{E}}$, $geomagneticFieldVector_{\mathrm{D}}$ –– Estimate of the geomagnetic field vector at the reference location.
- $magbias_{\mathrm{X}}$, $magbias_{\mathrm{Y}}$, $magbias_{\mathrm{Z}}$ –– Bias in the magnetometer readings.

Given the conventional formation of the process equation, $\dot{x} = f(x) + w$, $w$ is the process noise, $\dot{x}$ is the derivative of $x$, and:

$$f(x) = \begin{bmatrix} \frac{-(q_1)(angVel_{\mathrm{X}}) - (q_2)(angVel_{\mathrm{Y}}) - (q_3)(angVel_{\mathrm{Z}})}{2} \\ \frac{(q_0)(angVel_{\mathrm{X}}) - (q_3)(angVel_{\mathrm{Y}}) + (q_1)(angVel_{\mathrm{Z}})}{2} \\ \frac{(q_3)(angVel_{\mathrm{X}}) + (q_0)(angVel_{\mathrm{Y}}) - (q_1)(angVel_{\mathrm{Z}})}{2} \\ \frac{(q_1)(angVel_{\mathrm{X}}) - (q_2)(angVel_{\mathrm{Y}}) + (q_0)(angVel_{\mathrm{Z}})}{2} \\ 0 \\ 0 \\ 0 \\ v_{\mathrm{N}} \\ v_{\mathrm{E}} \\ v_{\mathrm{D}} \\ accel_{\mathrm{N}} \\ accel_{\mathrm{E}} \\ accel_{\mathrm{D}} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

# Version History

**Introduced in R2019a**

## Extended Capabilities

### C/C++ Code Generation
Generate C and C++ code using MATLAB® Coder™.

## See Also
`insfilterErrorState` | `insfilterNonholonomic` | `insfilterMARG`

# correct

Correct states using direct state measurements for `insfilterAsync`

## Syntax

`correct(FUSE,idx,measurement,measurementCovariance)`

## Description

`correct(FUSE,idx,measurement,measurementCovariance)` corrects the state and state estimation error covariance based on the measurement and measurement covariance. The measurement maps directly to the state specified by the indices `idx`.

## Input Arguments

**`FUSE` — `insfilterAsync` object**
object

`insfilterAsync`, specified as an object.

**`idx` — State vector index of measurement to correct**
*N*-element vector of increasing integers in the range [1, 28]

State vector index of measurement to correct, specified as an *N*-element vector of increasing integers in the range [1, 28].

The state values represent:

| State | Units | Index |
| --- | --- | --- |
| Orientation (quaternion parts) | N/A | 1:4 |
| Angular Velocity (XYZ) | rad/s | 5:7 |
| Position (NED) | m | 8:10 |
| Velocity (NED) | m/s | 11:13 |
| Acceleration (NED) | $m/s^2$ | 14:16 |
| Accelerometer Bias (XYZ) | $m/s^2$ | 17:19 |
| Gyroscope Bias (XYZ) | rad/s | 20:22 |
| Geomagnetic Field Vector (NED) | µT | 23:25 |
| Magnetometer Bias (XYZ) | µT | 26:28 |

Data Types: `single` | `double`

**`measurement` — Direct measurement of state**
*N*-element vector

Direct measurement of state, specified as an *N*-element vector. *N* is the number of elements of the index argument, `idx`.

Data Types: `single` | `double`

**`measurementCovariance` — Covariance of measurement**
scalar | *N*-element vector | *N*-by-*N* matrix

Covariance of measurement, specified as a scalar, *N*-element vector, or *N*-by-*N* matrix. *N* is the number of elements of the index argument, `idx`.

Data Types: `single` | `double`

# Version History
**Introduced in R2019a**

## Extended Capabilities

### C/C++ Code Generation
Generate C and C++ code using MATLAB® Coder™.

## See Also
`insfilterAsync` | `insfilter`

# copy

Create copy of `insfilterAsync`

## Syntax

```
newFilter = copy(filter)
```

## Description

`newFilter = copy(filter)` returns a copy of the `insfilterAsync`, `filter`, that has exactly the same property values.

## Input Arguments

**`filter` — Filter to be copied**
`insfilterAsync`

Filter to be copied, specified as an `insfilterAsync` object.

## Output Arguments

**`newFilter` — New copied filter**
`insfilterAsync`

New copied filter, returned as an `insfilterAsync` object.

# Version History

**Introduced in R2020b**

## See Also

`insfilterAsync`

# fuseaccel

Correct states using accelerometer data for `insfilterAsync`

## Syntax

```
[res,resCov] = fuseaccel(FUSE,acceleration,accelerationCovariance)
```

## Description

`[res,resCov] = fuseaccel(FUSE,acceleration,accelerationCovariance)` fuses accelerometer data to correct the state estimate.

## Input Arguments

**`FUSE` — `insfilterAsync` object**
object

`insfilterAsync`, specified as an object.

**`acceleration` — Accelerometer readings in local sensor body coordinate system ($m/s^2$)**
3-element row vector

Accelerometer readings in local sensor body coordinate system in $m/s^2$, specified as a 3-element row vector

Data Types: `single` | `double`

**`accelerationCovariance` — Acceleration error covariance of accelerometer measurement ($(m/s^2)^2$)**
scalar | 3-element row vector | 3-by-3 matrix

Acceleration error covariance of the accelerometer measurement in $(m/s^2)^2$, specified as a scalar, 3-element row vector, or 3-by-3 matrix.

Data Types: `single` | `double`

## Output Arguments

**`res` — Residual**
1-by-3 vector of real values

Residual, returned a 1-by-3 vector of real values in $m/s^2$.

**`resCov` — Residual covariance**
3-by-3 matrix of real values

Residual covariance, returned as a 3-by-3 matrix of real values in $(m/s^2)^2$.

## Version History

**Introduced in R2019a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`insfilterAsync` | `insfilter`

# fusegps

Correct states using GPS data for `insfilterAsync`

## Syntax

```
[res,resCov] = fusegps(FUSE,position,positionCovariance)
[res,resCov] = fusegps(FUSE,position,positionCovariance,velocity,
velocityCovariance)
```

## Description

`[res,resCov] = fusegps(FUSE,position,positionCovariance)` fuses GPS position data to correct the state estimate.

`[res,resCov] = fusegps(FUSE,position,positionCovariance,velocity, velocityCovariance)` fuses GPS position and velocity data to correct the state estimate.

## Input Arguments

**`FUSE` — `insfilterAsync` object**
object

`insfilterAsync`, specified as an object.

**`position` — Position of GPS receiver (LLA)**
3-element row vector

Position of GPS receiver in geodetic latitude, longitude, and altitude (LLA) specified as a real finite 3-element row vector. Latitude and longitude are in degrees with north and east being positive. Altitude is in meters.

Data Types: `single` | `double`

**`positionCovariance` — Position measurement covariance of GPS receiver ($m^2$)**
3-by-3 matrix

Position measurement covariance of GPS receiver in $m^2$, specified as a 3-by-3 matrix.

Data Types: `single` | `double`

**`velocity` — Velocity of GPS receiver in local NED coordinate system (m/s)**
3-element row vector

Velocity of the GPS receiver in the local NED coordinate system in m/s, specified as a 3-element row vector.

Data Types: `single` | `double`

**`velocityCovariance` — Velocity measurement covariance of GPS receiver ($m/s^2$)**
3-by-3 matrix

Velocity measurement covariance of the GPS receiver in the local NED coordinate system in $m/s^2$, specified as a 3-by-3 matrix.

Data Types: single | double

## Output Arguments

**res — Position and velocity residual**
1-by-6 vector of real values

Position and velocity residual, returned as a 1-by-6 vector of real values in m and m/s, respectively.

**resCov — Residual covariance**
6-by-6 matrix of real values

Residual covariance, returned as a 6-by-6 matrix of real values.

# Version History

**Introduced in R2019a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

insfilterAsync | insfilter | insfilterMARG

# fusegyro

Correct states using gyroscope data for `insfilterAsync`

## Syntax

`[res,resCov] = fusegyro(FUSE,gyroReadings,gyroCovariance)`

## Description

`[res,resCov] = fusegyro(FUSE,gyroReadings,gyroCovariance)` fuses gyroscope data to correct the state estimate.

## Input Arguments

**`FUSE` — `insfilterAsync` object**
object

`insfilterAsync`, specified as an object.

**`gyroReadings` — Gyroscope readings in local sensor body coordinate system (rad/s)**
3-element row vector

Gyroscope readings in local sensor body coordinate system in rad/s, specified as a 3-element row vector.

Data Types: `single` | `double`

**`gyroCovariance` — Covariance of gyroscope measurement error ((rad/s)$^2$)**
scalar | 3-element row vector | 3-by-3 matrix

Covariance of gyroscope measurement error in (rad/s)$^2$, specified as a scalar, 3-element row vector, or 3-by-3 matrix.

Data Types: `single` | `double`

## Output Arguments

**`res` — Residual**
1-by-3 vector of real values

Residual, returned as a 1-by-3 vector of real values in rad/s.

**`resCov` — Residual covariance**
3-by-3 matrix of real values

Residual covariance, returned as a 3-by-3 matrix of real values in (rad/s)$^2$.

# Version History

**Introduced in R2019a**

## Extended Capabilities

### C/C++ Code Generation
Generate C and C++ code using MATLAB® Coder™.

## See Also
insfilterAsync | insfilter

# fusemag

Correct states using magnetometer data for `insfilterAsync`

## Syntax

`[res,resCov] = fusemag(FUSE,magReadings,magReadingsCovariance)`

## Description

`[res,resCov] = fusemag(FUSE,magReadings,magReadingsCovariance)` fuses magnetometer data to correct the state estimate.

## Input Arguments

**`FUSE` — `insfilterAsync` object**
object

`insfilterAsync`, specified as an object.

**`magReadings` — Magnetometer readings (µT)**
3-element row vector

Magnetometer readings in µT, specified as a 3-element row vector of finite real numbers.

Data Types: `single` | `double`

**`magReadingsCovariance` — Magnetometer readings error covariance (µT$^2$)**
scalar | 3-element row vector | 3-by-3 matrix

Magnetometer readings error covariance in µT$^2$, specified as a scalar, 3-element row vector, or 3-by-3 matrix.

Data Types: `single` | `double`

## Output Arguments

**`res` — Residual**
1-by-3 vector of real values

Residual, returned a 1-by-3 vector of real values in µT.

Data Types: `single` | `double`

**`resCov` — Residual covariance**
3-by-3 matrix of real values

Residual covariance, returned a 3-by-3 matrix of real values in (µT)$^2$.

# Version History

**Introduced in R2019a**

## Extended Capabilities

### C/C++ Code Generation
Generate C and C++ code using MATLAB® Coder™.

## See Also
`insfilterAsync` | `insfilter`

# pose

Current position, orientation, and velocity estimate for `insfilterAsync`

## Syntax

```
[position,orientation,velocity] = pose(FUSE)
[position,orientation,velocity] = pose(FUSE,format)
```

## Description

`[position,orientation,velocity] = pose(FUSE)` returns the current estimate of the pose.

`[position,orientation,velocity] = pose(FUSE,format)` returns the current estimate of the pose with orientation in the specified orientation format.

## Input Arguments

**`FUSE` — `insfilterAsync` object**
object

`insfilterAsync`, specified as an object.

**`format` — Output orientation format**
`'quaternion'` (default) | `'rotmat'`

Output orientation format, specified as either `'quaternion'` for a `quaternion` or `'rotmat'` for a rotation matrix.

Data Types: `char` | `string`

## Output Arguments

**`position` — Position estimate expressed in the local coordinate system (m)**
3-element row vector

Position estimate expressed in the local coordinate system of the filter in meters, returned as a 3-element row vector.

Data Types: `single` | `double`

**`orientation` — Orientation estimate expressed in the local coordinate system**
quaternion (default) | 3-by-3 rotation matrix

Orientation estimate expressed in the local coordinate system of the filter, returned as a scalar quaternion or 3-by-3 rotation matrix. The quaternion or rotation matrix represents a frame rotation from the local reference frame of the filter to the body reference frame.

Data Types: `single` | `double` | `quaternion`

**`velocity` — Velocity estimate expressed in local coordinate system (m/s)**
3-element row vector

Velocity estimate expressed in the local coordinate system of the filter in m/s, returned as a 3-element row vector.

Data Types: `single` | `double`

# Version History

**Introduced in R2019a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`insfilterAsync` | `insfilter`

# predict

Update states based on motion model for `insfilterAsync`

## Syntax

```
predict(FUSE,dt)
```

## Description

`predict(FUSE,dt)` updates states based on the motion model.

## Input Arguments

**`FUSE` — `insfilterAsync` object**
object

`insfilterAsync`, specified as an object.

**`dt` — Delta time to propagate forward (s)**
scalar

Delta time to propagate forward in seconds, specified as a positive scalar.

Data Types: `single` | `double`

# Version History

**Introduced in R2019a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

`insfilterAsync` | `insfilter`

# reset

Reset internal states for `insfilterAsync`

## Syntax

`reset(FUSE)`

## Description

`reset(FUSE)` resets the `State` and `StateCovariance` properties of the `insfilterAsync` object to their default values.

## Input Arguments

**FUSE — `insfilterAsync` object**
object

`insfilterAsync`, specified as an object.

# Version History

**Introduced in R2019a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

`insfilterAsync` | `insfilter`

# residual

Residuals and residual covariances from direct state measurements for `insfilterAsync`

## Syntax

```
[res, resCov]= residual(FUSE,idx,measurement,measurementCovariance)
```

## Description

`[res, resCov]= residual(FUSE,idx,measurement,measurementCovariance)` computes the residual, `res`, and the residual covariance, `resCov`, based on the direct state measurement and measurement covariance. The `measurement` maps directly to the states specified by indices, `idx`.

## Input Arguments

**`FUSE` — `insfilterAsync`**
`ahrs10filter` | object

`insfilterAsync`, specified as an object.

**`idx` — State vector index of measurement to correct**
*N*-element vector of increasing integers in the range [1, 28]

State vector index of measurement to correct, specified as an *N*-element vector of increasing integers in the range [1, 28].

The state values represent:

| State | Units | Index |
|---|---|---|
| Orientation (quaternion parts) | N/A | 1:4 |
| Angular Velocity (XYZ) | rad/s | 5:7 |
| Position (NED) | m | 8:10 |
| Velocity (NED) | m/s | 11:13 |
| Acceleration (NED) | m/s$^2$ | 14:16 |
| Accelerometer Bias (XYZ) | m/s$^2$ | 17:19 |
| Gyroscope Bias (XYZ) | rad/s | 20:22 |
| Geomagnetic Field Vector (NED) | µT | 23:25 |
| Magnetometer Bias (XYZ) | µT | 26:28 |

Data Types: `single` | `double`

**`measurement` — Direct measurement of state**
*N*-element vector

Direct measurement of state, specified as a *N*-element vector. *N* is the number of elements of the index argument, `idx`.

#### `measurementCovariance` — Covariance of measurement
*N*-by-*N* matrix

Covariance of measurement, specified as an *N*-by-*N* matrix. *N* is the number of elements of the index argument, `idx`.

### Output Arguments

#### `res` — Measurement residual
1-by-*N* vector of real values

Measurement residual, returned as a 1-by-*N* vector of real values.

#### `resCov` — Residual covariance
*N*-by-*N* matrix of real values

Residual covariance, returned as a *N*-by-*N* matrix of real values.

## Version History
**Introduced in R2020a**

### Extended Capabilities

#### C/C++ Code Generation
Generate C and C++ code using MATLAB® Coder™.

### See Also
`insfilterAsync`

# residualaccel

Residuals and residual covariance from accelerometer measurements for `insfilterAsync`

## Syntax

```
[res,resCov] = residualaccel(FUSE,acceleration,accelerationCovariance)
```

## Description

`[res,resCov] = residualaccel(FUSE,acceleration,accelerationCovariance)` computes the residual, `res`, and the residual covariance, `resCov`, based on the acceleration readings and the corresponding covariance.

## Input Arguments

**FUSE — `insfilterAsync`**
`ahrs10filter` | object

`insfilterAsync`, specified as an object.

**`acceleration` — Accelerometer readings in local sensor body coordinate system ($m/s^2$)**
3-element row vector

Accelerometer readings in local sensor body coordinate system in $m/s^2$, specified as a 3-element row vector

Data Types: `single` | `double`

**`accelerationCovariance` — Acceleration error covariance of accelerometer measurement ($(m/s^2)^2$)**
scalar | 3-element row vector | 3-by-3 matrix

Acceleration error covariance of the accelerometer measurement in $(m/s^2)^2$, specified as a scalar, 3-element row vector, or 3-by-3 matrix.

Data Types: `single` | `double`

## Output Arguments

**`res` — Residual**
1-by-3 vector of real values

Residual, returned a 1-by-3 vector of real values in $m/s^2$.

**`resCov` — Residual covariance**
3-by-3 matrix of real values

Residual covariance, returned a 3-by-3 matrix of real values in $(m/s^2)^2$.

# Version History

**Introduced in R2020a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`insfilterAsync` | `insfilter`

# residualgps

Residuals and residual covariance from GPS measurements for `insfilterAsync`

## Syntax

```
[res,resCov] = residualgps(FUSE,position,positionCovariance)
[res,resCov] = residualgps(FUSE,position,positionCovariance,velocity,
velocityCovariance)
```

## Description

`[res,resCov] = residualgps(FUSE,position,positionCovariance)` computes the residual, `res`, and the residual covariance, `resCov`, based on the GPS position measurement and covariance.

`[res,resCov] = residualgps(FUSE,position,positionCovariance,velocity, velocityCovariance)` computes the residual, `res`, and the residual covariance, `resCov`, based on the GPS position measurement and covariance.

## Input Arguments

**`FUSE` — `insfilterAsync`**
`ahrs10filter` | object

`insfilterAsync`, specified as an object.

**`position` — Position of GPS receiver (LLA)**
3-element row vector

Position of GPS receiver in geodetic latitude, longitude, and altitude (LLA) specified as a real finite 3-element row vector. Latitude and longitude are in degrees with north and east being positive. Altitude is in meters.

Data Types: `single` | `double`

**`positionCovariance` — Position measurement covariance of GPS receiver ($m^2$)**
3-by-3 matrix

Position measurement covariance of GPS receiver in $m^2$, specified as a 3-by-3 matrix.

Data Types: `single` | `double`

**`velocity` — Velocity of GPS receiver in local NED coordinate system (m/s)**
3-element row vector

Velocity of the GPS receiver in the local NED coordinate system in m/s, specified as a 3-element row vector.

Data Types: `single` | `double`

**`velocityCovariance` — Velocity measurement covariance of GPS receiver ($m/s^2$)**
3-by-3 matrix

Velocity measurement covariance of the GPS receiver in the local NED coordinate system in $m/s^2$, specified as a 3-by-3 matrix.

Data Types: `single` | `double`

### Output Arguments

**`res` — Position and velocity residual**
1-by-3 vector of real values | 1-by-6 vector of real values

Position and velocity residual, returned as a 1-by-3 vector of real values if the inputs only contain position information, and returned as 1-by-6 vector of real values if the inputs also contain velocity information.

**`resCov` — Residual covariance**
3-by-3 matrix of real values | 6-by-6 matrix of real values

Residual covariance, returned as a 3-by-3 matrix of real values if the inputs only contain position information, and a 6-by-6 matrix of real values if the inputs also contain velocity information.

## Version History

**Introduced in R2020a**

### Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

### See Also

`insfilterAsync`

# residualgyro

Residuals and residual covariance from gyroscope measurements for `insfilterAsync`

## Syntax

```
[res,resCov] = residualgyro(FUSE,gyroReadings,gyroCovariance)
```

## Description

`[res,resCov] = residualgyro(FUSE,gyroReadings,gyroCovariance)` computes the residual, `res`, and the innovation covariance, `resCov`, based on the gyroscope readings and the corresponding covariance.

## Input Arguments

**`FUSE` — `insfilterAsync`**
`ahrs10filter` | object

`insfilterAsync`, specified as an object.

**`gyroReadings` — Gyroscope readings in local sensor body coordinate system (rad/s)**
3-element row vector

Gyroscope readings in local sensor body coordinate system in rad/s, specified as a 3-element row vector.

Data Types: `single` | `double`

**`gyroCovariance` — Covariance of gyroscope measurement error ($(rad/s)^2$)**
scalar | 3-element row vector | 3-by-3 matrix

Covariance of gyroscope measurement error in $(rad/s)^2$, specified as a scalar, 3-element row vector, or 3-by-3 matrix.

Data Types: `single` | `double`

## Output Arguments

**`res` — Residual**
1-by-3 vector of real values

Residual, returned as a 1-by-3 vector of real values in rad/s.

**`resCov` — Residual covariance**
3-by-3 matrix of real values

Residual covariance, returned as a 3-by-3 matrix of real values in $(rad/s)^2$.

## Version History

**Introduced in R2020a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`insfilterAsync` | `insfilter`

# residualmag

Residuals and residual covariance from magnetometer measurements for `insfilterAsync`

## Syntax

```
[res,resCov] = residualmag(FUSE,magReadings,magReadingsCovariance)
```

## Description

`[res,resCov] = residualmag(FUSE,magReadings,magReadingsCovariance)` computes the residual, `residual`, and the residual covariance, `resCov`, based on the magnetometer readings and the corresponding covariance.

## Input Arguments

**`FUSE` — `insfilterAsync`**
`ahrs10filter` | object

`insfilterAsync`, specified as an object.

**`magReadings` — Magnetometer readings (µT)**
3-element row vector

Magnetometer readings in µT, specified as a 3-element row vector of finite real numbers.

Data Types: `single` | `double`

**`magReadingsCovariance` — Magnetometer readings error covariance (µT$^2$)**
scalar | 3-element row vector | 3-by-3 matrix

Magnetometer readings error covariance in µT$^2$, specified as a scalar, 3-element row vector, or 3-by-3 matrix.

Data Types: `single` | `double`

## Output Arguments

**`res` — Residual**
1-by-3 vector of real values

Residual, returned as a 1-by-3 vector of real values in µT.

Data Types: `single` | `double`

**`resCov` — Residual covariance**
3-by-3 matrix of real values

Residual covariance, returned a 3-by-3 matrix of real values in (µT)$^2$.

## Version History

**Introduced in R2020a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`insfilterAsync`

# stateinfo

Display state vector information for `insfilterAsync`

## Syntax

```
stateinfo(FUSE)
info = stateinfo(FUSE)
```

## Description

`stateinfo(FUSE)` displays the description of each index of the `State` property of the `insfilterAsync` object and the associated units.

`info = stateinfo(FUSE)` returns a structure with fields containing descriptions of the elements of the state vector of the filter, `FUSE`.

## Examples

### State Information of `insfilterAsync`

Create an `insfilterAsync` object.

```
filter = insfilterAsync;
```

Display the state information of the created filter.

```
stateinfo(filter)
```

```
States                            Units    Index
Orientation (quaternion parts)             1:4
Angular Velocity (XYZ)            rad/s    5:7
Position (NAV)                    m        8:10
Velocity (NAV)                    m/s      11:13
Acceleration (NAV)                m/s^2    14:16
Accelerometer Bias (XYZ)          m/s^2    17:19
Gyroscope Bias (XYZ)              rad/s    20:22
Geomagnetic Field Vector (NAV)    µT       23:25
Magnetometer Bias (XYZ)           µT       26:28
```

Output the state information of the filter as a structure.

```
info = stateinfo(filter)
```

```
info = struct with fields:
               Orientation: [1 2 3 4]
           AngularVelocity: [5 6 7]
                  Position: [8 9 10]
                  Velocity: [11 12 13]
              Acceleration: [14 15 16]
         AccelerometerBias: [17 18 19]
             GyroscopeBias: [20 21 22]
```

```
    GeomagneticFieldVector: [23 24 25]
          MagnetometerBias: [26 27 28]
```

## Input Arguments

**FUSE — insfilterAsync object**
object

insfilterAsync, specified as an object.

## Output Arguments

**info — State information**
structure

State information, returned as a structure. The field names of the structure are names of the elements of the state vector in the filter. The values of each field are the corresponding indices of the state vector.

# Version History

**Introduced in R2019a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

insfilterAsync | insfilter

# tune

Tune `insfilterAsync` parameters to reduce estimation error

## Syntax

```
tunedMeasureNoise = tune(filter,measureNoise,sensorData,groundTruth)
tunedMeasureNoise = tune( ___ ,config)
```

## Description

`tunedMeasureNoise = tune(filter,measureNoise,sensorData,groundTruth)` adjusts the properties of the `insfilterAsync` filter object, `filter`, and measurement noises to reduce the root-mean-squared (RMS) state estimation error between the fused sensor data and the ground truth. The function also returns the tuned measurement noise, `tunedMeasureNoise`. The function uses the property values in the filter and the measurement noise provided in the `measureNoise` structure as the initial estimate for the optimization algorithm.

`tunedMeasureNoise = tune( ___ ,config)` specifies the tuning configuration based on a `tunerconfig` object, `config`.

## Examples

### Tune `insfilterAsync` to Optimize Pose Estimate

Load the recorded sensor data and ground truth data.

```
load('insfilterAsyncTuneData.mat');
```

Create timetables for the sensor data and the truth data.

```
sensorData = timetable(Accelerometer, Gyroscope, ...
    Magnetometer, GPSPosition, GPSVelocity, 'SampleRate', 100);
groundTruth = timetable(Orientation, Position, ...
    'SampleRate', 100);
```

Create an `insfilterAsync` filter object that has a few noise properties.

```
filter = insfilterAsync('State', initialState, ...
    'StateCovariance', initialStateCovariance, ...
    'AccelerometerBiasNoise', 1e-7, ...
    'GyroscopeBiasNoise', 1e-7, ...
    'MagnetometerBiasNoise', 1e-7, ...
    'GeomagneticVectorNoise', 1e-7);
```

Create a tuner configuration object for the filter. Set the maximum iterations to two. Also, set the tunable parameters as the unspecified properties.

```
config = tunerconfig('insfilterAsync','MaxIterations',8);
config.TunableParameters = setdiff(config.TunableParameters, ...
    {'GeomagneticVectorNoise', 'AccelerometerBiasNoise', ...
```

```
    'GyroscopeBiasNoise', 'MagnetometerBiasNoise'});
config.TunableParameters
```

```
ans = 1×10 string
    "AccelerationNoise"    "AccelerometerNoise"    "AngularVelocityNoise"    "GPSPositionNoise"
```

Use the tuner noise function to obtain a set of initial sensor noises used in the filter.

```
measNoise = tunernoise('insfilterAsync')
```

```
measNoise = struct with fields:
    AccelerometerNoise: 1
        GyroscopeNoise: 1
     MagnetometerNoise: 1
      GPSPositionNoise: 1
      GPSVelocityNoise: 1
```

Tune the filter and obtain the tuned parameters.

```
tunedParams = tune(filter,measNoise,sensorData,groundTruth,config);
```

```
    Iteration    Parameter               Metric
    _________    _________               ______
    1            AccelerationNoise       2.1345
    1            AccelerometerNoise      2.1264
    1            AngularVelocityNoise    1.9659
    1            GPSPositionNoise        1.9341
    1            GPSVelocityNoise        1.8420
    1            GyroscopeNoise          1.7589
    1            MagnetometerNoise       1.7362
    1            PositionNoise           1.7362
    1            QuaternionNoise         1.7218
    1            VelocityNoise           1.7218
    2            AccelerationNoise       1.7190
    2            AccelerometerNoise      1.7170
    2            AngularVelocityNoise    1.6045
    2            GPSPositionNoise        1.5948
    2            GPSVelocityNoise        1.5323
    2            GyroscopeNoise          1.4803
    2            MagnetometerNoise       1.4703
    2            PositionNoise           1.4703
    2            QuaternionNoise         1.4632
    2            VelocityNoise           1.4632
    3            AccelerationNoise       1.4596
    3            AccelerometerNoise      1.4548
    3            AngularVelocityNoise    1.3923
    3            GPSPositionNoise        1.3810
    3            GPSVelocityNoise        1.3322
    3            GyroscopeNoise          1.2998
    3            MagnetometerNoise       1.2976
    3            PositionNoise           1.2976
    3            QuaternionNoise         1.2943
    3            VelocityNoise           1.2943
    4            AccelerationNoise       1.2906
    4            AccelerometerNoise      1.2836
    4            AngularVelocityNoise    1.2491
    4            GPSPositionNoise        1.2258
```

```
    4           GPSVelocityNoise       1.1880
    4           GyroscopeNoise         1.1701
    4           MagnetometerNoise      1.1698
    4           PositionNoise          1.1698
    4           QuaternionNoise        1.1688
    4           VelocityNoise          1.1688
    5           AccelerationNoise      1.1650
    5           AccelerometerNoise     1.1569
    5           AngularVelocityNoise   1.1454
    5           GPSPositionNoise       1.1100
    5           GPSVelocityNoise       1.0778
    5           GyroscopeNoise         1.0709
    5           MagnetometerNoise      1.0675
    5           PositionNoise          1.0675
    5           QuaternionNoise        1.0669
    5           VelocityNoise          1.0669
    6           AccelerationNoise      1.0634
    6           AccelerometerNoise     1.0549
    6           AngularVelocityNoise   1.0549
    6           GPSPositionNoise       1.0180
    6           GPSVelocityNoise       0.9866
    6           GyroscopeNoise         0.9810
    6           MagnetometerNoise      0.9775
    6           PositionNoise          0.9775
    6           QuaternionNoise        0.9768
    6           VelocityNoise          0.9768
    7           AccelerationNoise      0.9735
    7           AccelerometerNoise     0.9652
    7           AngularVelocityNoise   0.9652
    7           GPSPositionNoise       0.9283
    7           GPSVelocityNoise       0.8997
    7           GyroscopeNoise         0.8947
    7           MagnetometerNoise      0.8920
    7           PositionNoise          0.8920
    7           QuaternionNoise        0.8912
    7           VelocityNoise          0.8912
    8           AccelerationNoise      0.8885
    8           AccelerometerNoise     0.8811
    8           AngularVelocityNoise   0.8807
    8           GPSPositionNoise       0.8479
    8           GPSVelocityNoise       0.8238
    8           GyroscopeNoise         0.8165
    8           MagnetometerNoise      0.8165
    8           PositionNoise          0.8165
    8           QuaternionNoise        0.8159
    8           VelocityNoise          0.8159
```

Fuse the sensor data using the tuned filter.

```
dt = seconds(diff(groundTruth.Time));
N = size(sensorData,1);
qEst = quaternion.zeros(N,1);
posEst = zeros(N,3);
% Iterate the filter for prediction and correction using sensor data.
for ii=1:N
    if ii ~= 1
        predict(filter, dt(ii-1));
    end
```

```
    if all(~isnan(Accelerometer(ii,:)))
        fuseaccel(filter,Accelerometer(ii,:), ...
            tunedParams.AccelerometerNoise);
    end
    if all(~isnan(Gyroscope(ii,:)))
        fusegyro(filter, Gyroscope(ii,:), ...
            tunedParams.GyroscopeNoise);
    end
    if all(~isnan(Magnetometer(ii,1)))
        fusemag(filter, Magnetometer(ii,:), ...
            tunedParams.MagnetometerNoise);
    end
    if all(~isnan(GPSPosition(ii,1)))
        fusegps(filter, GPSPosition(ii,:), ...
            tunedParams.GPSPositionNoise, GPSVelocity(ii,:), ...
            tunedParams.GPSVelocityNoise);
    end
    [posEst(ii,:), qEst(ii,:)] = pose(filter);
end
```

Compute the RMS errors.

```
orientationError = rad2deg(dist(qEst, Orientation));
rmsorientationError = sqrt(mean(orientationError.^2))
```

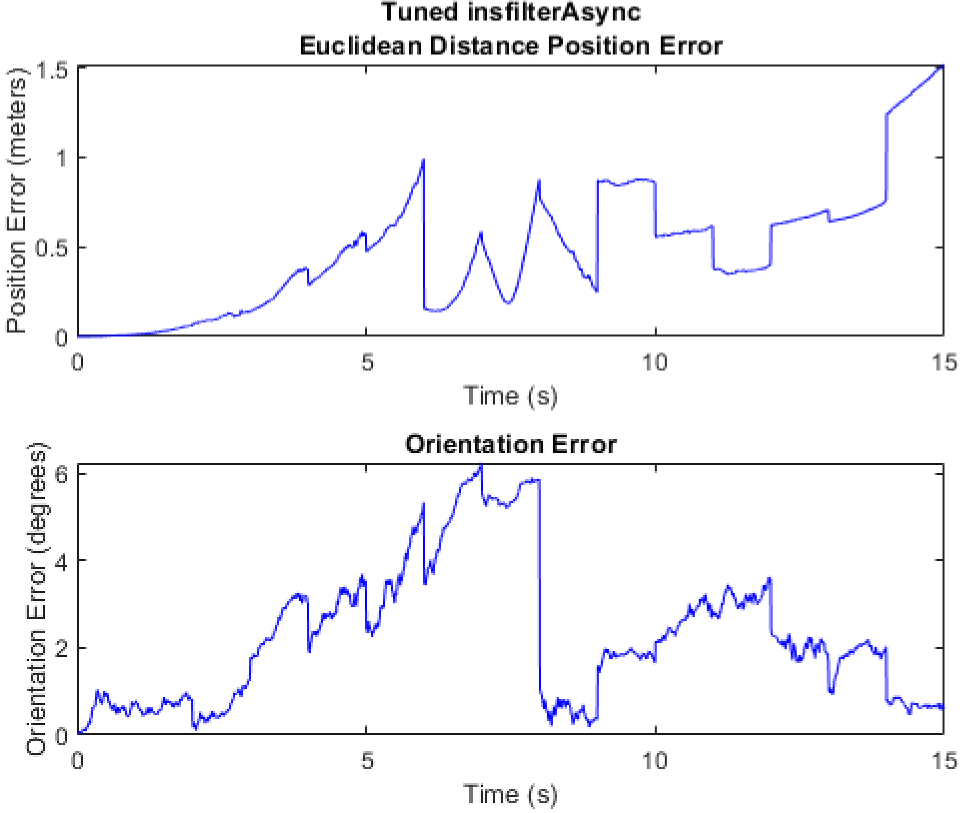
```
rmsorientationError = 2.7801
```

```
positionError = sqrt(sum((posEst - Position).^2, 2));
rmspositionError = sqrt(mean( positionError.^2))
```

```
rmspositionError = 0.5966
```

Visualize the results.

```
figure();
t = (0:N-1)./ groundTruth.Properties.SampleRate;
subplot(2,1,1)
plot(t, positionError, 'b');
title("Tuned insfilterAsync" + newline + "Euclidean Distance Position Error")
xlabel('Time (s)');
ylabel('Position Error (meters)')
subplot(2,1,2)
plot(t, orientationError, 'b');
title("Orientation Error")
xlabel('Time (s)');
ylabel('Orientation Error (degrees)');
```




## Input Arguments

**`filter` — Filter object**
`infilterAsync` object

Filter object, specified as an `insfilterAsync` object.

**`measureNoise` — Measurement noise**
structure

Measurement noise, specified as a structure. The function uses the measurement noise input as the initial guess for tuning the measurement noise. The structure must contain these fields:

| Field name | Description |
| --- | --- |
| `AccelerometerNoise` | Variance of accelerometer noise, specified as a scalar in ($m^2/s$) |
| `GyroscopeNoise` | Variance of gyroscope noise, specified as a scalar in $(rad/s)^2$ |
| `MagnetometerNoise` | Variance of magnetometer noise, specified as a scalar in $(\mu T)^2$ |
| `GPSPositionNoise` | Variance of GPS position noise, specified as a scalar in $m^2$ |

| Field name | Description |
| --- | --- |
| GPSVelocityNoise | Variance of GPS velocity noise, specified as a scalar in $(m/s)^2$ |

**sensorData — Sensor data**
duration

Sensor data, specified as a `timetable`. In each row, the time and sensor data is specified as:

- `Time` — Time at which the data is obtained, specified as a scalar in seconds.
- `Accelerometer` — Accelerometer data, specified as a 1-by-3 vector of scalars in $m^2/s$.
- `Gyroscope` — Gyroscope data, specified as a 1-by-3 vector of scalars in rad/s.
- `Magnetometer` — Magnetometer data, specified as a 1-by-3 vector of scalars in µT.
- `GPSPosition` — GPS position data, specified as a 1-by-3 vector of latitude in degrees, longitude in degrees, and altitude in meters.
- `GPSVelocity` — GPS velocity data, specified as a 1-by-3 vector of scalars in m/s.

If a sensor does not produce measurements, specify the corresponding entry as `NaN`. If you set the `Cost` property of the tuner configuration input, `config`, to `Custom`, then you can use other data types for the `sensorData` input based on your choice.

**groundTruth — Ground truth data**
duration

Ground truth data, specified as a `timetable`. In each row, the table can optionally contain any of these variables:

- `Orientation` — Orientation from the navigation frame to the body frame, specified as a `quaternion` or a 3-by-3 rotation matrix.
- `AngularVelocity` — Angular velocity in body frame, specified as a 1-by-3 vector of scalars in rad/s.
- `Position` — Position in navigation frame, specified as a 1-by-3 vector of scalars in meters.
- `Velocity` — Velocity in navigation frame, specified as a 1-by-3 vector of scalars in m/s.
- `Acceleration` — Acceleration in navigation frame, specified as a 1-by-3 vector of scalars in $m^2/s$.
- `AccelerometerBias` — Accelerometer delta angle bias in body frame, specified as a 1-by-3 vector of scalars in $m^2/s$.
- `GyroscopeBias` — Gyroscope delta angle bias in body frame, specified as a 1-by-3 vector of scalars in rad/s.
- `GeomagneticFieldVector` — Geomagnetic field vector in navigation frame, specified as a 1-by-3 vector of scalars.
- `MagnetometerBias` — Magnetometer bias in body frame, specified as a 1-by-3 vector of scalars in µT.

The function processes each row of the `sensorData` and `groundTruth` tables sequentially to calculate the state estimate and RMS error from the ground truth. State variables not present in `groundTruth` input are ignored for the comparison. The `sensorData` and the `groundTruth` tables must have the same time steps.

If you set the `Cost` property of the tuner configuration input, `config`, to `Custom`, then you can use other data types for the `groundTruth` input based on your choice.

**`config` — Tuner configuration**
`tunerconfig` object

Tuner configuration, specified as a `tunerconfig` object.

## Output Arguments

**`tunedMeasureNoise` — Tuned measurement noise**
structure

Tuned measurement noise, returned as a structure. The structure contains these fields.

| Field name | Description |
|---|---|
| `AccelerometerNoise` | Variance of accelerometer noise, specified as a scalar in $(m^2/s)^2$ |
| `GyroscopeNoise` | Variance of gyroscope noise, specified as a scalar in $(rad/s)^2$ |
| `MagnetometerNoise` | Variance of magnetometer noise, specified as a scalar in $(\mu T)^2$ |
| `GPSPositionNoise` | Variance of GPS position noise, specified as a scalar in $m^2$ |
| `GPSVelocityNoise` | Variance of GPS velocity noise, specified as a scalar in $(m/s)^2$ |

# Version History

**Introduced in R2020b**

## References

[1] Abbeel, P., Coates, A., Montemerlo, M., Ng, A.Y. and Thrun, S. Discriminative Training of Kalman Filters. In *Robotics: Science and systems*, Vol. 2, pp. 1, 2005.

## See Also

`tunerconfig` | `tunernoise`

# binaryOccupancyMap

Create occupancy grid with binary values

## Description

The binaryOccupancyMap creates a 2-D occupancy map object, which you can use to represent and visualize a robot workspace, including obstacles. The integration of sensor data and position estimates create a spatial representation of the approximate locations of the obstacles.

Occupancy grids are used in robotics algorithms such as path planning. They are also used in mapping applications, such as for finding collision-free paths, performing collision avoidance, and calculating localization. You can modify your occupancy grid to fit your specific application.

Each cell in the occupancy grid has a value representing the occupancy status of that cell. An occupied location is represented as true (1) and a free location is represented as false (0).

The object keeps track of three reference frames: world, local, and, grid. The world frame origin is defined by GridLocationInWorld, which defines the bottom-left corner of the map relative to the world frame. The LocalOriginInWorld property specifies the location of the origin of the local frame relative to the world frame. The first grid location with index (1,1) begins in the top-left corner of the grid.

**Note** This object was previously named robotics.BinaryOccupancyGrid.

## Creation

### Syntax

```
map = binaryOccupancyMap
map = binaryOccupancyMap(width,height)
map = binaryOccupancyMap(width,height,resolution)

map = binaryOccupancyMap(rows,cols,resolution,"grid")

map = binaryOccupancyMap(p)
map = binaryOccupancyMap(p,resolution)

map = binaryOccupancyMap(sourcemap)
map = binaryOccupancyMap(sourcemap,resolution)
```

#### Description

map = binaryOccupancyMap creates a 2-D binary occupancy grid with a width and height of 10m. The default grid resolution is one cell per meter.

map = binaryOccupancyMap(width,height) creates a 2-D binary occupancy grid representing a work space of width and height in meters. The default grid resolution is one cell per meter.

`map = binaryOccupancyMap(width,height,resolution)` creates a grid with the `Resolution` property specified in cells per meter. The map is in world coordinates by default.

`map = binaryOccupancyMap(rows,cols,resolution,"grid")` creates a 2-D binary occupancy grid of size (`rows`,`cols`).

`map = binaryOccupancyMap(p)` creates a grid from the values in matrix `p`. The size of the grid matches the size of the matrix, with each cell value interpreted from its location in the matrix. `p` contains any numeric or logical type with zeros (0) and ones (1).

`map = binaryOccupancyMap(p,resolution)` creates a map from a matrix with the `Resolution` property specified in cells per meter.

`map = binaryOccupancyMap(sourcemap)` creates an object using values from another `binaryOccupancyMap` object.

`map = binaryOccupancyMap(sourcemap,resolution)` creates an object using values from another `binaryOccupancyMap` object, but resamples the matrix to have the specified resolution.

### Input Arguments

#### `width` — Map width
positive scalar

Map width, specified as a positive scalar in meters.

#### `height` — Map height
positive scalar

Map height, specified as a positive scalar in meters.

#### `p` — Map grid values
matrix

Map grid values, specified as a matrix.

#### `sourcemap` — Occupancy map object
`binaryOccupancyMap` object

Occupancy map object, specified as a `binaryOccupancyMap` object.

## Properties

#### `GridSize` — Number of rows and columns in grid
two-element vector of form `[rows cols]`

This property is read-only.

Number of rows and columns in grid, stored as a two-element vector of the form `[rows cols]`.

#### `Resolution` — Grid resolution
`1` (default) | scalar

This property is read-only.

Grid resolution, stored as a scalar in cells per meter.

### `XLocalLimits` — Minimum and maximum values of *x*-coordinates in local frame
two-element vector of form `[min max]`

This property is read-only.

Minimum and maximum values of *x*-coordinates in local frame, stored as a two-element vector of the form `[min max]`. Local frame is defined by `LocalOriginInWorld` property.

### `YLocalLimits` — Minimum and maximum values of *y*-coordinates in local frame
two-element vector of form `[min max]`

This property is read-only.

Minimum and maximum values of *y*-coordinates in local frame, stored as a two-element vector of the form `[min max]`. Local frame is defined by `LocalOriginInWorld` property.

### `XWorldLimits` — Minimum and maximum values of *x*-coordinates in world frame
two-element vector of form `[min max]`

This property is read-only.

Minimum and maximum values of *x*-coordinates in world frame, stored as a two-element vector of the form `[min max]`. These values indicate the world range of the *x*-coordinates in the grid.

### `YWorldLimits` — Minimum and maximum values of *y*-coordinates
two-element vector of form `[min max]`

This property is read-only.

Minimum and maximum values of *y*-coordinates, stored as a two-element vector of the form `[min max]`. These values indicate the world range of the *y*-coordinates in the grid.

### `GridLocationInWorld` — Location of the grid in world coordinates
`[0 0]` (default) | two-element vector | `[xGrid yGrid]`

Location of the bottom-left corner of the grid in world coordinates, specified as a two-element vector, `[xGrid yGrid]`.

### `LocalOriginInWorld` — Location of the local frame in world coordinates
`[0 0]` (default) | two-element vector | `[xWorld yWorld]`

Location of the origin of the local frame in world coordinates, specified as a two-element vector, `[xLocal yLocal]`. Use the `move` function to shift the local frame as your vehicle moves.

### `GridOriginInLocal` — Location of the grid in local coordinates
`[0 0]` (default) | two-element vector | `[xLocal yLocal]`

Location of the bottom-left corner of the grid in local coordinates, specified as a two-element vector, `[xLocal yLocal]`.

### `DefaultValue` — Default value for unspecified map locations
`0` (default) | `1`

Default value for unspecified map locations including areas outside the map, specified as `0` or `1`.

## Object Functions

| | |
|---|---|
| copy | Create copy of binary occupancy map |
| checkOccupancy | Check if locations are free or occupied |
| getOccupancy | Get occupancy value of locations |
| grid2local | Convert grid indices to local coordinates |
| grid2world | Convert grid indices to world coordinates |
| inflate | Inflate each occupied location |
| insertRay | Insert ray from laser scan observation |
| local2grid | Convert local coordinates to grid indices |
| local2world | Convert local coordinates to world coordinates |
| move | Move map in world frame |
| occupancyMatrix | Convert occupancy grid to matrix |
| raycast | Compute cell indices along a ray |
| rayIntersection | Find intersection points of rays and occupied map cells |
| setOccupancy | Set occupancy value of locations |
| show | Display binary occupancy map |
| syncWith | Sync map with overlapping map |
| world2grid | Convert world coordinates to grid indices |
| world2local | Convert world coordinates to local coordinates |

## Examples

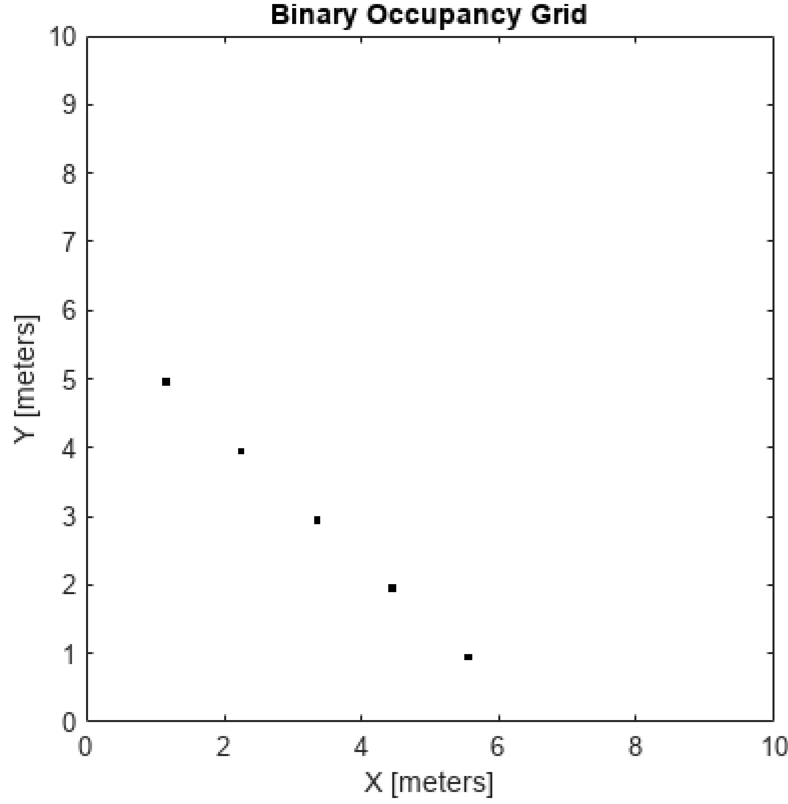
### Create and Modify Binary Occupancy Grid

Create a 10m x 10m empty map.

```
map = binaryOccupancyMap(10,10,10);
```

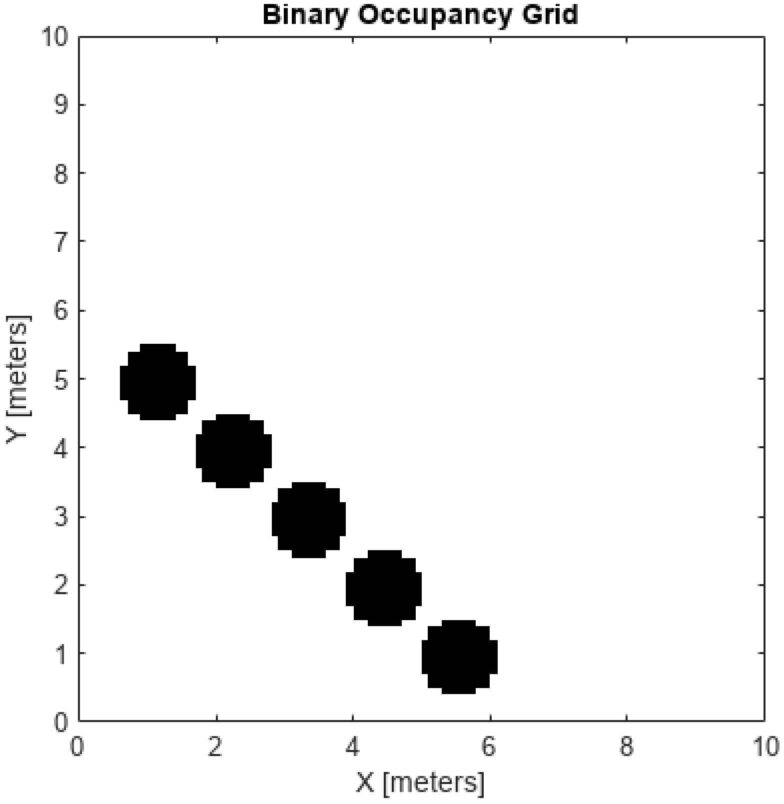
Set occupancy of world locations and show map.

```
x = [1.2; 2.3; 3.4; 4.5; 5.6];
y = [5.0; 4.0; 3.0; 2.0; 1.0];

setOccupancy(map, [x y], ones(5,1))
figure
show(map)
```




Inflate occupied locations by a given radius.

```
inflate(map, 0.5)
figure
show(map)
```




Get grid locations from world locations.

```
ij = world2grid(map, [x y]);
```

Set grid locations to free locations.

```
setOccupancy(map, ij, zeros(5,1), 'grid')
figure
show(map)
```

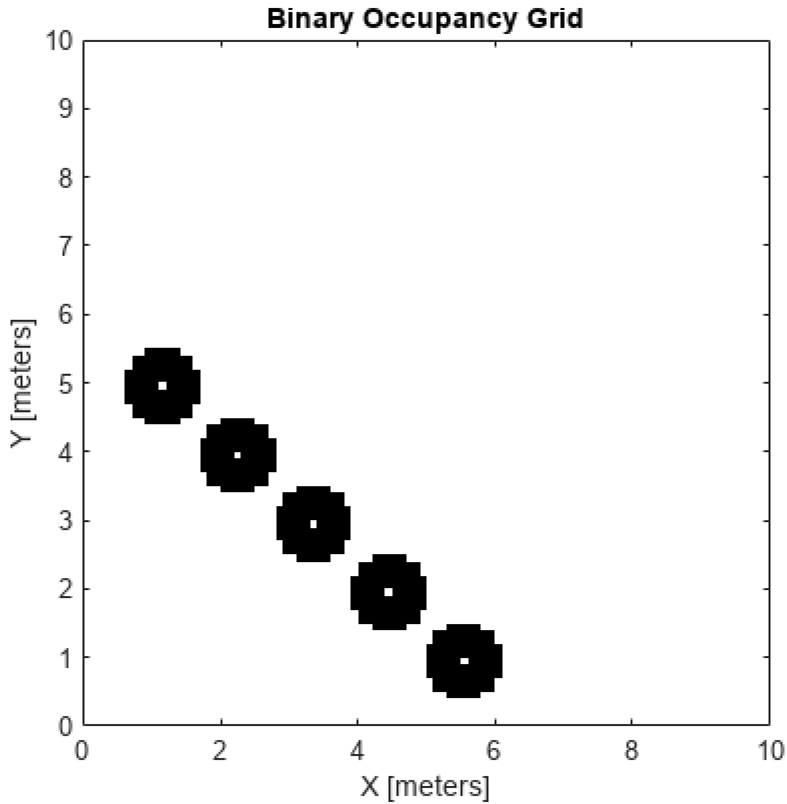



**Image to Binary Occupancy Grid Example**

This example shows how to convert an image to a binary occupancy grid for using with mapping and path planning.

Import image.

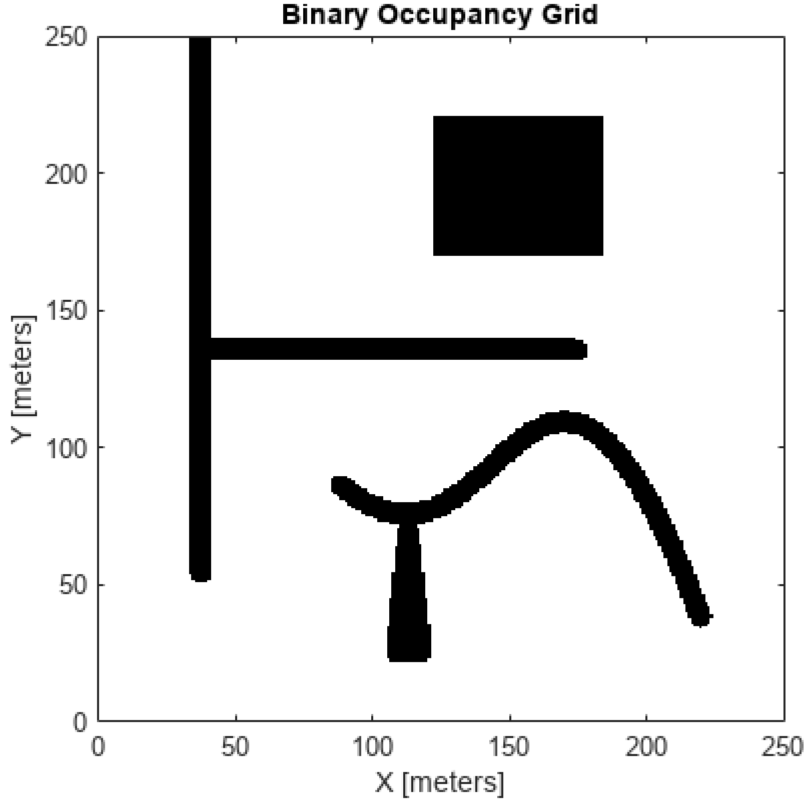
```
image = imread('imageMap.png');
```

Convert to grayscale and then black and white image based on given threshold value.

```
grayimage = rgb2gray(image);
bwimage = grayimage < 0.5;
```

Use black and white image as matrix input for binary occupancy grid.

```
grid = binaryOccupancyMap(bwimage);

show(grid)
```

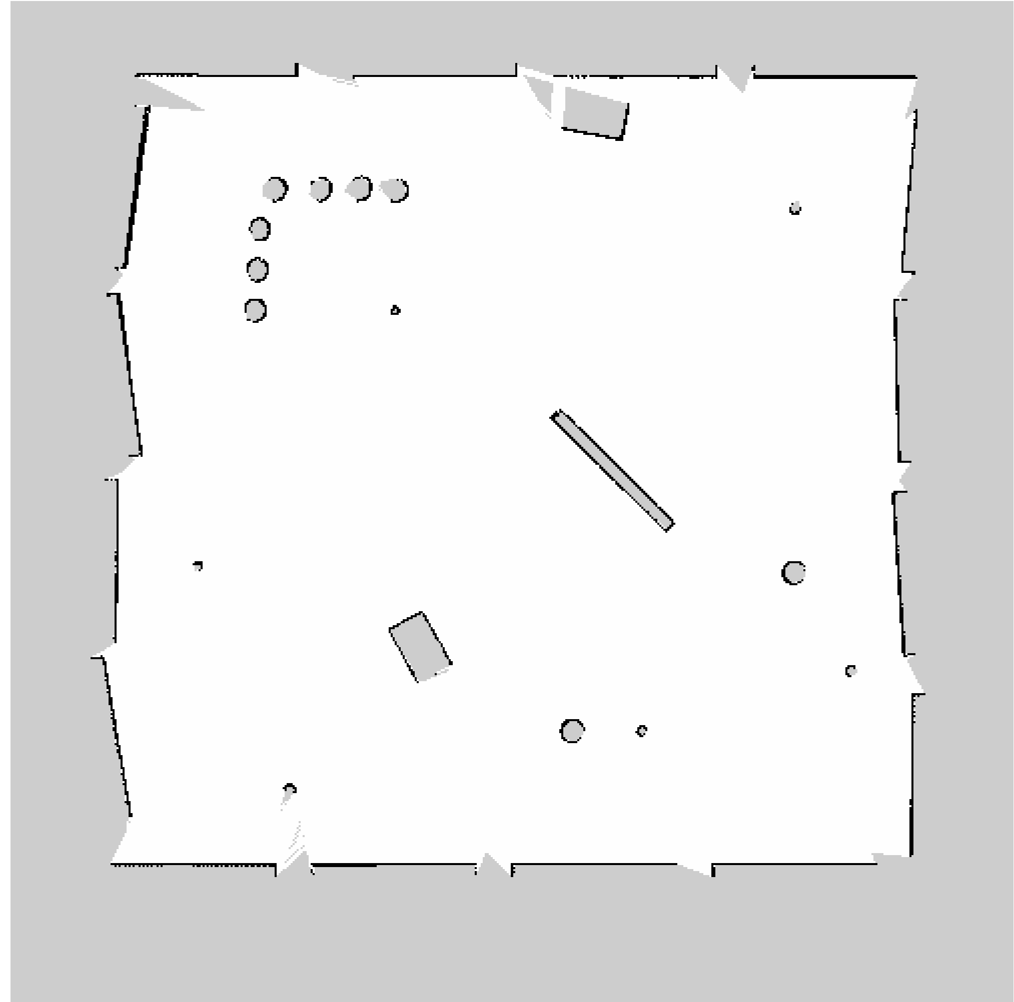



**Convert PGM Image to Map**

This example shows how to convert a `.pgm` file into a `binaryOccupancyMap` object for use in MATLAB.

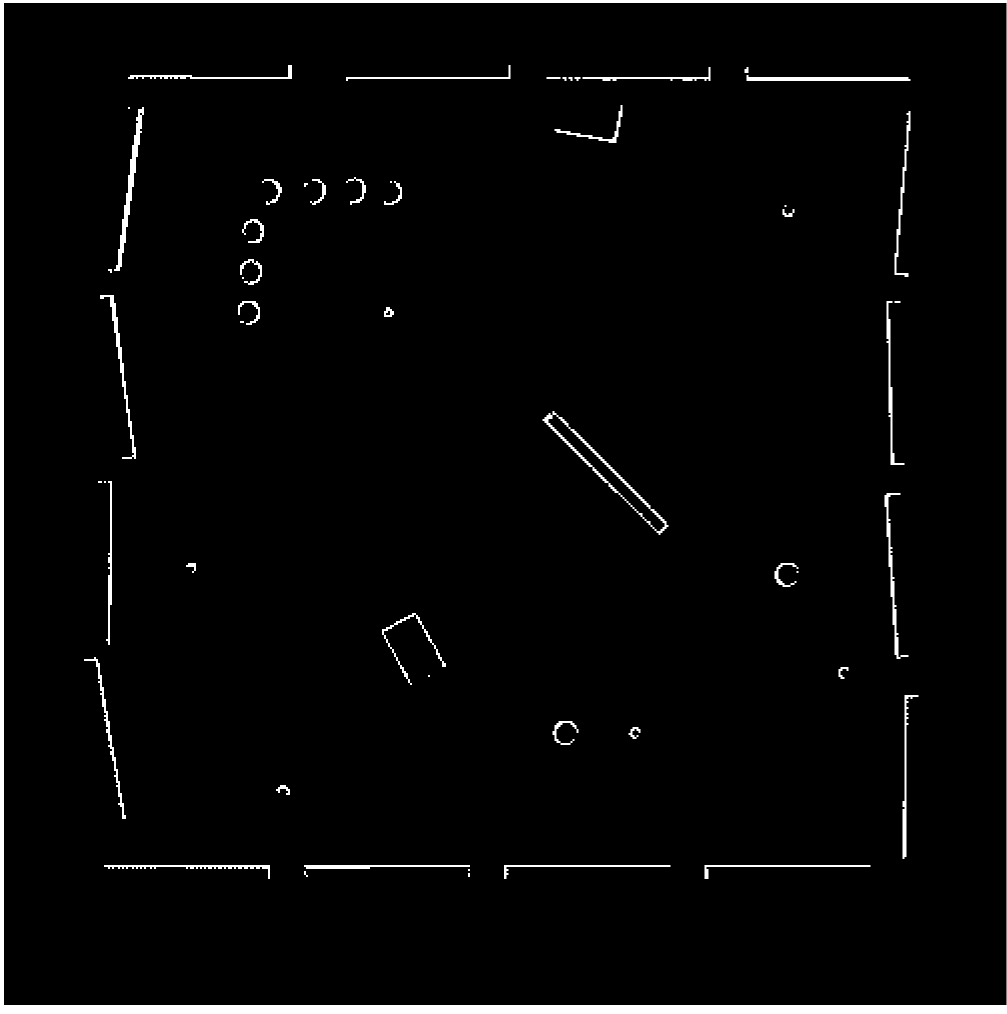
Import image using `imread`. The image is quite large and should be cropped to the relevant area.

```
image = imread('playpen_map.pgm');
imageCropped = image(750:1250,750:1250);
imshow(imageCropped)
```



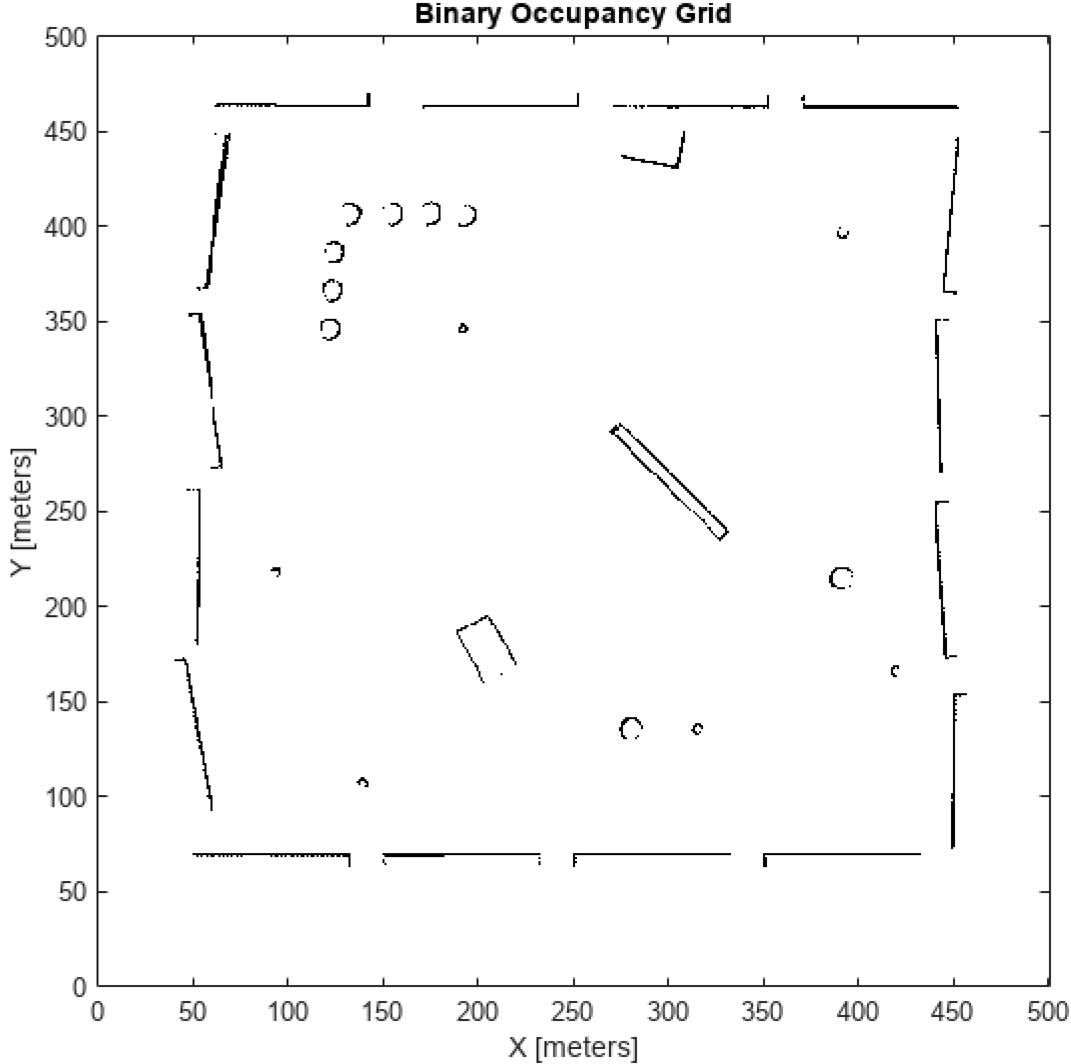
Unknown areas (gray) should be removed and treated as free space. Create a logical matrix based on a threshold. Depending on your image, this value could be different. Occupied space should be set as 1 (white in image).

```
imageBW = imageCropped < 100;
imshow(imageBW)
```



Create `binaryOccupancyMap` object using adjusted map image.

```
map = binaryOccupancyMap(imageBW);
show(map)
```




## Version History

**Introduced in R2015a**

**R2019b: `binaryOccupancyMap` was renamed**

*Behavior change in future release*

The `binaryOccupancyMap` object was renamed from `robotics.BinaryOccupancyGrid`. Use `binaryOccupancyMap` for all object creation.

## Extended Capabilities

**C/C++ Code Generation**

Generate C and C++ code using MATLAB® Coder™.

As of MATLAB R2022a, default map behavior during code generation has changed, which may result in backwards compatibility issues. Maps such as `binaryOccupancyMap` now support fixed-size code generation (`DynamicMemoryAllocation="off"`).

1. Maps that are either default-constructed or constructed with compile-time constant size information (or matrices that are of compile-time constant size) produce fixed-size maps.
2. To restore the previous behavior, use the `coder.ignoreConst` function when specifying size inputs, or `coder.varsize` matrix variable name specified as a string scalar or character vector, prior to constructing the map.

## See Also

`controllerPurePursuit`

**Topics**

"Occupancy Grids"

# checkOccupancy

Check if locations are free or occupied

## Syntax

```
occVal = checkOccupancy(map,xy)
occVal = checkOccupancy(map,xy,"local")
occVal = checkOccupancy(map,ij,"grid")
[occVal,validPts] = checkOccupancy( ___ )

occMatrix = checkOccupancy(map)
occMatrix = checkOccupancy(map,bottomLeft,matSize)
occMatrix = checkOccupancy(map,bottomLeft,matSize,"local")
occMatrix = checkOccupancy(map,topLeft,matSize,"grid")
```

## Description

`occVal = checkOccupancy(map,xy)` returns an array of occupancy values at the `xy` locations in the world frame. Obstacle-free cells return 0, occupied cells return 1. Unknown locations, including outside the map, return `-1`.

`occVal = checkOccupancy(map,xy,"local")` returns an array of occupancy values at the `xy` locations in the local frame. The local frame is based on the `LocalOriginInWorld` property of the `map`.

`occVal = checkOccupancy(map,ij,"grid")` specifies `ij` grid cell indices instead of `xy` locations. Grid indices start at (1,1) from the top left corner.

`[occVal,validPts] = checkOccupancy( ___ )` also outputs an `n`-element vector of logical values indicating whether input coordinates are within the map limits.

`occMatrix = checkOccupancy(map)` returns a matrix that contains the occupancy status of each location. Obstacle-free cells return 0, occupied cells return 1. Unknown locations, including outside the map, return `-1`.

`occMatrix = checkOccupancy(map,bottomLeft,matSize)` returns a matrix of occupancy values by specifying the bottom-left corner location in world coordinates and the matrix size in meters.

`occMatrix = checkOccupancy(map,bottomLeft,matSize,"local")` returns a matrix of occupancy values by specifying the bottom-left corner location in local coordinates and the matrix size in meters.

`occMatrix = checkOccupancy(map,topLeft,matSize,"grid")` returns a matrix of occupancy values by specifying the top-left cell index in grid coordinates and the matrix size.

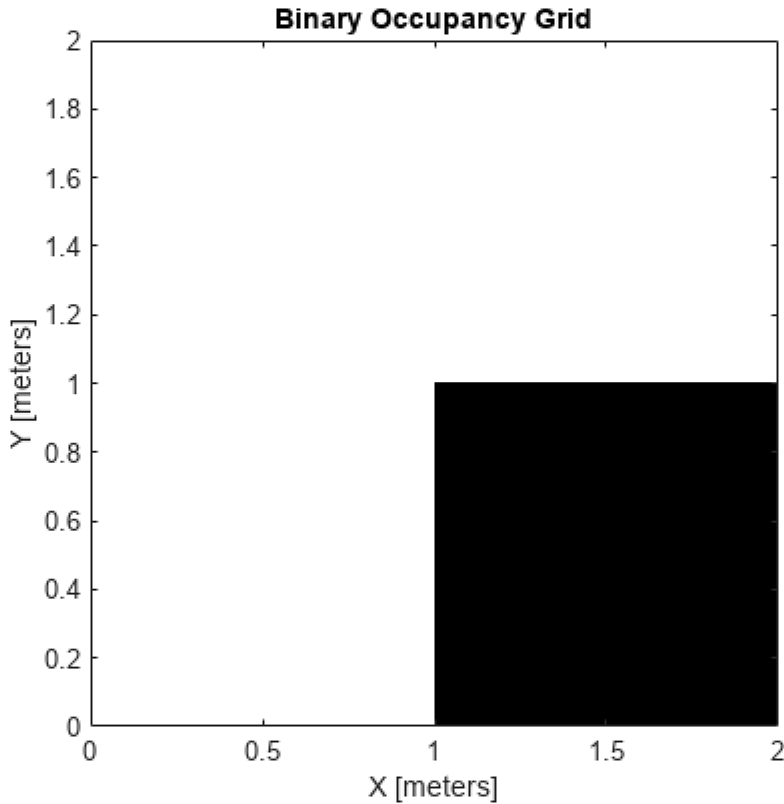
## Examples

**Get Occupancy Values and Check Occupancy Status**

Access occupancy values and check their occupancy status based on the occupied and free thresholds of the `occupancyMap` object.

Create a matrix and populate it with values. Use this matrix to create an occupancy map.

```
p = zeros(20,20);
p(11:20,11:20) = ones(10,10);
map = binaryOccupancyMap(p,10);
show(map)
```




Get the occupancy of different locations and check their occupancy statuses. The occupancy status returns 0 for free space and 1 for occupied space. Unknown values return –1.

```
pocc = getOccupancy(map,[1.5 1]);
occupied = checkOccupancy(map,[1.5 1]);
pocc2 = getOccupancy(map,[5 5],'grid');
```

## Input Arguments

**map — Map representation**
`binaryOccupancyMap` object

Map representation, specified as a `binaryOccupancyMap` object.

**xy — Coordinates in the map**
*n*-by-2 matrix

Coordinates in the map, specified as an *n*-by-2 matrix of `[x y]` pairs, where *n* is the number of coordinates. Coordinates can be world or local coordinates depending on the syntax.

Data Types: `double`

**ij — Grid locations in the map**
*n*-by-2 matrix

Grid locations in the map, specified as an *n*-by-2 matrix of `[i j]` pairs, where *n* is the number of locations. Grid locations are given as `[row col]`.

Data Types: `double`

**bottomLeft — Location of output matrix in world or local**
two-element vector | `[xCoord yCoord]`

Location of bottom left corner of output matrix in world or local coordinates, specified as a two-element vector, `[xCoord yCoord]`. Location is in world or local coordinates based on syntax.

Data Types: `double`

**matSize — Output matrix size**
two-element vector | `[xLength yLength]` | `[gridRow gridCol]`

Output matrix size, specified as a two-element vector, `[xLength yLength]`, or `[gridRow gridCol]`. Size is in world, local, or grid coordinates based on syntax.

Data Types: `double`

**topLeft — Location of grid**
two-element vector | `[iCoord jCoord]`

Location of top left corner of grid, specified as a two-element vector, `[iCoord jCoord]`.

Data Types: `double`

## Output Arguments

**occVal — Occupancy values**
*n*-by-1 column vector

Occupancy values, returned as an *n*-by-1 column vector equal in length to `xy` or `ij` input. Occupancy values can be obstacle free (0), occupied (1), or unknown (-1).

**validPts — Valid map locations**
*n*-by-1 column vector

Valid map locations, returned as an *n*-by-1 column vector equal in length to `xy` or `ij`. Locations inside the map return a value of 1. Locations outside the map limits return a value of 0.

**occMatrix — Matrix of occupancy values**
matrix

Matrix of occupancy values, returned as matrix with size equal to `matSize` or the size of your `map`. Occupancy values can be obstacle free (0), occupied (1), or unknown (-1).

# Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`binaryOccupancyMap` | `getOccupancy` | `occupancyMap`

# copy

Create copy of binary occupancy map

## Syntax

```
copyMap = copy(map)
```

## Description

`copyMap = copy(map)` creates a deep copy of the `binaryOccupancyMap` object with the same properties.

## Examples

### Copy Binary Occupancy Grid Map

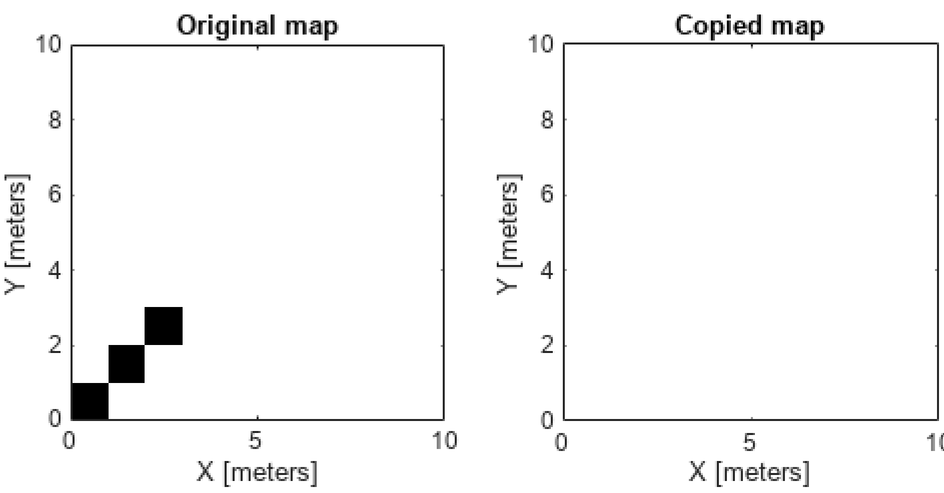
Copy a `binaryOccupancyMap` object. Once copied, the original object can be modified without affecting the copied map.

Create an occupancy map with zeros for an empty map.

```
p = zeros(10);
map = binaryOccupancyMap(p);
```

Copy the occupancy map. Modify the original map. The copied map is not modified. Plot the two maps side by side.

```
mapCopy = copy(map);
setOccupancy(map,[1:3;1:3]',ones(3,1));
subplot(1,2,1)
show(map)
title('Original map')
subplot(1,2,2)
show(mapCopy)
title('Copied map')
```




## Input Arguments

**map — Map representation**
binaryOccupancyMap object

Map representation, specified as a `binaryOccupancyMap` object. This object represents the environment of the vehicle.

## Output Arguments

**copyMap — Copied map representation**
binaryOccupancyMap object

Copied map representation, returned as a `binaryOccupancyMap` object. The properties are the same as the input object, `map`, but the copy has a different object handle.

# Version History

**Introduced in R2015a**

## See Also

`binaryOccupancyMap` | `occupancyMap`

# getOccupancy

Get occupancy value of locations

## Syntax

```
occVal = getOccupancy(map,xy)
occVal = getOccupancy(map,xy,"local")
occVal = getOccupancy(map,ij,"grid")
[occVal,validPts] = getOccupancy( ___ )
```

```
occMatrix = getOccupancy(map)
occMatrix = getOccupancy(map,bottomLeft,matSize)
occMatrix = getOccupancy(map,bottomLeft,matSize,"local")
occMatrix = getOccupancy(map,topLeft,matSize,"grid")
```

## Description

`occVal = getOccupancy(map,xy)` returns an array of occupancy values at the `xy` locations in the world frame. Unknown locations, including outside the map, return `map.DefaultValue`.

`occVal = getOccupancy(map,xy,"local")` returns an array of occupancy values at the `xy` locations in the local frame.

`occVal = getOccupancy(map,ij,"grid")` specifies `ij` grid cell indices instead of `xy` locations.

`[occVal,validPts] = getOccupancy( ___ )` additionally outputs an `n`-element vector of logical values indicating whether input coordinates are within the map limits.

`occMatrix = getOccupancy(map)` returns all occupancy values in the map as a matrix.

`occMatrix = getOccupancy(map,bottomLeft,matSize)` returns a matrix of occupancy values by specifying the bottom-left corner location in world coordinates and the matrix size in meters.

`occMatrix = getOccupancy(map,bottomLeft,matSize,"local")` returns a matrix of occupancy values by specifying the bottom-left corner location in local coordinates and the matrix size in meters.

`occMatrix = getOccupancy(map,topLeft,matSize,"grid")` returns a matrix of occupancy values by specifying the top-left cell index in grid indices and the matrix size.

## Examples

### Insert Laser Scans into Binary Occupancy Map

Create an empty binary occupancy grid map.

```
map = binaryOccupancyMap(10,10,20);
```

Input pose of the vehicle, ranges, angles, and the maximum range of the laser scan.

```
pose = [5,5,0];
ranges = 3*ones(100,1);
angles = linspace(-pi/2,pi/2,100);
maxrange = 20;
```

Create a `lidarScan` object with the specified ranges and angles.

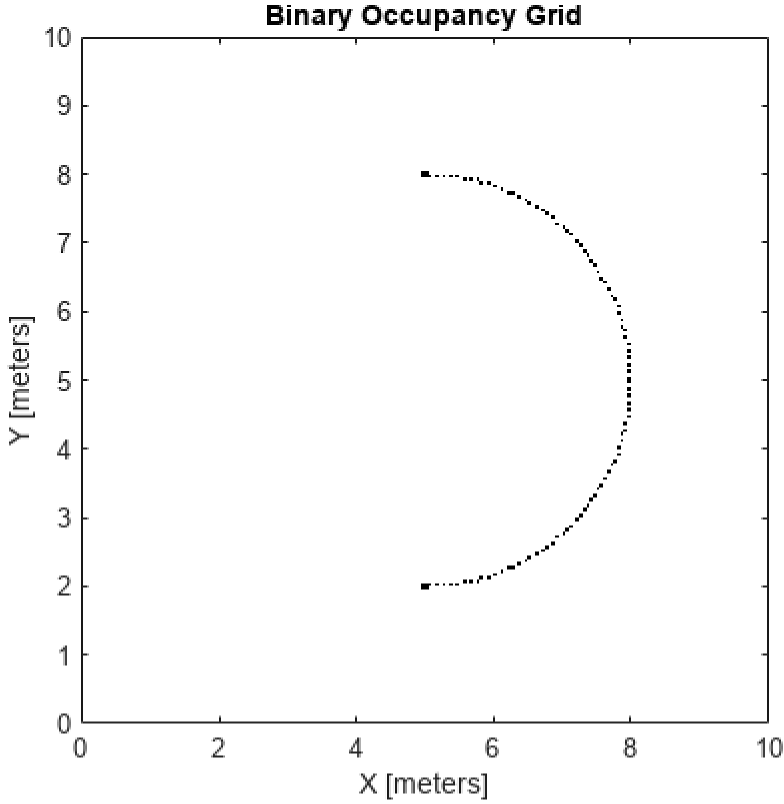
```
scan = lidarScan(ranges,angles);
```

Insert the laser scan data into the occupancy map.

```
insertRay(map,pose,scan,maxrange);
```

Show the map to see the results of inserting the laser scan.

```
show(map)
```




Check the occupancy of the spot directly in front of the vehicle.

```
getOccupancy(map,[8 5])
```

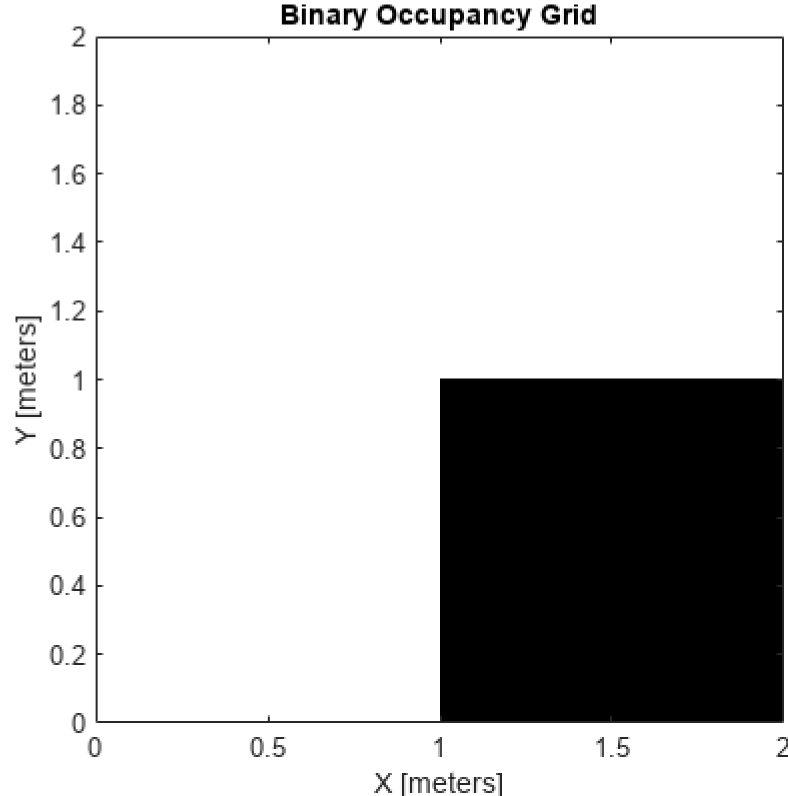
```
ans = logical
   1
```

### Get Occupancy Values and Check Occupancy Status

Access occupancy values and check their occupancy status based on the occupied and free thresholds of the occupancyMap object.

Create a matrix and populate it with values. Use this matrix to create an occupancy map.

```
p = zeros(20,20);
p(11:20,11:20) = ones(10,10);
map = binaryOccupancyMap(p,10);
show(map)
```




Get the occupancy of different locations and check their occupancy statuses. The occupancy status returns 0 for free space and 1 for occupied space. Unknown values return –1.

```
pocc = getOccupancy(map,[1.5 1]);
occupied = checkOccupancy(map,[1.5 1]);
pocc2 = getOccupancy(map,[5 5],'grid');
```

## Input Arguments

**map — Map representation**
binaryOccupancyMap object

Map representation, specified as a binaryOccupancyMap object. This object represents the environment of the vehicle.

**`xy` — Coordinates in the map**
*n*-by-2 matrix

Coordinates in the map, specified as an *n*-by-2 matrix of `[x y]` pairs, where *n* is the number of coordinates. Coordinates can be world or local coordinates depending on the syntax.

Data Types: `double`

**`ij` — Grid locations in the map**
*n*-by-2 matrix

Grid locations in the map, specified as an *n*-by-2 matrix of `[i j]` pairs, where *n* is the number of locations. Grid locations are given as `[row col]`.

Data Types: `double`

**`bottomLeft` — Location of output matrix in world or local**
two-element vector | `[xCoord yCoord]`

Location of bottom left corner of output matrix in world or local coordinates, specified as a two-element vector, `[xCoord yCoord]`. Location is in world or local coordinates based on syntax.

Data Types: `double`

**`matSize` — Output matrix size**
two-element vector | `[xLength yLength]` | `[gridRow gridCol]`

Output matrix size, specified as a two-element vector, `[xLength yLength]` or `[gridRow gridCol]`. The size is in world coordinates, local coordinates, or grid indices based on syntax.

Data Types: `double`

**`topLeft` — Location of grid**
two-element vector | `[iCoord jCoord]`

Location of top left corner of grid, specified as a two-element vector, `[iCoord jCoord]`.

Data Types: `double`

## Output Arguments

**`occVal` — Occupancy values**
*n*-by-1 column vector

Occupancy values, returned as an *n*-by-1 column vector equal in length to `xy` or `ij`. Occupancy values can be obstacle free (0) or occupied (1).

**`validPts` — Valid map locations**
*n*-by-1 column vector

Valid map locations, returned as an *n*-by-1 column vector equal in length to `xy` or `ij`. Locations inside the map return a value of 1. Locations outside the map limits return a value of 0.

**`occMatrix` — Matrix of occupancy values**
matrix

Matrix of occupancy values, returned as matrix with size equal to `matSize` or the size of `map`.

## Version History

**Introduced in R2015a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`binaryOccupancyMap` | `setOccupancy`

### Topics

"Occupancy Grids"

# grid2local

Convert grid indices to local coordinates

## Syntax

`xy = grid2local(map,ij)`

## Description

`xy = grid2local(map,ij)` converts a `[row col]` array of grid indices, `ij`, to an array of local coordinates, `xy`.

## Examples

### Convert Grid Indices in Binary Occupancy Map to Local Coordinates

Create an empty binary occupancy map with a width and height of 10 meters.

```
map = binaryOccupancyMap(10,10);
```

Get local coordinates from grid indices.

```
[i,j] = meshgrid(1:5);
xyLocal = grid2local(map,[i(:) j(:)]);
```

## Input Arguments

**`map` — Map representation**
`binaryOccupancyMap` object

Map representation, specified as a `binaryOccupancyMap` object. This object represents the environment of the robot. The object contains a matrix grid with binary values indicating obstacles as `true` (`1`) and free locations as `false` (`0`).

**`ij` — Grid positions**
*n*-by-2 vertical array

Grid positions, specified as an *n*-by-2 vertical array of `[i j]` pairs in `[rows cols]` format, where *n* is the number of grid positions.

## Output Arguments

**`xy` — Local coordinates**
*n*-by-2 vertical array

Local coordinates, specified as an *n*-by-2 vertical array of `[x y]` pairs, where *n* is the number of local coordinates.

## Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`binaryOccupancyMap` | `world2grid`

# grid2world

Convert grid indices to world coordinates

## Syntax

`xy = grid2world(map,ij)`

## Description

`xy = grid2world(map,ij)` converts a `[row col]` array of grid indices, `ij`, to an array of world coordinates, `xy`.

## Examples

### Convert Grid Indices in Binary Occupancy Map to World Coordinates

Create an empty binary occupancy map with a width and height of 10 meters.

```
map = binaryOccupancyMap(10,10);
```

Get world coordinates from grid indices.

```
[i,j] = meshgrid(1:5);
xyWorld = grid2world(map,[i(:) j(:)]);
```

## Input Arguments

**`map` — Map representation**
`binaryOccupancyMap` object

Map representation, specified as a `binaryOccupancyMap` object. This object represents the environment of the robot. The object contains a matrix grid with binary values indicating obstacles as `true` (`1`) and free locations as `false` (`0`).

**`ij` — Grid positions**
*n*-by-2 vertical array

Grid positions, specified as an *n*-by-2 vertical array of `[i j]` pairs in `[rows cols]` format, where *n* is the number of grid positions.

## Output Arguments

**xy — World coordinates**
*n*-by-2 vertical array

World coordinates, specified as an *n*-by-2 vertical array of `[x y]` pairs, where *n* is the number of world coordinates.

## Version History

**Introduced in R2015a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`binaryOccupancyMap` | `world2grid` | `grid2local`

# inflate

Inflate each occupied location

## Syntax

```
inflate(map,radius)
inflate(map,gridradius,'grid')
```

## Description

`inflate(map,radius)` inflates each occupied position of the `map` by the radius given in meters. `radius` is rounded up to the nearest cell equivalent based on the resolution of the map. Every cell within the radius is set to `true` (`1`).

`inflate(map,gridradius,'grid')` inflates each occupied position by the radius given in number of cells.

## Examples

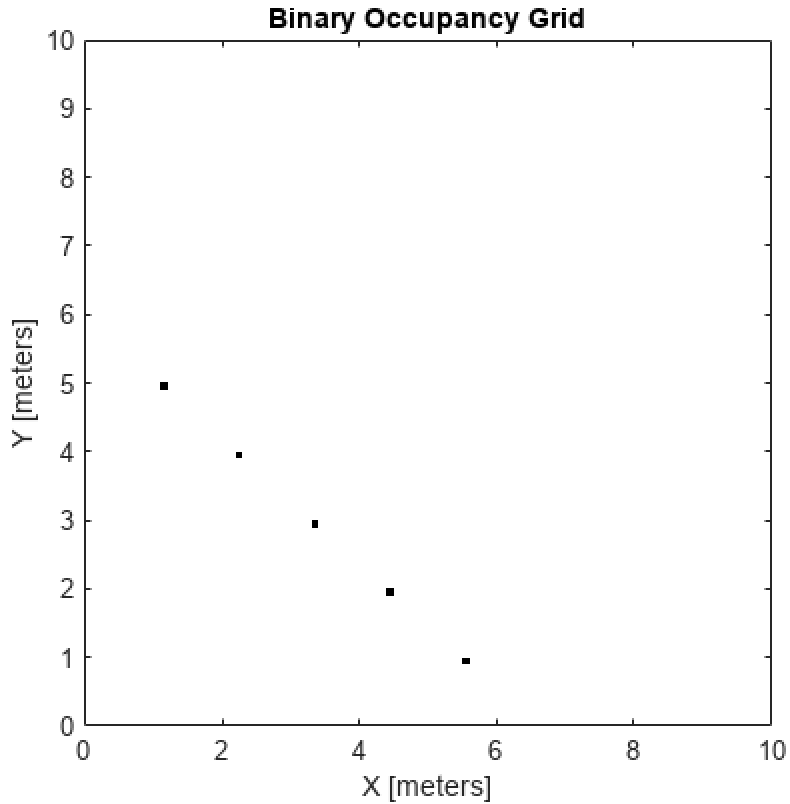
### Create and Modify Binary Occupancy Grid

Create a 10m x 10m empty map.

```
map = binaryOccupancyMap(10,10,10);
```

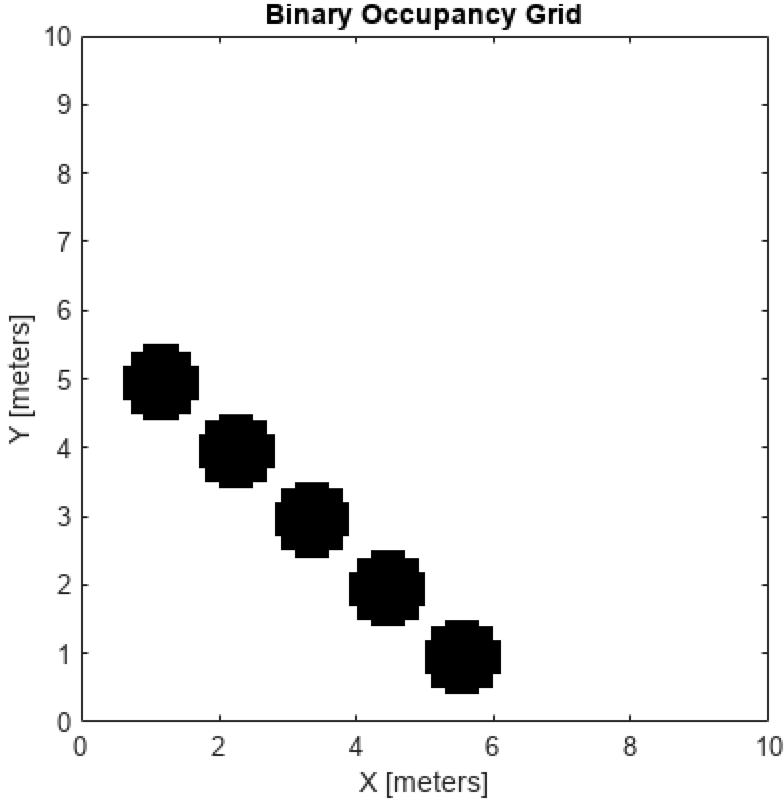
Set occupancy of world locations and show map.

```
x = [1.2; 2.3; 3.4; 4.5; 5.6];
y = [5.0; 4.0; 3.0; 2.0; 1.0];

setOccupancy(map, [x y], ones(5,1))
figure
show(map)
```




Inflate occupied locations by a given radius.

```
inflate(map, 0.5)
figure
show(map)
```

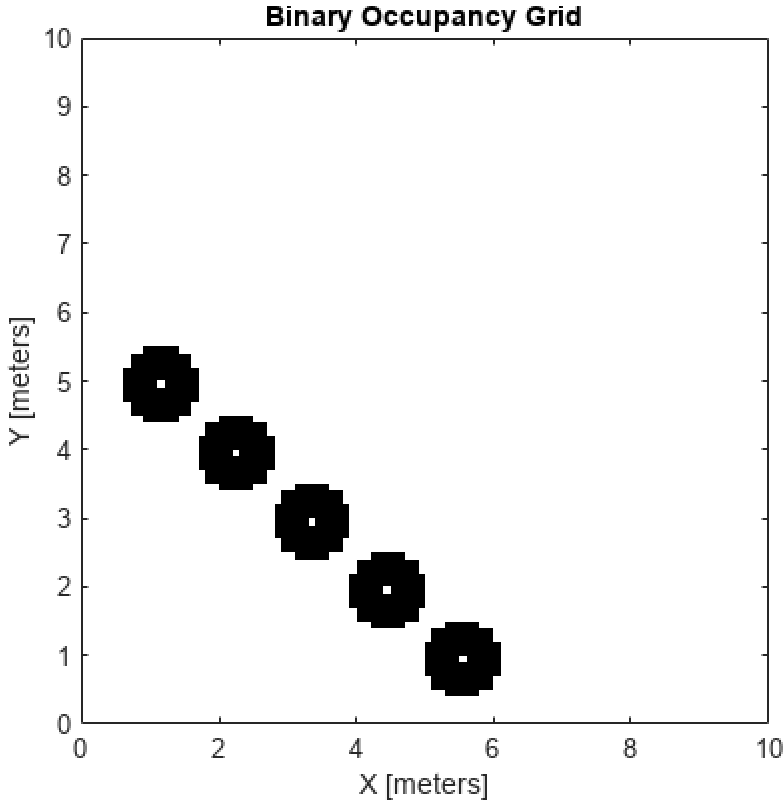



Get grid locations from world locations.

```
ij = world2grid(map, [x y]);
```

Set grid locations to free locations.

```
setOccupancy(map, ij, zeros(5,1), 'grid')
figure
show(map)
```




## Input Arguments

**map — Map representation**
binaryOccupancyMap object

Map representation, specified as a `binaryOccupancyMap` object. This object represents the environment of the robot. The object contains a matrix grid with binary values indicating obstacles as `true` (`1`) and free locations as `false` (`0`).

**radius — Dimension the defines how much to inflate occupied locations**
scalar

Dimension that defines how much to inflate occupied locations, specified as a scalar. `radius` is rounded up to the nearest cell value.

Data Types: `double`

**gridradius — Dimension the defines how much to inflate occupied locations**
positive scalar

Dimension that defines how much to inflate occupied locations, specified as a positive scalar. `gridradius` is the number of cells to inflate the occupied locations.

Data Types: `double`

# Version History

**Introduced in R2015a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`binaryOccupancyMap` | `setOccupancy`

### Topics

"Occupancy Grids"

# insertRay

Insert ray from laser scan observation

## Syntax

```
insertRay(map,pose,scan,maxrange)
insertRay(map,pose,ranges,angles,maxrange)
insertRay(map,startpt,endpoints)
```

## Description

`insertRay(map,pose,scan,maxrange)` inserts one or more lidar scan sensor observations in the occupancy grid, `map`, using the input `lidarScan` object, `scan`, to get ray endpoints. End point locations are updated with an occupied value. If the ranges are above `maxrange`, the ray endpoints are considered free space. All other points along the ray are treated as obstacle-free.

`insertRay(map,pose,ranges,angles,maxrange)` specifies the range readings as vectors defined by the input `ranges` and `angles`.

`insertRay(map,startpt,endpoints)` inserts observations between the line segments from the start point to the end points. The endpoints are updated are occupied space and other points along the line segments are updated as free space.

## Examples

### Insert Laser Scans into Binary Occupancy Map

Create an empty binary occupancy grid map.

```
map = binaryOccupancyMap(10,10,20);
```

Input pose of the vehicle, ranges, angles, and the maximum range of the laser scan.

```
pose = [5,5,0];
ranges = 3*ones(100,1);
angles = linspace(-pi/2,pi/2,100);
maxrange = 20;
```

Create a `lidarScan` object with the specified ranges and angles.

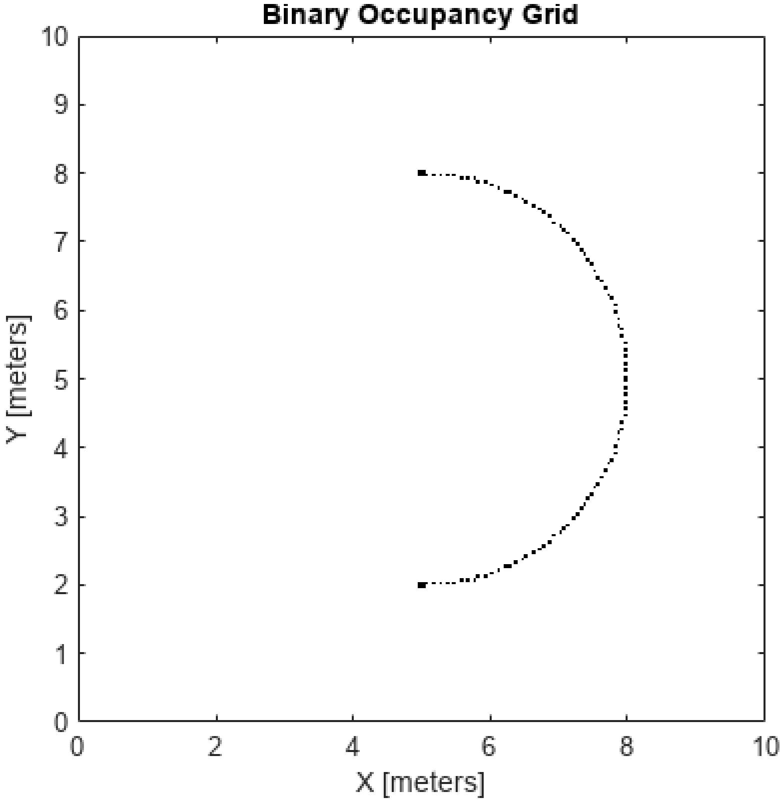
```
scan = lidarScan(ranges,angles);
```

Insert the laser scan data into the occupancy map.

```
insertRay(map,pose,scan,maxrange);
```

Show the map to see the results of inserting the laser scan.

```
show(map)
```




Check the occupancy of the spot directly in front of the vehicle.

```
getOccupancy(map,[8 5])
```

```
ans = logical
   1
```

## Input Arguments

**map — Map representation**
binaryOccupancyMap object

Map representation, specified as a `binaryOccupancyMap` object. This object represents the environment of the robot. The object contains a matrix grid with binary values indicating obstacles as `true` (1) and free locations as `false` (0).

**pose — Position and orientation of vehicle**
three-element vector

Position and orientation of vehicle, specified as an `[x y theta]` vector. The vehicle pose is an *x* and *y* position with angular orientation *theta* (in radians) measured from the *x*-axis.

**scan — Lidar scan readings**
lidarScan object

Lidar scan readings, specified as a `lidarScan` object.

**`ranges` — Range values from scan data**
vector

Range values from scan data, specified as a vector of elements measured in meters. These range values are distances from a sensor at given `angles`. The vector must be the same length as the corresponding `angles` vector.

**`angles` — Angle values from scan data**
vector

Angle values from scan data, specified as a vector of elements measured in radians. These angle values correspond to the given `ranges`. The vector must be the same length as the corresponding `ranges` vector.

**`maxrange` — Maximum range of sensor**
scalar

Maximum range of laser range sensor, specified as a scalar in meters. Range values greater than or equal to `maxrange` are considered free along the whole length of the ray, up to `maxrange`.

**`startpt` — Start point for rays**
two-element vector

Start point for rays, specified as a two-element vector, `[x y]`, in the world coordinate frame. All rays are line segments that originate at this point.

**`endpoints` — Endpoints for rays**
*n*-by-2 matrix

Endpoints for rays, specified as an *n*-by-2 matrix of `[x y]` pairs in the world coordinate frame, where *n* is the length of `ranges` or `angles`. All rays are line segments that originate at `startpt`.

# Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`occupancyMap` | `binaryOccupancyMap` | `lidarScan`

### Topics

"Occupancy Grids"

# local2grid

Convert local coordinates to grid indices

## Syntax

```
ij = local2grid(map,xy)
```

## Description

`ij = local2grid(map,xy)` converts an array of local coordinates, `xy`, to an array of grid indices, `ij` in `[row col]` format.

## Examples

### Convert Local Coordinates in Binary Occupancy Map to Grid Indices

Create an empty binary occupancy map with a width and height of 10 meters.

```
map = binaryOccupancyMap(10,10);
```

Get grid indices from local coordinates.

```
[xLocal,yLocal] = meshgrid(0:0.5:2);
ij = local2grid(map,[xLocal(:) yLocal(:)]);
```

## Input Arguments

**map — Map representation**
`binaryOccupancyMap` object

Map representation, specified as a `binaryOccupancyMap` object. This object represents the environment of the vehicle.

**xy — Local coordinates**
*n*-by-2 matrix

Local coordinates, specified as an *n*-by-2 matrix of `[x y]` pairs, where *n* is the number of local coordinates.

Data Types: `double`

## Output Arguments

**ij — Grid positions**
*n*-by-2 matrix

Grid positions, returned as an *n*-by-2 matrix of `[i j]` pairs in `[row col]` format, where *n* is the number of grid positions. The grid cell locations are counted from the top left corner of the grid.

Data Types: `double`

## Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`binaryOccupancyMap` | `occupancyMap` | `grid2world` | `grid2world`

### Topics

"Occupancy Grids"

# local2world

Convert local coordinates to world coordinates

## Syntax

```
xyWorld = local2world(map,xy)
```

## Description

`xyWorld = local2world(map,xy)` converts an array of local coordinates to world coordinates.

## Examples

### Convert Local Coordinates in Binary Occupancy Map to World Coordinates

Create an empty binary occupancy map with a width and height of 10 meters.

```
map = binaryOccupancyMap(10,10);
```

Get world coordinates from local coordinates.

```
[xLocal,yLocal] = meshgrid(0:0.5:2);
xyWorld = local2world(map,[xLocal(:) yLocal(:)]);
```

## Input Arguments

**map — Map representation**
`binaryOccupancyMap` object

Map representation, specified as a `binaryOccupancyMap` object. This object represents the environment of the vehicle.

**xy — Local coordinates**
*n*-by-2 matrix

Local coordinates, specified as an *n*-by-2 matrix of `[x y]` pairs, where *n* is the number of local coordinates.

Data Types: `double`

## Output Arguments

**xyWorld — World coordinates**
*n*-by-2 matrix

World coordinates, specified as an *n*-by-2 matrix of `[x y]` pairs, where *n* is the number of world coordinates.

Data Types: `double`

## Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Topics

"Occupancy Grids"

# move

Move map in world frame

## Syntax

```
move(map,moveValue)
move(map,moveValue,Name,Value)
```

## Description

`move(map,moveValue)` moves the local origin of the map to an absolute location, `moveValue`, in the world frame, and updates the map limits. Move values are truncated based on the resolution of the map. By default, newly revealed regions are set to `map.DefaultValue`.

`move(map,moveValue,Name,Value)` specifies additional options specified by one or more name-value pair arguments.

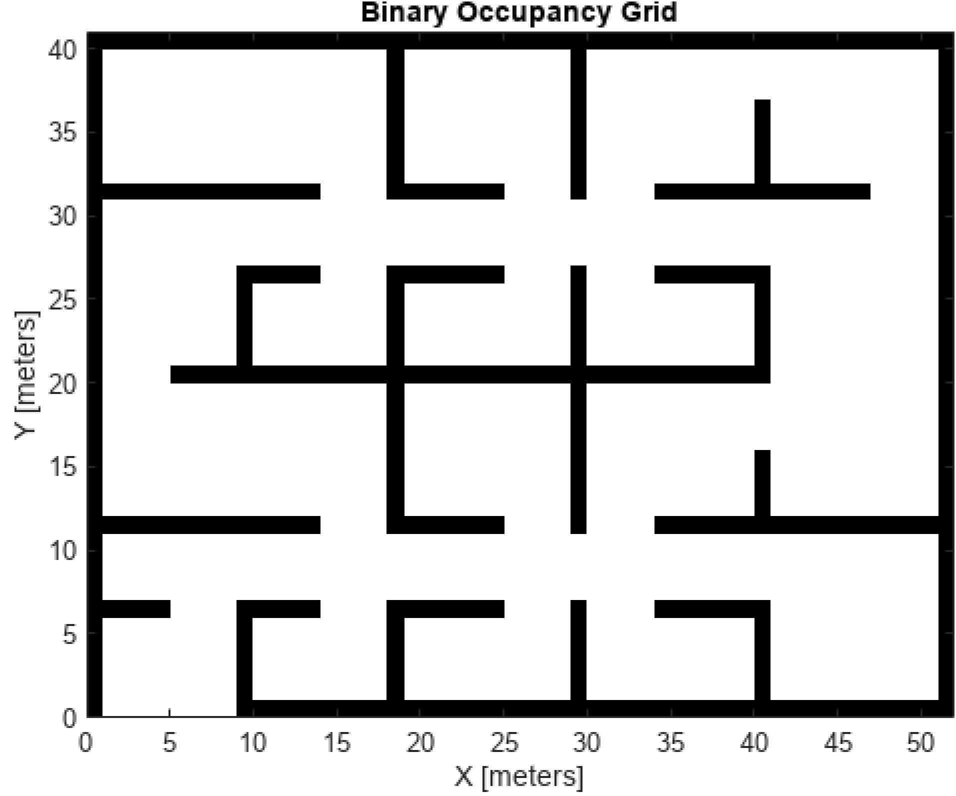
## Examples

### Move Local Map and Sync with World Map

This example shows how to move a local egocentric map and sync it with a larger world map. This process emulates a vehicle driving in an environment and getting updates on obstacles in the new areas.

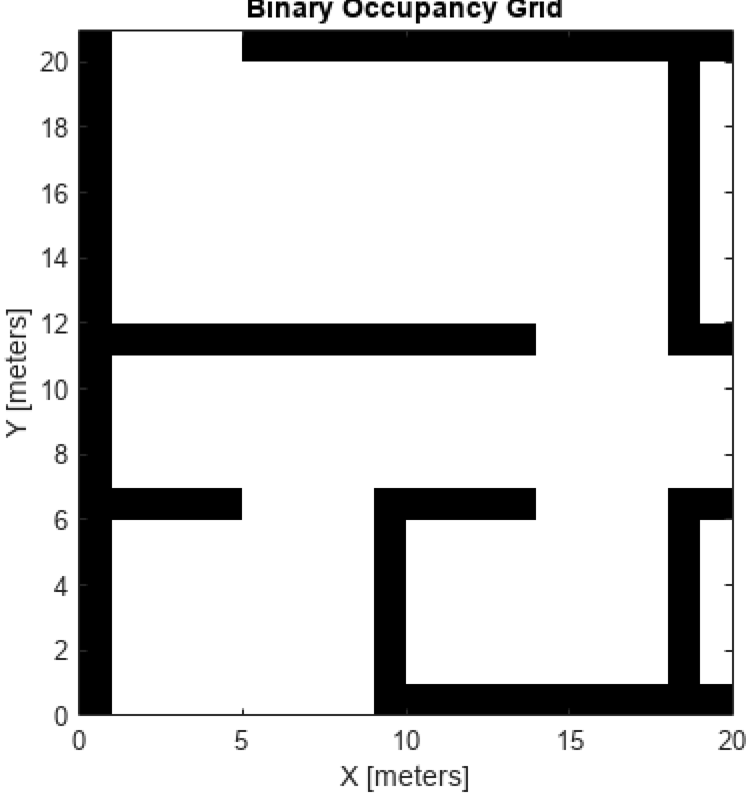
Load example maps. Create a binary occupancy map from the `complexMap`.

```
load exampleMaps.mat
map = binaryOccupancyMap(complexMap);
show(map)
```




Create a smaller local map.

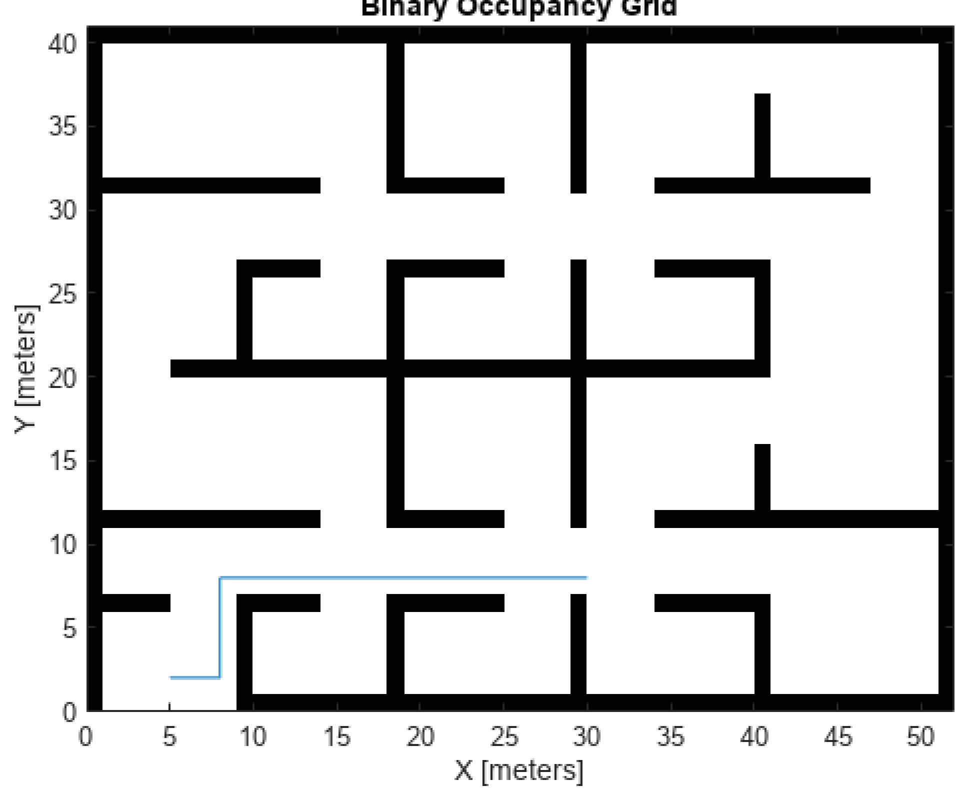
```
mapLocal = binaryOccupancyMap(complexMap(end-20:end,1:20));
show(mapLocal)
```




Follow a path planned in the world map and update the local map as you move your local frame.

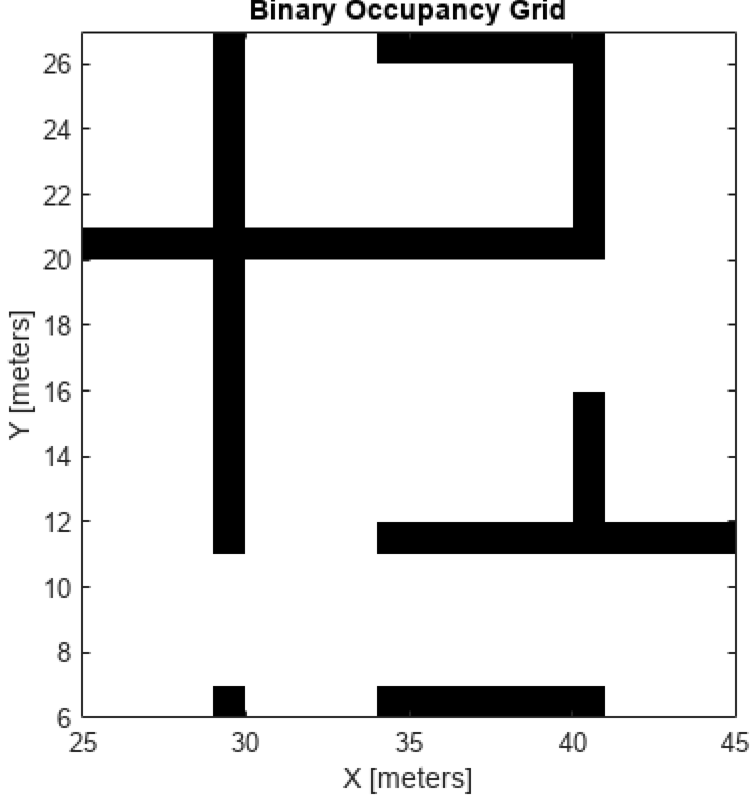
Specify path locations and plot on the map.

```
path = [5 2
        8 2
        8 8
        30 8];
show(map)
hold on
plot(path(:,1),path(:,2))
hold off
```




Create a loop for moving between points by the map resolution. Divide the difference between points by the map resolution to see how many incremental moves you can make.

```
for i = 1:length(path)-1
    moveAmount = (path(i+1,:)-path(i,:))/map.Resolution;
    for j = 1:abs(moveAmount(1)+moveAmount(2))
        moveValue = sign(moveAmount).*map.Resolution;
        move(mapLocal,moveValue, ...
            "MoveType","relative","SyncWith",map)

        show(mapLocal)
        drawnow limitrate
        pause(0.2)
    end
end
```




## Input Arguments

**map — Map representation**
binaryOccupancyMap object

Map representation, specified as a binaryOccupancyMap object. This object represents the environment of the vehicle.

**moveValue — Local map origin move value**
[x y] vector

Local map origin move value, specified as an [x y] vector. By default, the value is an absolute location to move the local origin to in the world frame. Use the MoveType name-value pair to specify a relative move.

### Name-Value Pair Arguments

Specify optional pairs of arguments as Name1=Value1,...,NameN=ValueN, where Name is the argument name and Value is the corresponding value. Name-value arguments must appear after other arguments, but the order of the pairs does not matter.

*Before R2021a, use commas to separate each name and value, and enclose* Name *in quotes.*

Example: 'MoveType','relative'

**`MoveType` — Type of move**
`'absolute'` (default) | `'relative'`

Type of move, specified as `'absolute'` or `'relative'`. For relative moves, specify a relative `[x y]` vector for `moveValue` based on your current local frame.

**`FillValue` — Fill value for revealed locations**
`0` (default) | `1`

Fill value for revealed locations because of the shifted map limits, specified as `0` or `1`.

**`SyncWith` — Secondary map to sync with**
`binaryOccupancyMap` object

Secondary map to sync with, specified as a `binaryOccupancyMap` object. Any revealed locations based on the move are updated with values in this map using the world coordinates.

# Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`binaryOccupancyMap` | `occupancyMap` | `occupancyMatrix`

# occupancyMatrix

Convert occupancy grid to matrix

## Syntax

```
mat = occupancyMatrix(map)
```

## Description

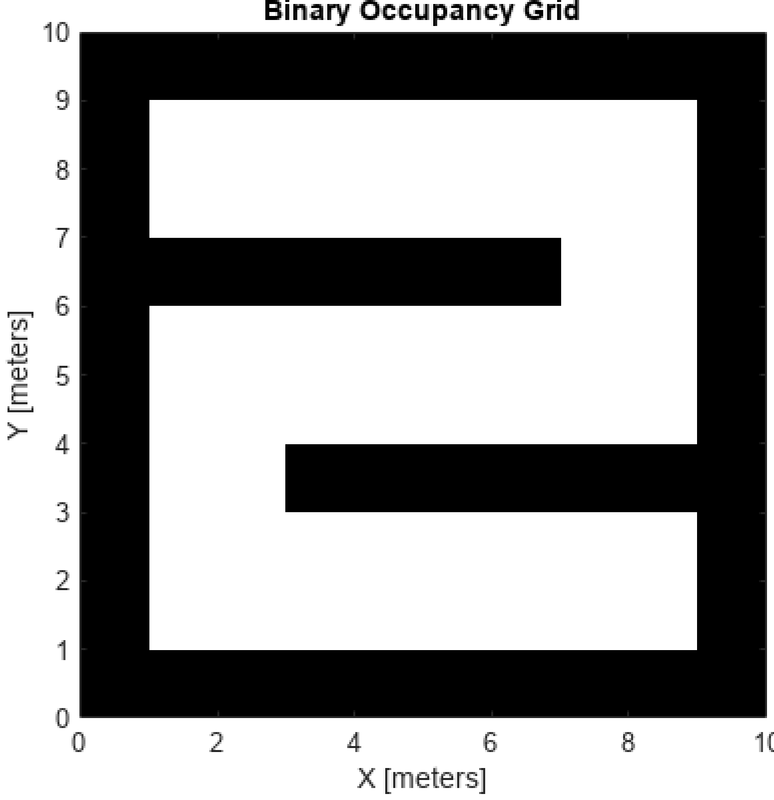
`mat = occupancyMatrix(map)` returns occupancy values stored in the occupancy grid object as a matrix.

## Examples

### Convert Binary Occupancy Map to Matrix

Generate a random 2-D maze map.

```
map = mapMaze(2,MapSize=[10 10],MapResolution=1);
show(map)
```



Convert the binary occupancy map to occupancy values matrix.

```
occupancyMatrix(map)
```

```
ans = 10x10 logical array

   1   1   1   1   1   1   1   1   1   1
   1   0   0   0   0   0   0   0   0   1
   1   0   0   0   0   0   0   0   0   1
   1   1   1   1   1   1   1   0   0   1
   1   0   0   0   0   0   0   0   0   1
   1   0   0   0   0   0   0   0   0   1
   1   0   0   1   1   1   1   1   1   1
   1   0   0   0   0   0   0   0   0   1
   1   0   0   0   0   0   0   0   0   1
   1   1   1   1   1   1   1   1   1   1
```

## Input Arguments

### `map` — Map representation

`binaryOccupancyMap` object

Map representation, specified as a `binaryOccupancyMap` object. This object represents the environment of the robot. The object contains a matrix grid with binary values indicating obstacles as `true` (`1`) and free locations as `false` (`0`).

## Output Arguments

### `mat` — Occupancy values

matrix

Occupancy values, returned as an $h$-by-$w$ matrix, where $h$ and $w$ are defined by the two elements of the `GridSize` property of the occupancy grid object.

Data Types: `double`

# Version History

**Introduced in R2016b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`binaryOccupancyMap` | `occupancyMap`

### Topics

“Occupancy Grids”

# raycast

Compute cell indices along a ray

## Syntax

```
[endpoints,midpoints] = raycast(map,pose,range,angle)
[endpoints,midpoints] = raycast(map,p1,p2)
```

## Description

`[endpoints,midpoints] = raycast(map,pose,range,angle)` returns cell indices of the specified `map` for all cells traversed by a ray originating from the specified `pose` at the specified `angle` and `range` values. `endpoints` contains all indices touched by the end of the ray, with all other points included in `midpoints`.

`[endpoints,midpoints] = raycast(map,p1,p2)` returns the cell indices of the line segment between the two specified points.

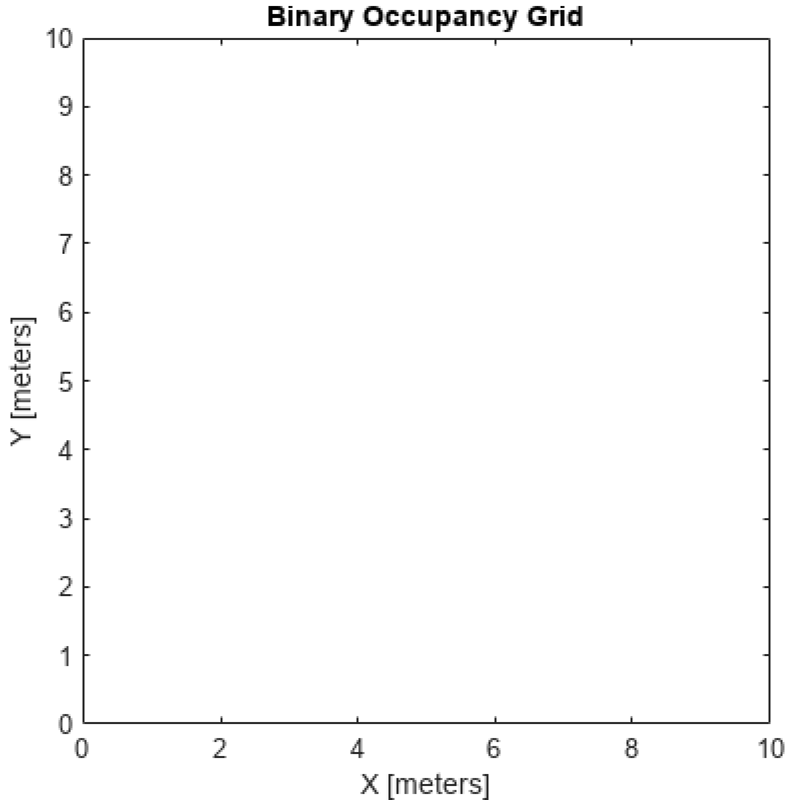
## Examples

### Compute Grid Cell Indices Along a Ray

Use the `raycast` function to generate cell indices for all cells traversed by a ray.

Create an empty map. A low-resolution map is used to illustrate the affected grid locations.

```
map = binaryOccupancyMap(10,10,1);
show(map)
```

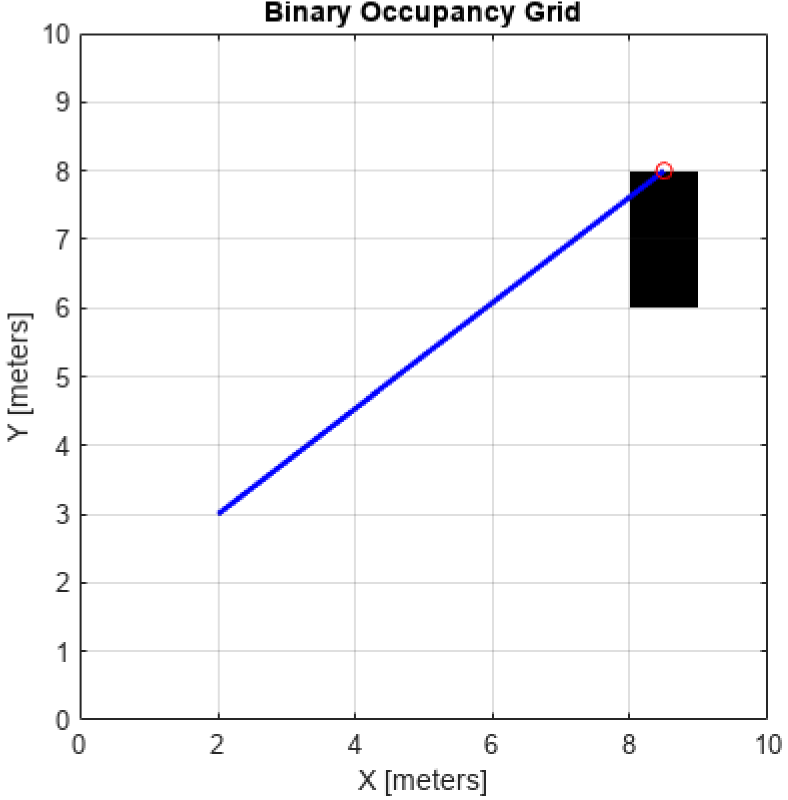



Get the grid indices of the midpoints and end points of a ray from `[2 3]` to `[8.5 8]`. Set occupancy values for these grid indices. Midpoints are treated as open space. Update endpoints with an occupied observation.

```
p1 = [2 3];
p2 = [8.5 8];
[endPts,midPts] = raycast(map,p1,p2);
setOccupancy(map,midPts,zeros(length(midPts),1),'grid');
setOccupancy(map,endPts,ones(length(endPts),1),'grid');
```

Plot the original ray over the map. Each grid cell touched by the line is updated. The starting point overlaps multiple cells, and the line touches the edge of certain cells, but all the cells are still updated.

```
show(map)
hold on
plot([p1(1) p2(1)],[p1(2) p2(2)],"-b","LineWidth",2)
plot(p2(1),p2(2),"or")
grid on
```




## Input Arguments

**map — Map representation**
binaryOccupancyMap object

Map representation, specified as a `binaryOccupancyMap` object. This object represents the environment of the robot. The object contains a matrix grid with binary values indicating obstacles as `true` (`1`) and free locations as `false` (`0`).

**pose — Position and orientation of sensor**
three-element vector

Position and orientation of sensor, specified as an `[x y theta]` vector. The sensor pose is an *x* and *y* position with angular orientation *theta* (in radians) measured from the *x*-axis.

**range — Range of ray**
scalar

Range of ray, specified as a scalar in meters.

**angle — Angle of ray**
scalar

Angle of ray, specified as a scalar in radians. The angle value is for the corresponding `range`.

#### p1 — Starting point of ray

two-element vector

Starting point of ray, specified as an `[x y]` two-element vector. Points are defined with respect to the world-frame.

#### p2 — Endpoint of ray

two-element vector

Endpoint of ray, specified as an `[x y]` two-element vector. Points are defined with respect to the world-frame.

### Output Arguments

#### `endpoints` — Endpoint grid indices

*n*-by-2 matrix

Endpoint indices, returned as an *n*-by-2 matrix of `[i j]` pairs, where *n* is the number of grid indices. The endpoints are where the `range` value hits at the specified `angle`. Multiple indices are returned when the endpoint lies on the boundary of multiple cells.

#### `midpoints` — Midpoint grid indices

*n*-by-2 matrix

Midpoint indices, returned as an *n*-by-2 matrix of `[i j]` pairs, where *n* is the number of grid indices. This argument includes all grid indices the ray intersects, excluding the endpoint.

## Version History

**Introduced in R2019b**

### Extended Capabilities

#### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

### See Also

`binaryOccupancyMap` | `insertRay` | `occupancyMap`

#### Topics

"Occupancy Grids" (Robotics System Toolbox)
"Occupancy Grids"

# rayIntersection

Find intersection points of rays and occupied map cells

## Syntax

`intersectionPts = rayIntersection(map,pose,angles,maxrange)`

## Description

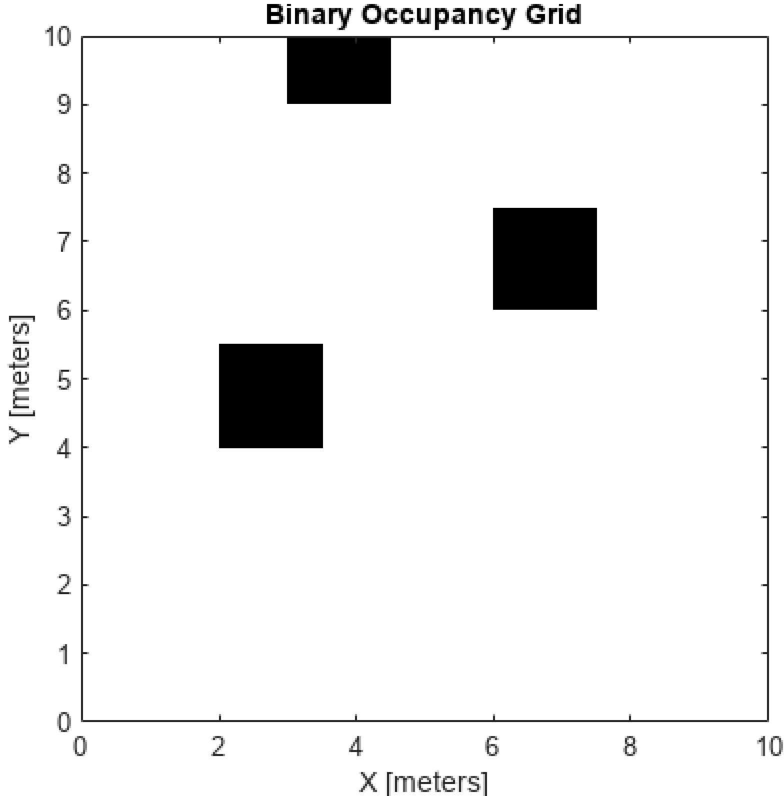
`intersectionPts = rayIntersection(map,pose,angles,maxrange)` returns intersection points of rays and occupied cells in the specified `map`. Rays emanate from the specified `pose` and `angles`. Intersection points are returned in the world coordinate frame. If there is no intersection up to the specified `maxrange`, `[NaN NaN]` is returned.

## Examples

### Get Ray Intersection Points on Occupancy Map

Create a binary occupancy grid map. Add obstacles and inflate them. A lower resolution map is used to illustrate the importance of the size of your grid cells. Show the map.

```
map = binaryOccupancyMap(10,10,2);
obstacles = [4 10; 3 5; 7 7];
setOccupancy(map,obstacles,ones(length(obstacles),1))
inflate(map,0.25)
show(map)
```



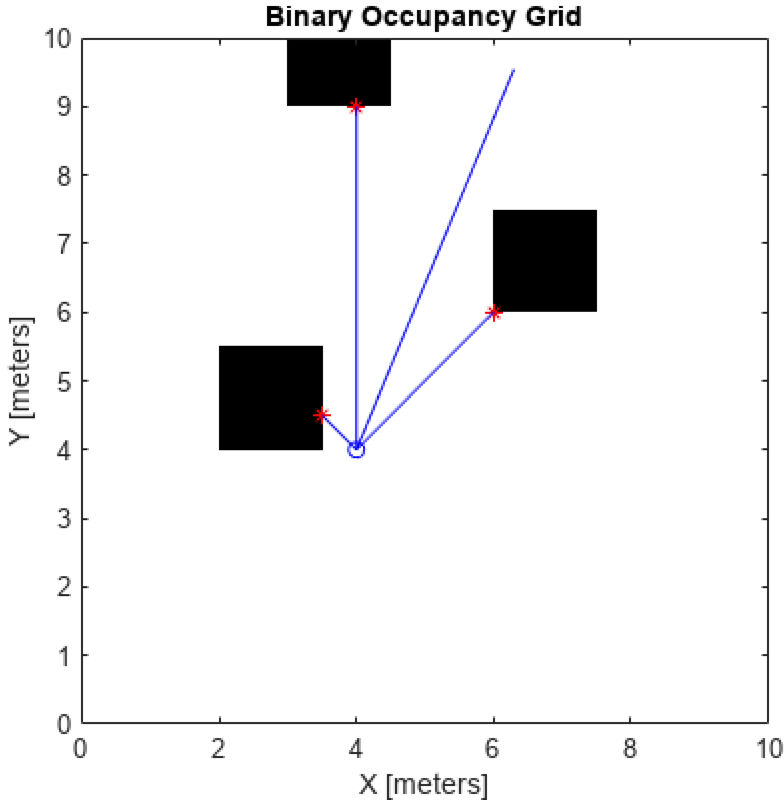

Find the intersection points of occupied cells and rays that emit from the given vehicle pose. Specify the max range and angles for these rays. The last ray does not intersect with an obstacle within the max range, so it has no collision point.

```
maxrange = 6;
angles = [pi/4,-pi/4,0,-pi/8];
vehiclePose = [4,4,pi/2];
intsectionPts = rayIntersection(map,vehiclePose,angles,maxrange)
```

```
intsectionPts = 4×2

    3.5000    4.5000
    6.0000    6.0000
    4.0000    9.0000
       NaN       NaN
```

Plot the intersection points and plot rays from the pose to the intersection points.

```
hold on
plot(intsectionPts(:,1),intsectionPts(:,2),'*r') % Intersection points
plot(vehiclePose(1),vehiclePose(2),'ob') % Vehicle pose
for i = 1:3
    plot([vehiclePose(1),intsectionPts(i,1)],...
        [vehiclePose(2),intsectionPts(i,2)],'-b') % Plot intersecting rays
end
plot([vehiclePose(1),vehiclePose(1)-6*sin(angles(4))],...
    [vehiclePose(2),vehiclePose(2)+6*cos(angles(4))],'-b') % No intersection ray
```




## Input Arguments

**map — Map representation**
binaryOccupancyMap object

Map representation, specified as a `binaryOccupancyMap` object. This object represents the environment of the robot. The object contains a matrix grid with binary values indicating obstacles as `true` (`1`) and free locations as `false` (`0`).

**pose — Position and orientation of sensor**
three-element vector

Position and orientation of the sensor, specified as an `[x y theta]` vector. The sensor pose is an *x* and *y* position with angular orientation *theta* (in radians) measured from the *x*-axis.

**angles — Ray angles emanating from sensor**
vector

Ray angles emanating from the sensor, specified as a vector with elements in radians. These angles are relative to the specified sensor `pose`.

**maxrange — Maximum range of sensor**
scalar

Maximum range of laser range sensor, specified as a scalar in meters. Range values greater than or equal to `maxrange` are considered free along the whole length of the ray, up to `maxrange`.

### Output Arguments

**`intersectionPts` — Intersection points**
*n*-by-2 matrix

Intersection points, returned as *n*-by-2 matrix of `[x y]` pairs in the world coordinate frame, where *n* is the length of `angles`.

## Version History

**Introduced in R2019b**

### Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

### See Also

`binaryOccupancyMap` | `occupancyMap`

**Topics**
"Occupancy Grids" (Robotics System Toolbox)
"Occupancy Grids" (Robotics System Toolbox)

# setOccupancy

Set occupancy value of locations

## Syntax

```
setOccupancy(map,xy,occval)
setOccupancy(map,xy,occval,"local")
setOccupancy(map,ij,occval,"grid")
validPts = setOccupancy( ___ )
```

```
setOccupancy(map,bottomLeft,inputMatrix)
setOccupancy(map,bottomLeft,inputMatrix,"local")
setOccupancy(map,topLeft,inputMatrix,"grid")
```

## Description

`setOccupancy(map,xy,occval)` assigns occupancy values, `occval`, to the input array of world coordinates, `xy` in the occupancy grid, `map`. Each row of the array, `xy`, is a point in the world and is represented as an `[x y]` coordinate pair. `occval` is either a scalar or a single column array of the same length as `xy` . An occupied location is represented as `true` (`1`), and a free location is represented as `false` (`0`).

`setOccupancy(map,xy,occval,"local")` assigns occupancy values, `occval`, to the input array of local coordinates, `xy`, as local coordinates.

`setOccupancy(map,ij,occval,"grid")` assigns occupancy values, `occval`, to the input array of grid indices, `ij`, as `[rows cols]`.

`validPts = setOccupancy( ___ )` outputs an `n`-element vector of logical values indicating whether input coordinates are within the map limits.

`setOccupancy(map,bottomLeft,inputMatrix)` assigns a matrix of occupancy values by specifying the bottom-left corner location in world coordinates.

`setOccupancy(map,bottomLeft,inputMatrix,"local")` assigns a matrix of occupancy values by specifying the bottom-left corner location in local coordinates.

`setOccupancy(map,topLeft,inputMatrix,"grid")` assigns a matrix of occupancy values by specifying the top-left cell index in grid indices and the matrix size.

## Examples

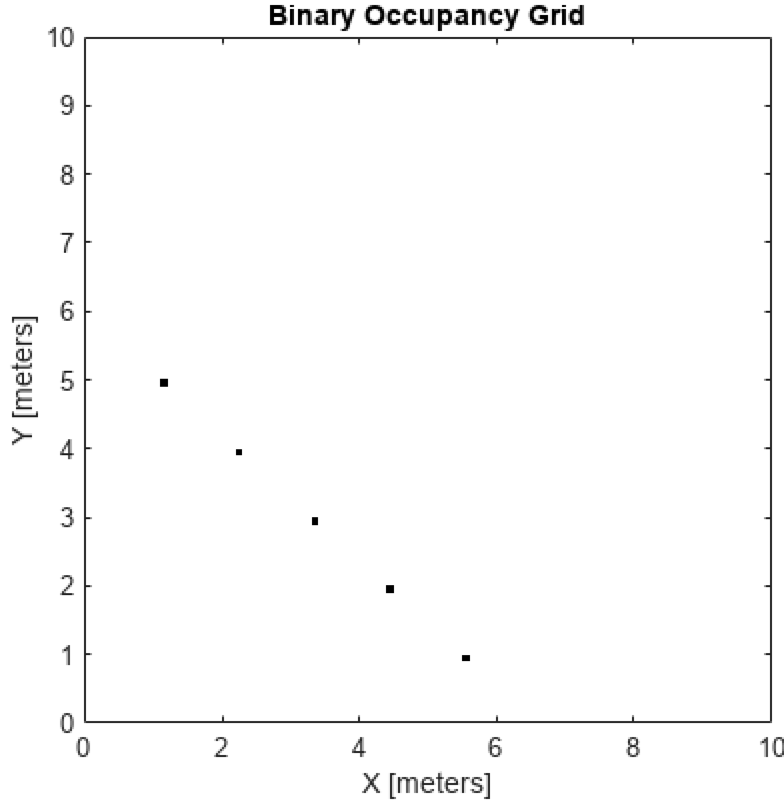
### Create and Modify Binary Occupancy Grid

Create a 10m x 10m empty map.

```
map = binaryOccupancyMap(10,10,10);
```

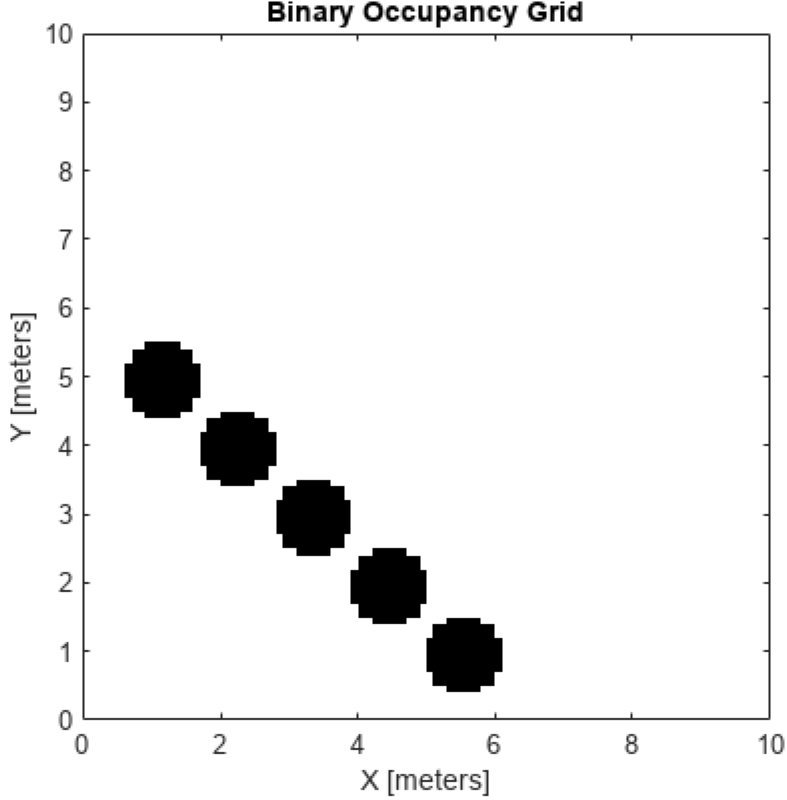
Set occupancy of world locations and show map.

```
x = [1.2; 2.3; 3.4; 4.5; 5.6];
y = [5.0; 4.0; 3.0; 2.0; 1.0];

setOccupancy(map, [x y], ones(5,1))
figure
show(map)
```




Inflate occupied locations by a given radius.

```
inflate(map, 0.5)
figure
show(map)
```

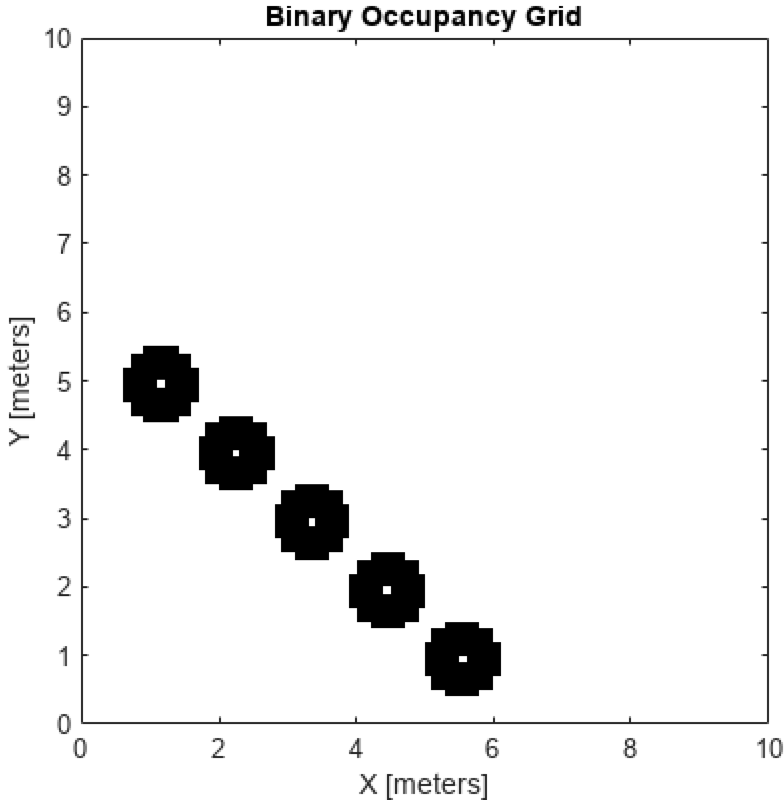



Get grid locations from world locations.

```
ij = world2grid(map, [x y]);
```

Set grid locations to free locations.

```
setOccupancy(map, ij, zeros(5,1), 'grid')
figure
show(map)
```




## Input Arguments

**map — Map representation**
binaryOccupancyMap object

Map representation, specified as a `binaryOccupancyMap` object. This object represents the environment of the robot. The object contains a matrix grid with binary values indicating obstacles as `true` (`1`) and free locations as `false` (`0`).

**xy — World coordinates**
*n*-by-2 vertical array

World coordinates, specified as an *n*-by-2 vertical array of `[x y]` pairs, where *n* is the number of world coordinates.

Data Types: `double`

**ij — Grid positions**
*n*-by-2 vertical array

Grid positions, specified as an *n*-by-2 vertical array of `[i j]` pairs in `[rows cols]` format, where *n* is the number of grid positions.

Data Types: `double`

**`occval` — Occupancy values**
*n*-by-1 vertical array

Occupancy values of the same length as either `xy` or `ij`, returned as an *n*-by-1 vertical array, where *n* is the same *n* in either `xy` or `ij`. Values are given between 0 and 1 inclusively.

**`inputMatrix` — Occupancy values**
matrix

Occupancy values, specified as a matrix. Values are given between 0 and 1 inclusively.

**`bottomLeft` — Location of output matrix in world or local**
two-element vector | `[xCoord yCoord]`

Location of bottom left corner of output matrix in world or local coordinates, specified as a two-element vector, `[xCoord yCoord]`. Location is in world or local coordinates based on syntax.

Data Types: `double`

**`topLeft` — Location of grid**
two-element vector | `[iCoord jCoord]`

Location of top left corner of grid, specified as a two-element vector, `[iCoord jCoord]`.

Data Types: `double`

## Output Arguments

**`validPts` — Valid map locations**
*n*-by-1 column vector

Valid map locations, returned as an *n*-by-1 column vector equal in length to `xy` or `ij`. Locations inside the map return a value of 1. Locations outside the map limits return a value of 0.

# Version History

**Introduced in R2015a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

`binaryOccupancyMap` | `getOccupancy` | `occupancyMap`

# show

Display binary occupancy map

## Syntax

```
show(map)
show(map, "local")
show(map, "grid")
show( ___ ,Name,Value)
mapImage = show( ___ )
```

## Description

`show(map)` displays the binary occupancy grid `map` in the current axes, with the axes labels representing the world coordinates.

`show(map, "local")` displays the binary occupancy grid `map` in the current axes, with the axes labels representing the local coordinates instead of world coordinates.

`show(map, "grid")` displays the binary occupancy grid `map` in the current axes, with the axes labels representing the grid coordinates.

`show( ___ ,Name,Value)` specifies additional options specified by one or more name-value pair arguments.

`mapImage = show( ___ )` returns the handle to the image object created by `show`.

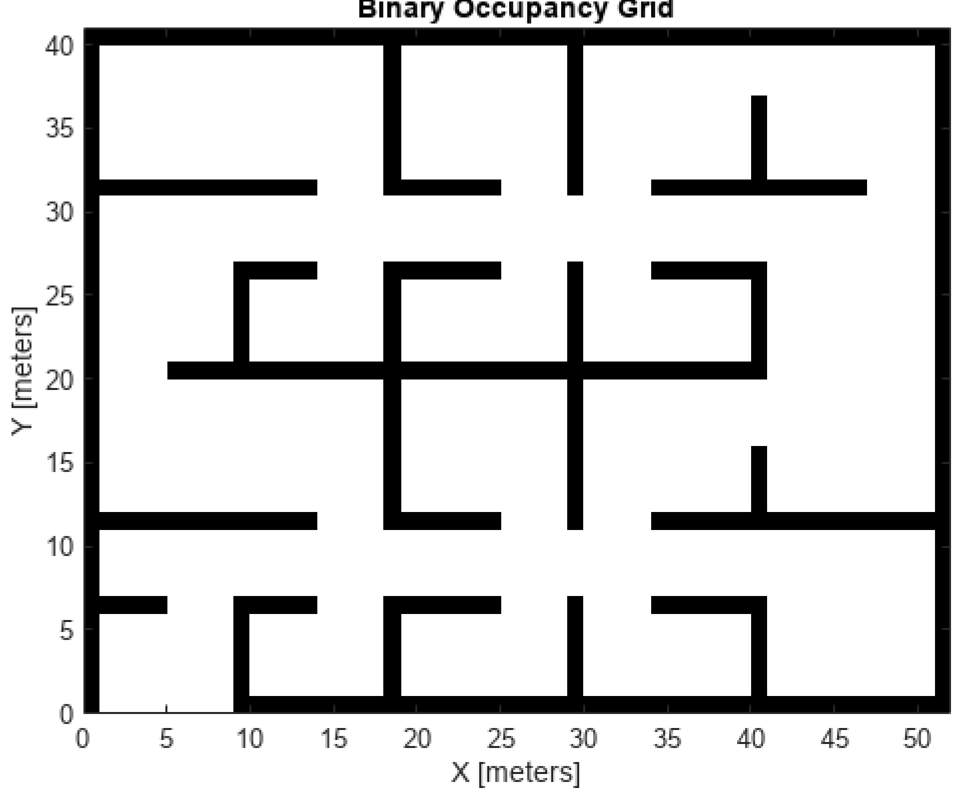
## Examples

### Move Local Map and Sync with World Map

This example shows how to move a local egocentric map and sync it with a larger world map. This process emulates a vehicle driving in an environment and getting updates on obstacles in the new areas.

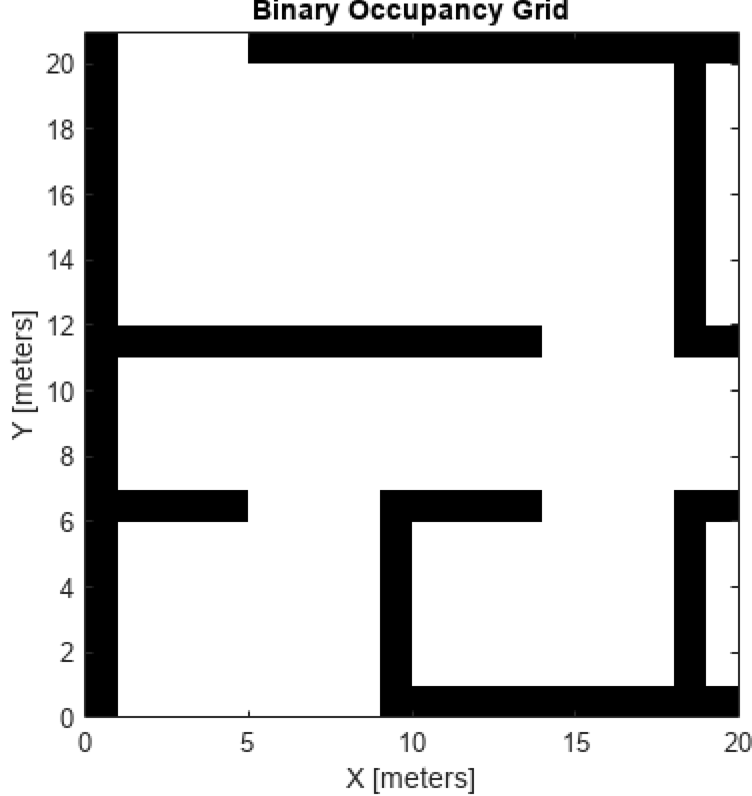
Load example maps. Create a binary occupancy map from the `complexMap`.

```
load exampleMaps.mat
map = binaryOccupancyMap(complexMap);
show(map)
```




Create a smaller local map.

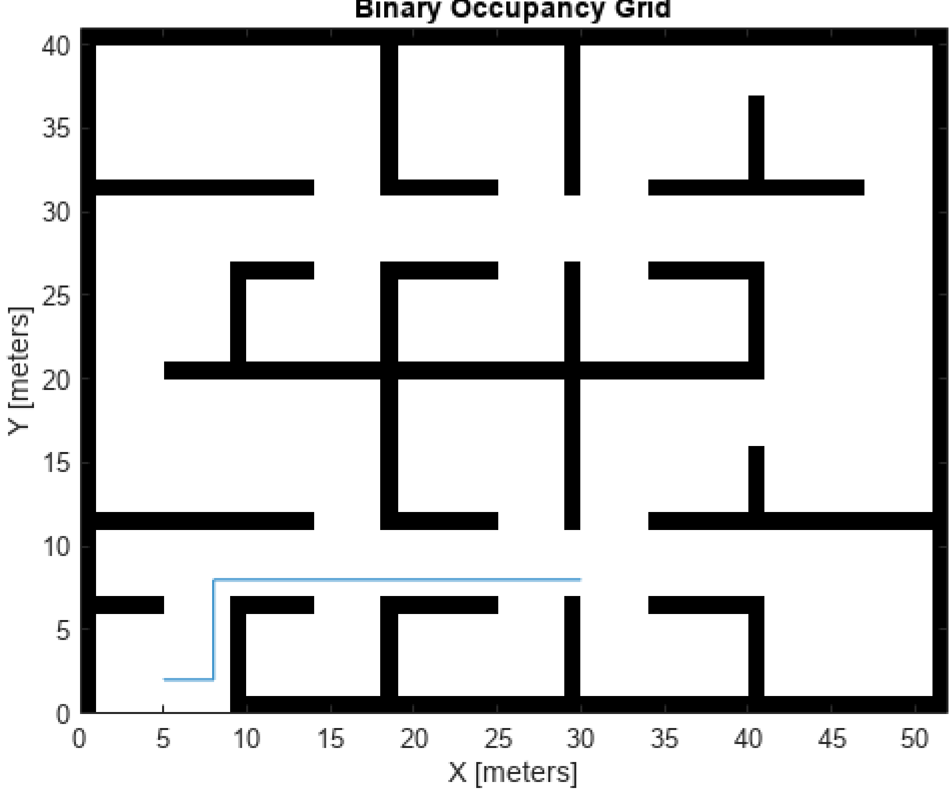
```
mapLocal = binaryOccupancyMap(complexMap(end-20:end,1:20));
show(mapLocal)
```




Follow a path planned in the world map and update the local map as you move your local frame.

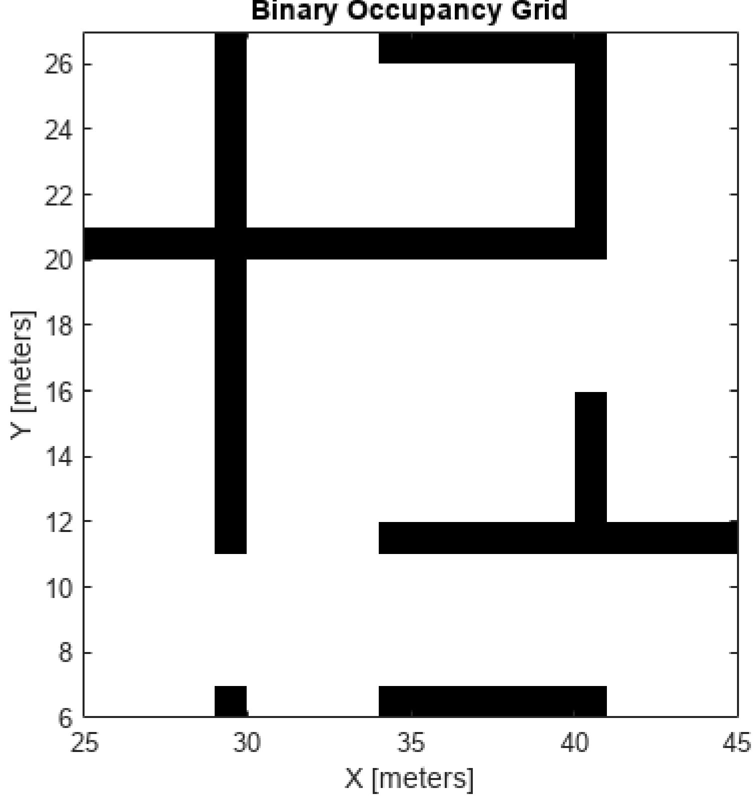
Specify path locations and plot on the map.

```
path = [5 2
        8 2
        8 8
        30 8];
show(map)
hold on
plot(path(:,1),path(:,2))
hold off
```




Create a loop for moving between points by the map resolution. Divide the difference between points by the map resolution to see how many incremental moves you can make.

```
for i = 1:length(path)-1
    moveAmount = (path(i+1,:)-path(i,:))/map.Resolution;
    for j = 1:abs(moveAmount(1)+moveAmount(2))
        moveValue = sign(moveAmount).*map.Resolution;
        move(mapLocal,moveValue, ...
            "MoveType","relative","SyncWith",map)

        show(mapLocal)
        drawnow limitrate
        pause(0.2)
    end
end
```




## Input Arguments

**map — Map representation**
binaryOccupancyMap object

Map representation, specified as a binaryOccupancyMap object. This object represents the environment of the vehicle.

### Name-Value Pair Arguments

Specify optional pairs of arguments as Name1=Value1,...,NameN=ValueN, where Name is the argument name and Value is the corresponding value. Name-value arguments must appear after other arguments, but the order of the pairs does not matter.

*Before R2021a, use commas to separate each name and value, and enclose* Name *in quotes.*

Example: 'Parent',axHandle

**Parent — Axes to plot the map**
Axes object | UIAxes object

Axes to plot the map specified as either an Axes or UIAxesobject. See axes or uiaxes.

**FastUpdate — Update existing map plot**
0 (default) | 1

Update existing map plot, specified as `0` or `1`. If you previously plotted your map on your figure, set to `1` for a faster update to the figure. This is useful for updating the figure in a loop for fast animations.

# Version History

**Introduced in R2015a**

## See Also

`binaryOccupancyMap` | `occupancyMap`

# syncWith

Sync map with overlapping map

## Syntax

```
mat = syncWith(map,sourcemap)
```

## Description

`mat = syncWith(map,sourcemap)` updates `map` with data from another `binaryOccupancyMap` object, `sourcemap`. Locations in `map` that are also found in `sourcemap` are updated. All other cells in `map` are set to `map.DefaultValue`.

## Examples

### Sync Map With an Overlapping Map

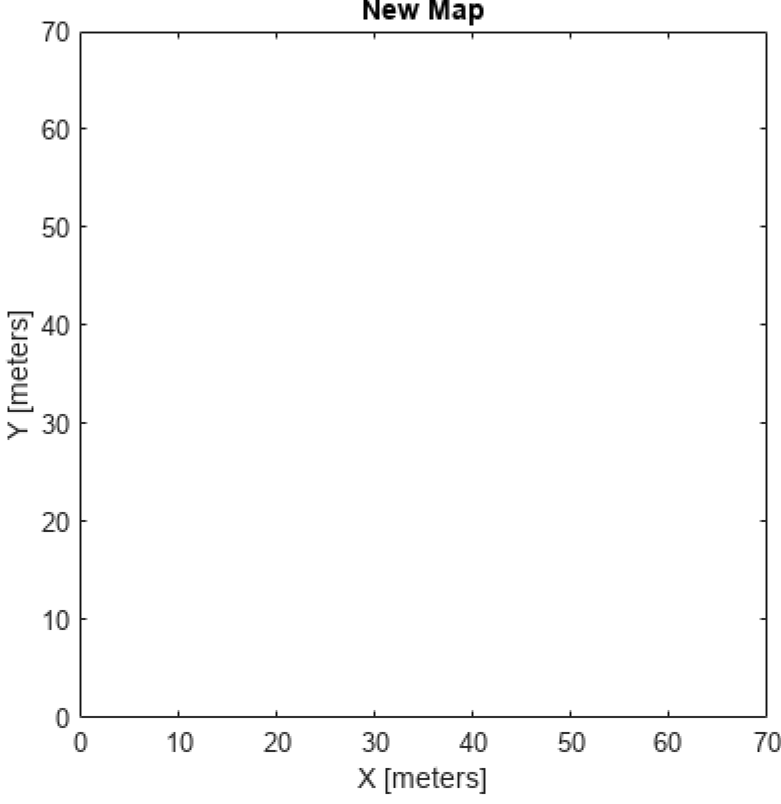
This example shows how to sync two overlapping maps using the `syncWith` function.

2-D occupancy maps are used to represent and visualize robot workspaces. In this example 2-D occupancy maps are created using existing map grid values stored inside `exampleMaps.mat`.

```
load('exampleMaps.mat');
```

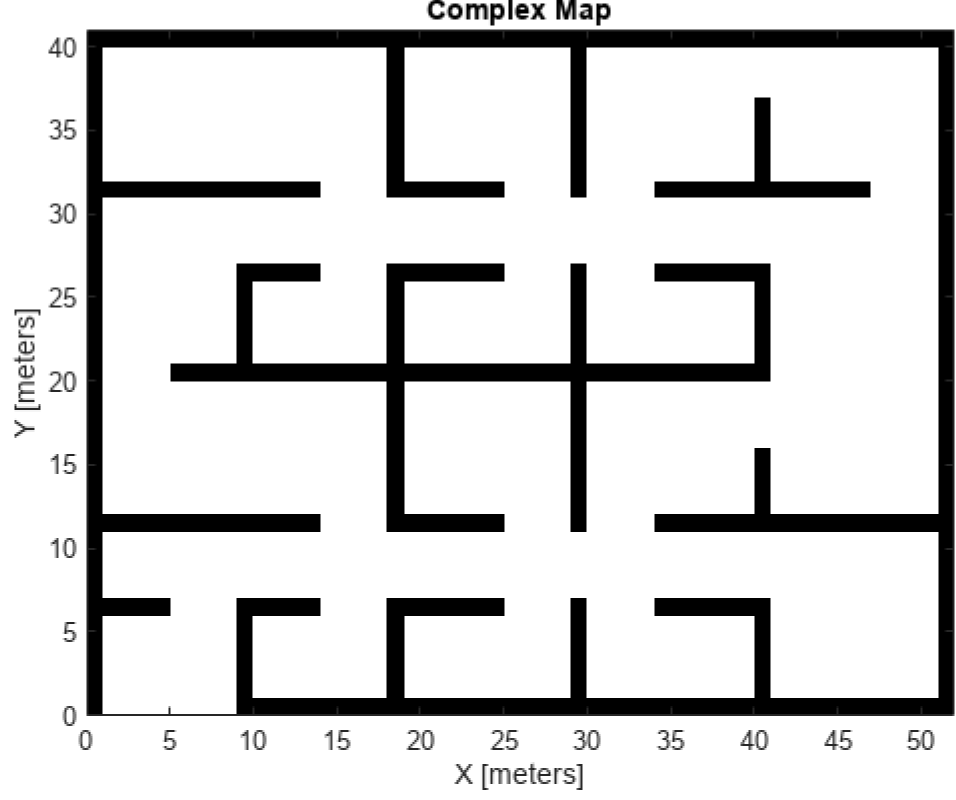
Create and display a new empty 2-D occupancy map object using `binaryOccupancyMap` function.

```
map1 = binaryOccupancyMap(70,70);
show(map1)
title('New Map')
```



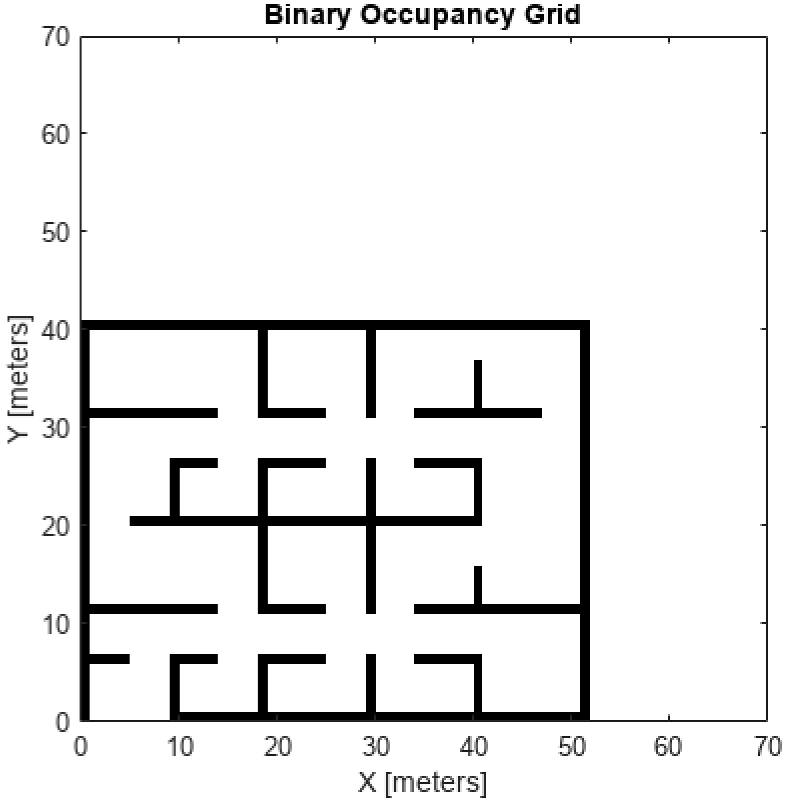

Create and display 2-D occupancy map using the map grid values stored in `complexMap`.

```
map2 = binaryOccupancyMap(complexMap);
show(map2)
title('Complex Map')
```




Now update `map1` with `map2` using the `syncWith` function.

```
syncWith(map1,map2);
show(map1)
```




## Input Arguments

**`map` — Map representation**
`binaryOccupancyMap` object

Map representation, specified as a `binaryOccupancyMap` object.

**`sourcemap` — Map representation**
`binaryOccupancyMap` object

Map representation, specified as a `binaryOccupancyMap` object.

# Version History

**Introduced in R2019b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

`binaryOccupancyMap` | `occupancyMap`

**Topics**
"Occupancy Grids"

# world2grid

Convert world coordinates to grid indices

## Syntax

```
ij = world2grid(map,xy)
```

## Description

`ij = world2grid(map,xy)` converts an array of world coordinates, `xy`, to a `[rows cols]` array of grid indices, `ij`.

## Examples

### Convert World Coordinates in Binary Occupancy Map to Grid Indices

Create an empty binary occupancy map with a width and height of 10 meters.

```
map = binaryOccupancyMap(10,10);
```

Get grid indices from world coordinates.

```
[xWorld,yWorld] = meshgrid(0:0.5:2);
ij = world2grid(map,[xWorld(:) yWorld(:)]);
```

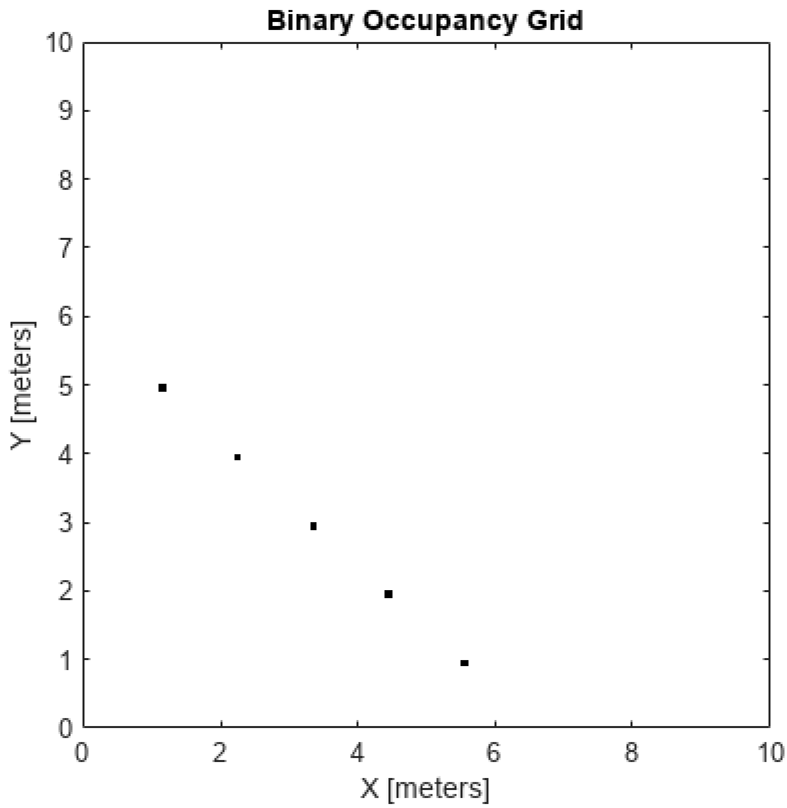
### Create and Modify Binary Occupancy Grid

Create a 10m x 10m empty map.

```
map = binaryOccupancyMap(10,10,10);
```

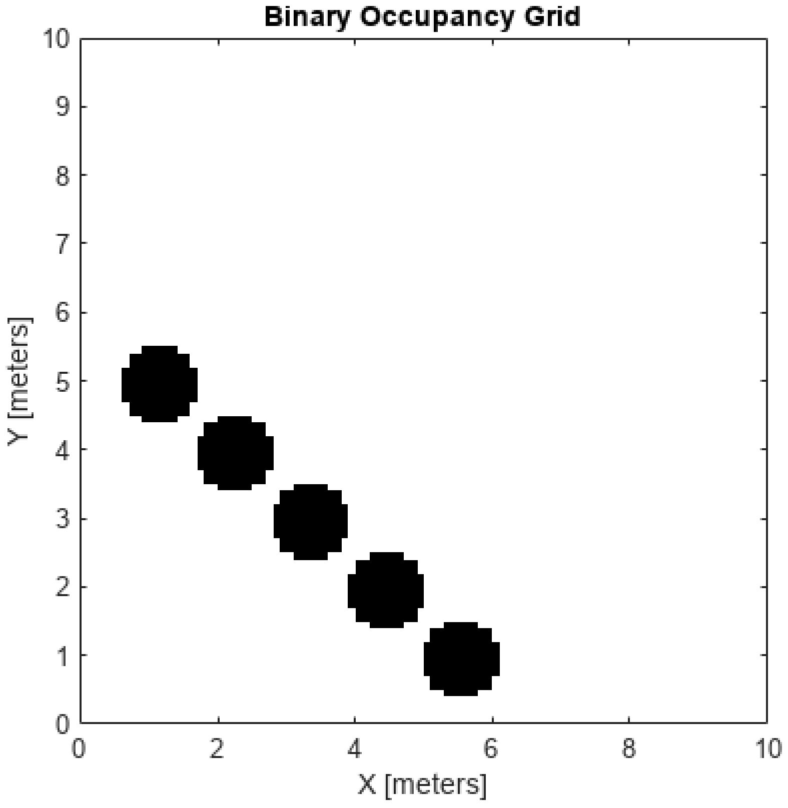
Set occupancy of world locations and show map.

```
x = [1.2; 2.3; 3.4; 4.5; 5.6];
y = [5.0; 4.0; 3.0; 2.0; 1.0];

setOccupancy(map, [x y], ones(5,1))
figure
show(map)
```




Inflate occupied locations by a given radius.

```
inflate(map, 0.5)
figure
show(map)
```

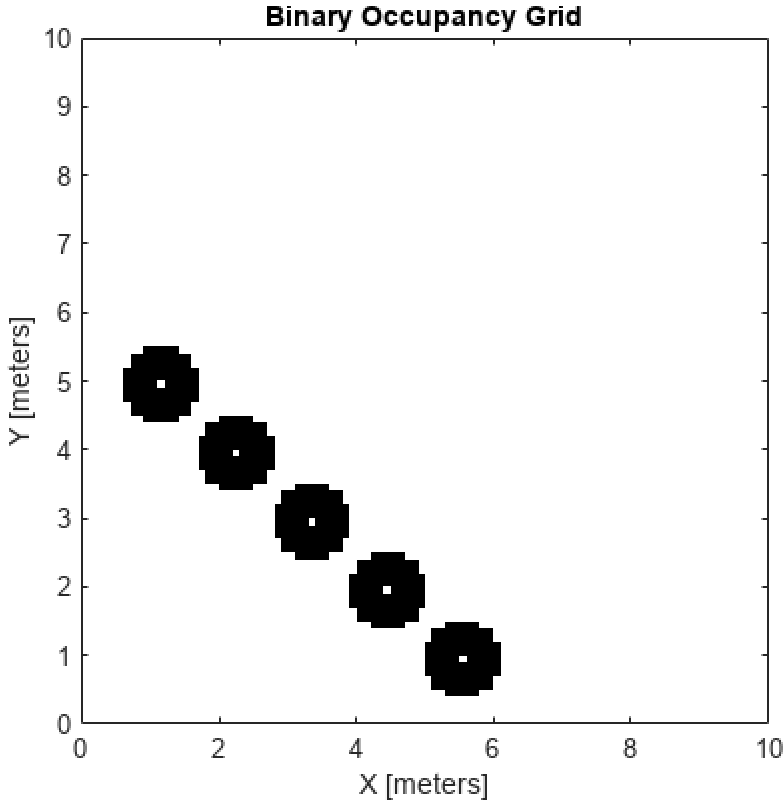



Get grid locations from world locations.

```
ij = world2grid(map, [x y]);
```

Set grid locations to free locations.

```
setOccupancy(map, ij, zeros(5,1), 'grid')
figure
show(map)
```




## Input Arguments

**map — Map representation**
`binaryOccupancyMap` object

Map representation, specified as a `binaryOccupancyMap` object.

**xy — World coordinates**
*n*-by-2 vertical array

World coordinates, specified as an *n*-by-2 vertical array of `[x y]` pairs, where *n* is the number of world coordinates.

## Output Arguments

**ij — Grid indices**
*n*-by-2 vertical array

Grid indices, specified as an *n*-by-2 vertical array of `[i j]` pairs in `[rows cols]` format, where *n* is the the number of grid positions.

# Version History

**Introduced in R2015a**

## Extended Capabilities

### C/C++ Code Generation
Generate C and C++ code using MATLAB® Coder™.

## See Also
`binaryOccupancyMap` | `grid2world`

# world2local

Convert world coordinates to local coordinates

## Syntax

```
xyLocal = world2local(map,xy)
```

## Description

`xyLocal = world2local(map,xy)` converts an array of world coordinates to local coordinates.

## Examples

### Convert World Coordinates in Binary Occupancy Map to Local Coordinates

Create an empty binary occupancy map with a width and height of 10 meters.

```
map = binaryOccupancyMap(10,10);
```

Get local coordinates from world coordinates.

```
[xWorld,yWorld] = meshgrid(0:0.5:2);
xyLocal = world2local(map,[xWorld(:) yWorld(:)]);
```

## Input Arguments

**`map` — Map representation**
`binaryOccupancyMap` object

Map representation, specified as a `binaryOccupancyMap` object.

**xy — World coordinates**
*n*-by-2 vertical array

World coordinates, specified as an *n*-by-2 vertical array of `[x y]` pairs, where *n* is the number of world coordinates.

## Output Arguments

**`xyLocal` — Local coordinates**
*n*-by-2 vertical array

Local coordinates, specified as an *n*-by-2 vertical array of `[x y]` pairs, where *n* is the number of local coordinates.

# Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`binaryOccupancyMap` | `grid2world` | `local2world`

# controllerVFH

Avoid obstacles using vector field histogram

## Description

The `controllerVFH` System object enables your vehicle to avoid obstacles based on range sensor data using vector field histograms (VFH) . Given laser scan readings and a target direction to drive toward, the object computes an obstacle-free steering direction.

`controllerVFH` specifically uses the VFH+ algorithm to compute an obstacle-free direction. First, the algorithm takes the ranges and angles from laser scan data and builds a polar histogram for obstacle locations. Then, the input histogram thresholds are used to calculate a binary histogram that indicates occupied and free directions. Finally, the algorithm computes a masked histogram, which is computed from the binary histogram based on the minimum turning radius of the vehicle.

The algorithm selects multiple steering directions based on the open space and possible driving directions. A cost function, with weights corresponding to the previous, current, and target directions, calculates the cost of different possible directions. The object then returns an obstacle-free direction with minimal cost. Using the obstacle-free direction, you can input commands to move your vehicle in that direction.

To use this object for your own application and environment, you must tune the properties of the algorithm. Property values depend on the type of vehicle, the range sensor, and the hardware you use.

To find an obstacle-free steering direction:

1. Create the `controllerVFH` object and set its properties.
2. Call the object with arguments, as if it were a function.

To learn more about how System objects work, see What Are System Objects?

# Creation

## Syntax

```
VFH = controllerVFH
VFH = controllerVFH(Name,Value)
```

### Description

`VFH = controllerVFH` returns a vector field histogram object that computes the obstacle-free steering direction using the `VFH+` algorithm.

`VFH = controllerVFH(Name,Value)` returns a vector field histogram object with additional options specified by one or more `Name,Value` pairs. Name is the property name and Value is the corresponding value. Name must appear inside single quotes (`' '`). You can specify several name-

value pair arguments in any order as Name1,Value1,...,NameN,ValueN. Properties not specified retain their default values.

## Properties

**NumAngularSectors — Number of angular sectors in histogram**
180 (default) | positive integer

Number of angular sectors in the vector field histogram, specified as a scalar. This property defines the number of bins used to create the histograms. This property is non-tunable. You can only set this when the object is initialized.

**DistanceLimits — Limits for range readings**
[0.05 2] (default) | 2-element vector

Limits for range readings, specified as a 2-element vector with elements measured in meters. The range readings specified when calling the object are considered only if they fall within the distance limits. Use the lower distance limit to ignore false positives from poor sensor performance at lower ranges. Use the upper limit to ignore obstacles that are too far from the vehicle.

**RobotRadius — Radius of vehicle**
0.1 (default) | scalar

Radius of the vehicle in meters, specified as a scalar. This dimension defines the smallest circle that can circumscribe your vehicle. The vehicle radius is used to account for vehicle size when computing the obstacle-free direction.

**SafetyDistance — Safety distance around vehicle**
0.1 (default) | scalar

Safety distance around the vehicle, specified as a scalar in meters. This is a safety distance to leave around the vehicle position in addition to the value of the RobotRadius parameter. The sum of the vehicle radius and the safety distance is used to compute the obstacle-free direction.

**MinTurningRadius — Minimum turning radius at current speed**
0.1 (default) | scalar

Minimum turning radius in meters for the vehicle moving at its current speed, specified as a scalar.

**TargetDirectionWeight — Cost function weight for target direction**
5 (default) | scalar

Cost function weight for moving toward the target direction, specified as a scalar. To follow a target direction, set this weight to be higher than the sum of the CurrentDirectionWeight and PreviousDirectionWeight properties. To ignore the target direction cost, set this weight to zero.

**CurrentDirectionWeight — Cost function weight for current direction**
2 (default) | scalar

Cost function weight for moving the robot in the current heading direction, specified as a scalar. Higher values of this weight produce efficient paths. To ignore the current direction cost, set this weight to zero.

**PreviousDirectionWeight — Cost function weight for previous direction**
2 (default) | scalar

Cost function weight for moving in the previously selected steering direction, specified as a scalar. Higher values of this weight produces smoother paths. To ignore the previous direction cost, set this weight to zero.

#### HistogramThresholds — Thresholds for binary histogram computation

[3 10] (default) | 2-element vector

Thresholds for binary histogram computation, specified as a 2-element vector. The algorithm uses these thresholds to compute the binary histogram from the polar obstacle density. Polar obstacle density values higher than the upper threshold are represented as occupied space (1) in the binary histogram. Values smaller than the lower threshold are represented as free space (0). Values that fall between the limits are set to the values in the previous binary histogram, with the default being free space (0).

#### UseLidarScan — Use lidarScan object as scan input

false (default) | true

Use lidarScan object as scan input, specified as either true or false.

## Usage

## Syntax

```
steeringDir = vfh(scan,targetDir)
steeringDir = vfh(ranges,angles,targetDir)
```

### Description

steeringDir = vfh(scan,targetDir) finds an obstacle-free steering direction using the VFH+ algorithm for the input lidarScan object, scan. A target direction is given based on the target location.

To enable this syntax, you must set the UseLidarScan property to true. For example:

```
mcl = monteCarloLocalization('UseLidarScan',true);
...
[isUpdated,pose,covariance] = mcl(odomPose,scan);
```

steeringDir = vfh(ranges,angles,targetDir) defines the lidar scan with two vectors: ranges and angles.

### Input Arguments

#### scan — Lidar scan readings

lidarScan object

Lidar scan readings, specified as a lidarScan object.

##### Dependencies

To use this argument, you must set the UseLidarScan property to true.

```
mcl.UseLidarScan = true;
```

**ranges — Range values from scan data**
vector

Range values from scan data, specified as a vector in meters. These range values are distances from a sensor at given `angles`. The vector must be the same length as the corresponding `angles` vector.

**angles — Angle values from scan data**
vector

Angle values from scan data, specified as a vector in radians. These angle values are the specific angles of the given `ranges`. The vector must be the same length as the corresponding `ranges` vector.

**targetDir — Target direction for vehicle**
scalar

Target direction for the vehicle, specified as a scalar in radians. The forward direction of the vehicle is considered zero radians, with positive angles measured counterclockwise.

### Output Arguments

**steeringDir — Steering direction for vehicle**
scalar

Steering direction for the vehicle, specified as a scalar in radians. This obstacle-free direction is calculated based on the VFH+ algorithm. The forward direction of the vehicle is considered zero radians, with positive angles measured counterclockwise.

## Object Functions

To use an object function, specify the System object as the first input argument. For example, to release system resources of a System object named `obj`, use this syntax:

```
release(obj)
```

## Specific to controllerVFH

| | |
|---|---|
| show | Display VectorFieldHistogram information in figure window |

## Common to All System Objects

| | |
|---|---|
| step | Run System object algorithm |
| release | Release resources and allow changes to System object property values and input characteristics |
| reset | Reset internal states of System object |

## Examples

### Create a Vector Field Histogram Object and Visualize Data

This example shows how to calculate a steering direction based on input laser scan data.

Create a `controllerVFH` object. Set the `UseLidarScan` property to `true`.

```
vfh = controllerVFH;
vfh.UseLidarScan = true;
```

Input laser scan data and target direction.

```
ranges = 10*ones(1,500);
ranges(1,225:275) = 1.0;
angles = linspace(-pi,pi,500);
targetDir = 0;
```

Create a `lidarScan` object by specifying the ranges and angles.

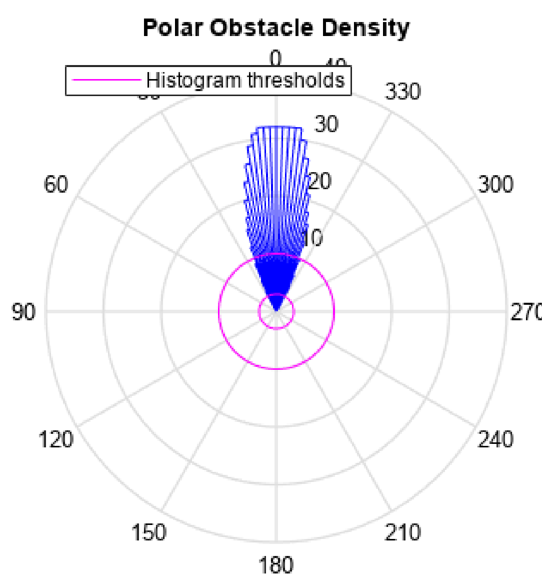
```
scan = lidarScan(ranges,angles);
```

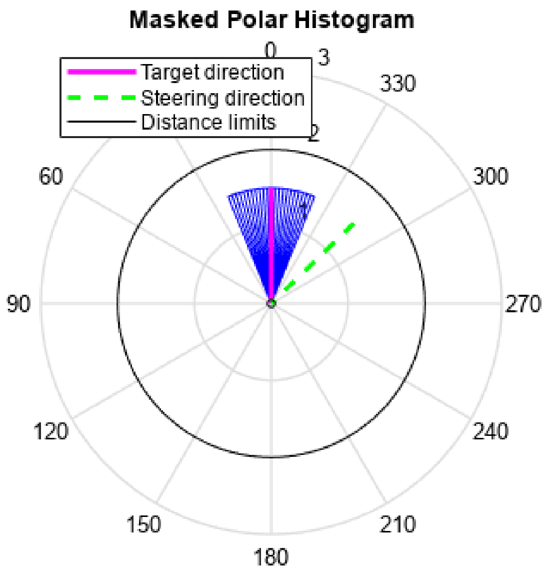
Compute an obstacle-free steering direction.

```
steeringDir = vfh(scan,targetDir);
```

Visualize the `VectorFieldHistogram` computation.

```
h = figure;
set(h,'Position',[50 50 800 400])
show(vfh)
```




## Version History

**Introduced in R2019b**

## References

[1] Borenstein, J., and Y. Koren. "The Vector Field Histogram - Fast Obstacle Avoidance for Mobile Robots." IEEE Journal of Robotics and Automation. Vol. 7, Number 3, 1991, pp.278–88.

[2] Ulrich, I., and J. Borenstein. "VFH : Reliable Obstacle Avoidance for Fast Mobile Robots." *Proceedings. 1998 IEEE International Conference on Robotics and Automation*. (1998): 1572–1577.

## Extended Capabilities

### C/C++ Code Generation
Generate C and C++ code using MATLAB® Coder™.

Usage notes and limitations:

Use in a MATLAB Function block is not supported.

Lidar scans require a limited size in code generation. The lidar scans, `scan`, are limited to 4000 points (range and angles) as a maximum.

For additional information about code generation for System objects, see “System Objects in MATLAB Code Generation” (MATLAB Coder)

## See Also
`lidarScan` | `show`

### Topics
“Obstacle Avoidance with TurtleBot and VFH”
“Vector Field Histogram”

# show

Display `VectorFieldHistogram` information in figure window

## Syntax

`show(vfh)`

`show(vfh,'Parent',parent)`

`h = show( ___ )`

## Description

`show(vfh)` shows histograms calculated by the VFH+ algorithm in a figure window. The figure also includes the parameters of the `controllerVFH` object and range values from the last object call.

`show(vfh,'Parent',parent)` sets the specified axes handle, `parent`, to the axes.

`h = show( ___ )` returns the figure object handle created by `show` using any of the arguments from the previous syntaxes.

## Examples

### Create a Vector Field Histogram Object and Visualize Data

This example shows how to calculate a steering direction based on input laser scan data.

Create a `controllerVFH` object. Set the `UseLidarScan` property to `true`.

```
vfh = controllerVFH;
vfh.UseLidarScan = true;
```

Input laser scan data and target direction.

```
ranges = 10*ones(1,500);
ranges(1,225:275) = 1.0;
angles = linspace(-pi,pi,500);
targetDir = 0;
```

Create a `lidarScan` object by specifying the ranges and angles.

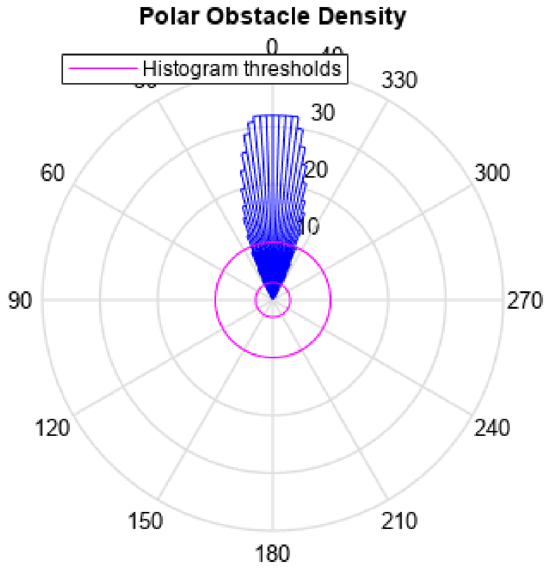
```
scan = lidarScan(ranges,angles);
```

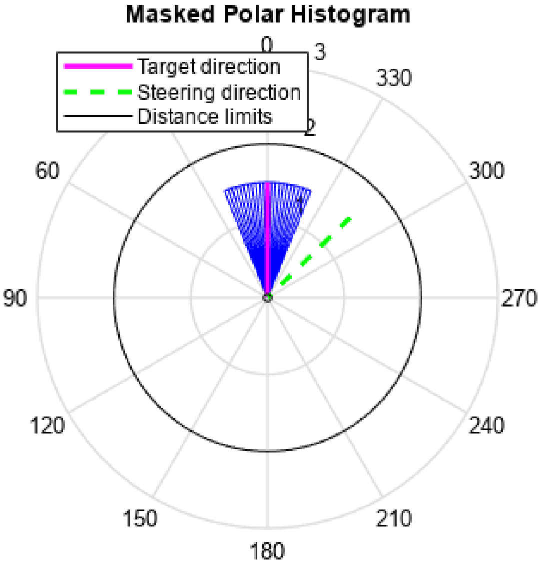
Compute an obstacle-free steering direction.

```
steeringDir = vfh(scan,targetDir);
```

Visualize the `VectorFieldHistogram` computation.

```
h = figure;
set(h,'Position',[50 50 800 400])
show(vfh)
```




## Input Arguments

**vfh — Vector field histogram algorithm**
`controllerVFH` object

Vector field histogram algorithm, specified as a `controllerVFH` object. This object contains all the parameters for tuning the VFH+ algorithm.

**parent — Axes properties**
handle

Axes properties, specified as a handle.

## Output Arguments

**h — Axes handles for VFH algorithm display**
`Axes` array

Axes handles for VFH algorithm display, specified as an `Axes` array. The VFH histogram and `HistogramThresholds` are shown in the first axes. The binary histogram, range sensor readings, target direction, and steering directions are shown in the second axes.

# Version History

**Introduced in R2019b**

## See Also

`controllerVFH`

# controllerPurePursuit

Create controller to follow set of waypoints

## Description

The `controllerPurePursuit` System object creates a controller object used to make a differential-drive vehicle follow a set of waypoints. The object computes the linear and angular velocities for the vehicle given the current pose. Successive calls to the object with updated poses provide updated velocity commands for the vehicle. Use the `MaxAngularVelocity` and `DesiredLinearVelocity` properties to update the velocities based on the vehicle's performance.

The `LookaheadDistance` property computes a look-ahead point on the path, which is a local goal for the vehicle. The angular velocity command is computed based on this point. Changing `LookaheadDistance` has a significant impact on the performance of the algorithm. A higher look-ahead distance results in a smoother trajectory for the vehicle, but can cause the vehicle to cut corners along the path. A low look-ahead distance can result in oscillations in tracking the path, causing unstable behavior. For more information on the pure pursuit algorithm, see “Pure Pursuit Controller”.

To compute linear and angular velocity control commands:

1. Create the `controllerPurePursuit` object and set its properties.
2. Call the object with arguments, as if it were a function.

To learn more about how System objects work, see What Are System Objects?

# Creation

## Syntax

`controller = controllerPurePursuit`

`controller = controllerPurePursuit(Name,Value)`

### Description

`controller = controllerPurePursuit` creates a pure pursuit object that uses the pure pursuit algorithm to compute the linear and angular velocity inputs for a differential drive vehicle.

`controller = controllerPurePursuit(Name,Value)` creates a pure pursuit object with additional options specified by one or more `Name,Value` pairs. Name is the property name and Value is the corresponding value. Name must appear inside single quotes (`' '`). You can specify several name-value pair arguments in any order as `Name1,Value1,...,NameN,ValueN`. Properties not specified retain their default values.

Example: `controller = controllerPurePursuit('DesiredLinearVelocity', 0.5)`

## Properties

**`DesiredLinearVelocity` — Desired constant linear velocity**
`0.1` (default) | scalar in meters per second

Desired constant linear velocity, specified as a scalar in meters per second. The controller assumes that the vehicle drives at a constant linear velocity and that the computed angular velocity is independent of the linear velocity.

Data Types: `double`

**`LookaheadDistance` — Look-ahead distance**
`1.0` (default) | scalar in meters

Look-ahead distance, specified as a scalar in meters. The look-ahead distance changes the response of the controller. A vehicle with a higher look-ahead distance produces smooth paths but takes larger turns at corners. A vehicle with a smaller look-ahead distance follows the path closely and takes sharp turns, but potentially creating oscillations in the path.

Data Types: `double`

**`MaxAngularVelocity` — Maximum angular velocity**
`1.0` (default) | scalar in radians per second

Maximum angular velocity, specified a scalar in radians per second. The controller saturates the absolute angular velocity output at the given value.

Data Types: `double`

**`Waypoints` — Waypoints**
[ ] (default) | *n*-by-2 array

Waypoints, specified as an *n*-by-2 array of `[x y]` pairs, where *n* is the number of waypoints. You can generate the waypoints from the `mobileRobotPRM` class or from another source.

Data Types: `double`

## Usage

## Syntax

```
[vel,angvel] = controller(pose)
[vel,angvel,lookaheadpoint] = controller(pose)
```

### Description

`[vel,angvel] = controller(pose)` processes the vehicle's position and orientation, `pose`, and outputs the linear velocity, `vel`, and angular velocity, `angvel`.

`[vel,angvel,lookaheadpoint] = controller(pose)` returns the look-ahead point, which is a location on the path used to compute the velocity commands. This location on the path is computed using the `LookaheadDistance` property on the `controller` object.

### Input Arguments

**pose — Position and orientation of vehicle**
3-by-1 vector in the form [x y theta]

Position and orientation of vehicle, specified as a 3-by-1 vector in the form `[x y theta]`. The vehicle pose is an *x* and *y* position with angular orientation θ (in radians) measured from the *x*-axis.

### Output Arguments

**vel — Linear velocity**
scalar in meters per second

Linear velocity, specified as a scalar in meters per second.

Data Types: `double`

**angvel — Angular velocity**
scalar in radians per second

Angular velocity, specified as a scalar in radians per second.

Data Types: `double`

**lookaheadpoint — Look-ahead point on path**
[x y] vector

Look-ahead point on the path, returned as an `[x y]` vector. This value is calculated based on the `LookaheadDistance` property.

## Object Functions

To use an object function, specify the System object as the first input argument. For example, to release system resources of a System object named `obj`, use this syntax:

```
release(obj)
```

## Specific to controllerPurePursuit

| | |
|---|---|
| info | Characteristic information about controllerPurePursuit object |

## Common to All System Objects

| | |
|---|---|
| step | Run System object algorithm |
| release | Release resources and allow changes to System object property values and input characteristics |
| reset | Reset internal states of System object |

## Examples

### Get Additional Pure Pursuit Object Information

Use the `info` method to get more information about a `controllerPurePursuit` object. The `info` function returns two fields, `RobotPose` and `LookaheadPoint`, which correspond to the current

position and orientation of the robot and the point on the path used to compute outputs from the last call of the object.

Create a `controllerPurePursuit` object.

```
pp = controllerPurePursuit;
```

Assign waypoints.

```
pp.Waypoints = [0 0;1 1];
```

Compute control commands using the `pp` object with the initial pose `[x y theta]` given as the input.

```
[v,w] = pp([0 0 0]);
```

Get additional information.

```
s = info(pp)
```

```
s = struct with fields:
         RobotPose: [0 0 0]
    LookaheadPoint: [0.7071 0.7071]
```

## Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

Usage notes and limitations:

Use in a MATLAB Function block is not supported.

For additional information about code generation for System objects, see “System Objects in MATLAB Code Generation” (MATLAB Coder)

## See Also

`binaryOccupancyMap` | `occupancyMap` | `binaryOccupancyMap` | `occupancyMap` | `controllerVFH`

### Topics

“Pure Pursuit Controller”

# info

Characteristic information about `controllerPurePursuit` object

## Syntax

```
controllerInfo = info(controller)
```

## Description

`controllerInfo = info(controller)` returns a structure, `controllerInfo`, with additional information about the status of the `controllerPurePursuit` object, `controller`. The structure contains the fields, `RobotPose` and `LookaheadPoint`.

## Examples

### Get Additional Pure Pursuit Object Information

Use the `info` method to get more information about a `controllerPurePursuit` object. The `info` function returns two fields, `RobotPose` and `LookaheadPoint`, which correspond to the current position and orientation of the robot and the point on the path used to compute outputs from the last call of the object.

Create a `controllerPurePursuit` object.

```
pp = controllerPurePursuit;
```

Assign waypoints.

```
pp.Waypoints = [0 0;1 1];
```

Compute control commands using the `pp` object with the initial pose `[x y theta]` given as the input.

```
[v,w] = pp([0 0 0]);
```

Get additional information.

```
s = info(pp)
```

```
s = struct with fields:
         RobotPose: [0 0 0]
    LookaheadPoint: [0.7071 0.7071]
```

## Input Arguments

**`controller` — Pure pursuit controller**
`controllerPurePursuit` object

Pure pursuit controller, specified as a `controllerPurePursuit` object.

## Output Arguments

**`controllerInfo` — Information on the `controllerPurePursuit` object**
structure

Information on the `controllerPurePursuit` object, returned as a structure. The structure contains two fields:

- `RobotPose` – A three-element vector in the form `[x y theta]` that corresponds to the *x*-*y* position and orientation of the vehicle. The angle, `theta`, is measured in radians with positive angles measured counterclockwise from the *x*-axis.
- `LookaheadPoint`– A two-element vector in the form `[x y]`. The location is a point on the path that was used to compute outputs of the last call to the object.

# Version History

**Introduced in R2019b**

## See Also

`controllerPurePursuit`

**Topics**

"Pure Pursuit Controller"

# controllerTEB

Avoid unseen obstacles with time-optimal trajectories

## Description

The `controllerTEB` object creates a controller (local planner) using the Timed Elastic Band (TEB) algorithm. The controller enables a robot to follow a reference path typically generated by a global planner, such as RRT or Hybrid A*. Additionally, the planner avoids obstacles and smooths the path while optimizing travel time, and maintains a safe distance from obstacles known or unknown to the global planner. The object also computes velocity commands and an optimal trajectory using the current pose of the robot and its current linear and angular velocities.

## Creation

### Syntax

```
controller = controllerTEB(refpath)
controller = controllerTEB(refpath,map)
controller = controllerTEB( ___ ,Name=Value)
```

#### Description

`controller = controllerTEB(refpath)` creates a TEB controller object, `controller`, that computes the linear and angular velocity commands for a differential-drive robot to follow the reference path `refpath` and travel for 5 seconds in an obstacle-free environment. The `refpath` input sets the value of the ReferencePath property.

`controller = controllerTEB(refpath,map)` attempts to avoid obstacles in the specified occupancy map `map`. The controller assumes the space outside the map boundary is free. The `map` input sets the value of the Map property.

`controller = controllerTEB( ___ ,Name=Value)` specifies properties using one or more name-value arguments in addition to any combination of input arguments from the previous syntaxes.

### Properties

**`ReferencePath` — Reference path to follow**
*N*-by-2 matrix | *N*-by-3 matrix | `navPath` object with SE(2) state space

Reference path to follow, specified as an *N*-by-2 matrix, *N*-by-3 matrix, or `navPath` object with an SE(2) state space. When specified as a matrix, each row represents a pose on the path. Use the LookAheadTime property to select a part of the `ReferencePath` for which to optimize the trajectory and generate velocity commands.

**Note** If you specify the reference path as an *N*-by-2 matrix, then the object computes the orientation using the `headingFromXY` function and appends it as the third column.

Data Types: single | double

**Map — Occupancy map representing environment**
binaryOccupancyMap() (default) | binaryOccupancyMap object | occupancyMap object

Occupancy map representing the environment, specified as a binaryOccupancyMap object or occupancyMap object containing the obstacles in the vicinity of the robot. When optimizing the trajectory, the controller considers the space outside the boundary of the map to be free. Larger maps can lead to slower performance.

**CostWeights — Weights for cost function optimization**
struct("Time",10,"Smoothness",1000,"Obstacle",50) (default) | structure

Weights for cost function optimization, specified as a structure. The fields of the structure are:

| Field | Description |
|---|---|
| Time | Cost function weight for time, specified as a positive scalar. To lower the travel time, increase this weight value. |
| Smoothness | Cost function weight for smooth motion, specified as a positive scalar. To obtain a smoother path, increase this weight value. |
| Obstacles | Cost function weight for maintaining a safe distance from obstacles, specified as a positive scalar. To prioritize maintaining a safe distance from obstacles, increase this weight value. |

Data Types: struct

**RobotInformation — Robot geometry information for collision checking**
struct("Dimension",[1 0.67],"Shape","Rectangle") (default) | structure

Robot geometry information for collision checking, specified as a structure. The fields of the structure are:

| Field | Description |
|---|---|
| Dimension | Size of the robot, specified as a two-element positive vector of the form [*length width*], in meters. |
| Shape | Shape of the robot, specified as "Rectangle" or "Point".<br><br>**Note** When you set Shape is "Point", the Dimension field is set to [0 0]. |

Data Types: struct

**ObstacleSafetyMargin — Safe distance between robot and obstacles**
0.5 (default) | positive scalar

Safe distance between the robot and the obstacles, specified as a positive scalar, in meters. Note that this is a soft constraint that the planner may ignore.

Data Types: `single` | `double`

**`NumIteration` — Number of iterations to optimize trajectory**
2 (default) | positive integer

Number of iterations to optimize the trajectory, specified as a positive integer. This value is the number of times interpolation occurs and the controller calls the solver for trajectory optimization.

Data Types: `single` | `double`

**`MaxVelocity` — Maximum limits of linear and angular velocity**
`[0.8 1.6]` (default) | two-element positive vector

Maximum limits of linear and angular velocity for velocity commands, specified as a two-element positive vector. The first element is the linear velocity limit, in meters per second, and the second element is the angular velocity limit, in radians per second.

Data Types: `single` | `double`

**`MaxAcceleration` — Maximum limits of linear and angular acceleration**
`[2.4 4.8]` (default) | two-element positive vector

Maximum limits of linear and angular acceleration for velocity commands, specified as a two-element positive vector. The first element is the linear acceleration limit, in meters per second squared, and the second element is the angular acceleration limit, in radians per second squared.

Data Types: `single` | `double`

**`ReferenceDeltaTime` — Reference travel time between consecutive poses**
`0.3` (default) | positive scalar

Reference travel time between consecutive poses, specified as a positive scalar in seconds. This property affects the addition and deletion of poses for the optimized trajectory. Increase the value of this property to have fewer poses and reduce it to have more poses in the output path.

Data Types: `single` | `double`

**`LookAheadTime` — Look-ahead time**
5 (default) | positive scalar

Look-ahead time, specified as a positive scalar in seconds. The controller generates velocity commands and optimizes the trajectory until the controller reaches the look-ahead time. A higher look-ahead time generates velocity commands further into the future. This enables the robot to react earlier to unseen obstacles, but increases the controller execution time. Conversely, a shorter look-ahead time reduces the available time to react to new, unknown obstacles, but enables the controller to run at a faster rate.

**Note** This property impacts the number of velocity commands, timestamps, and poses in the path.

Data Types: `single` | `double`

## Object Functions

step Compute velocity commands and optimal trajectory for subsequent time steps

clone Create deep clone of controllerTEB object

## Examples

### Compute Velocity Commands and Optimal Trajectory for Differential-Drive Robot Using Timed Elastic Band Algorithm

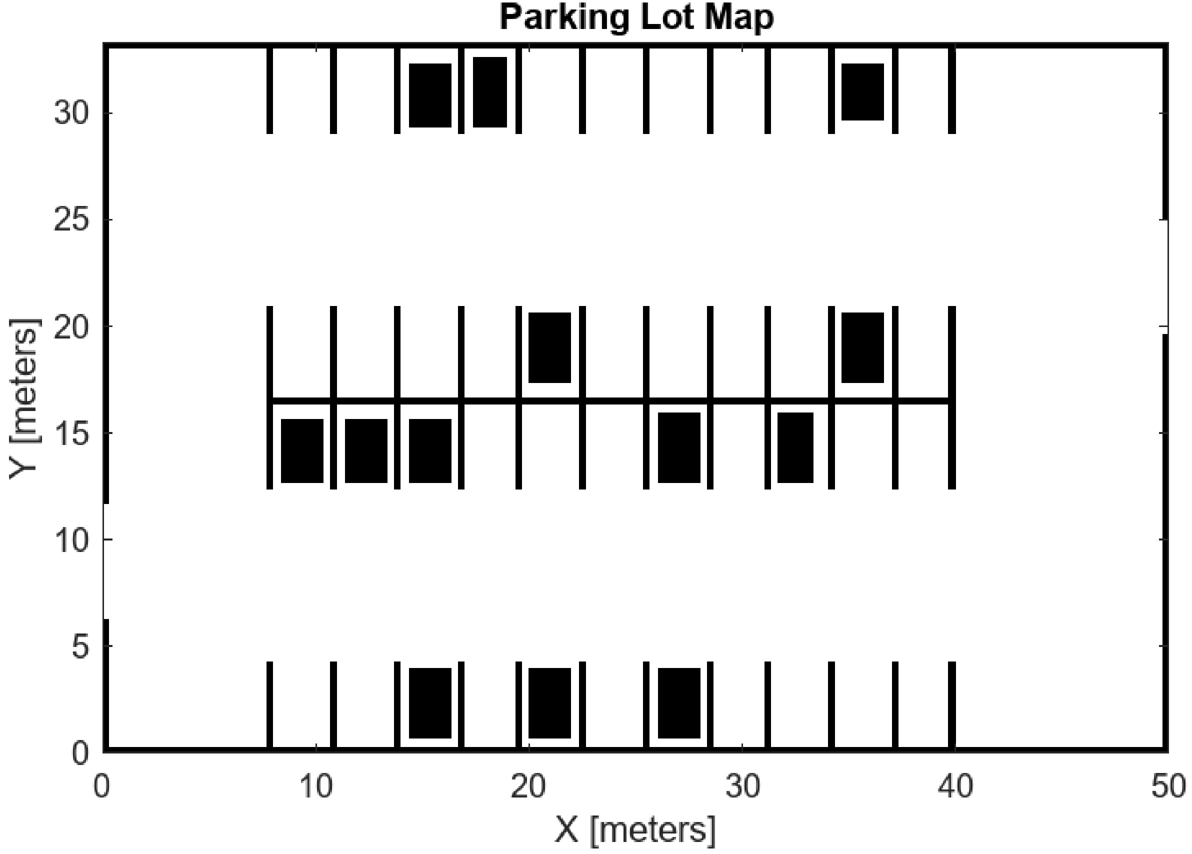
#### Set Up Parking Lot Environment

Create an `occupancyMap` object from a parking lot map and set the map resolution to 3 cells per meter.

```
load parkingMap.mat;
resolution = 3;
map = occupancyMap(map,resolution);
```

Visualize the map. The map contains the floor plan of a parking lot with some parking slots already occupied.

```
show(map)
title("Parking Lot Map")
hold on
```




**Set Up and Run Global Planner**

Create a `validatorOccupancyMap` state validator using the `stateSpaceSE2` definition. Specify the map and the distance for interpolating and validating path segments.

```
validator = validatorOccupancyMap(stateSpaceSE2,Map=map);
validator.ValidationDistance = 0.1;
```

Create an RRT* path planner. Increase the maximum connection distance.

```
rrtstar = plannerRRTStar(validator.StateSpace,validator);
rrtstar.MaxConnectionDistance = 0.2;
```

Set the start and goal states.

```
start = [2 9 0];
goal = [27 18 -pi/2];
```

Plan a path with default settings.

```
rng(42,"twister") % Set random number generator seed for repeatable result.
route = plan(rrtstar,start,goal);
refpath = route.States;
```

RRT* uses a random orientation, which can cause unnecessary turns.

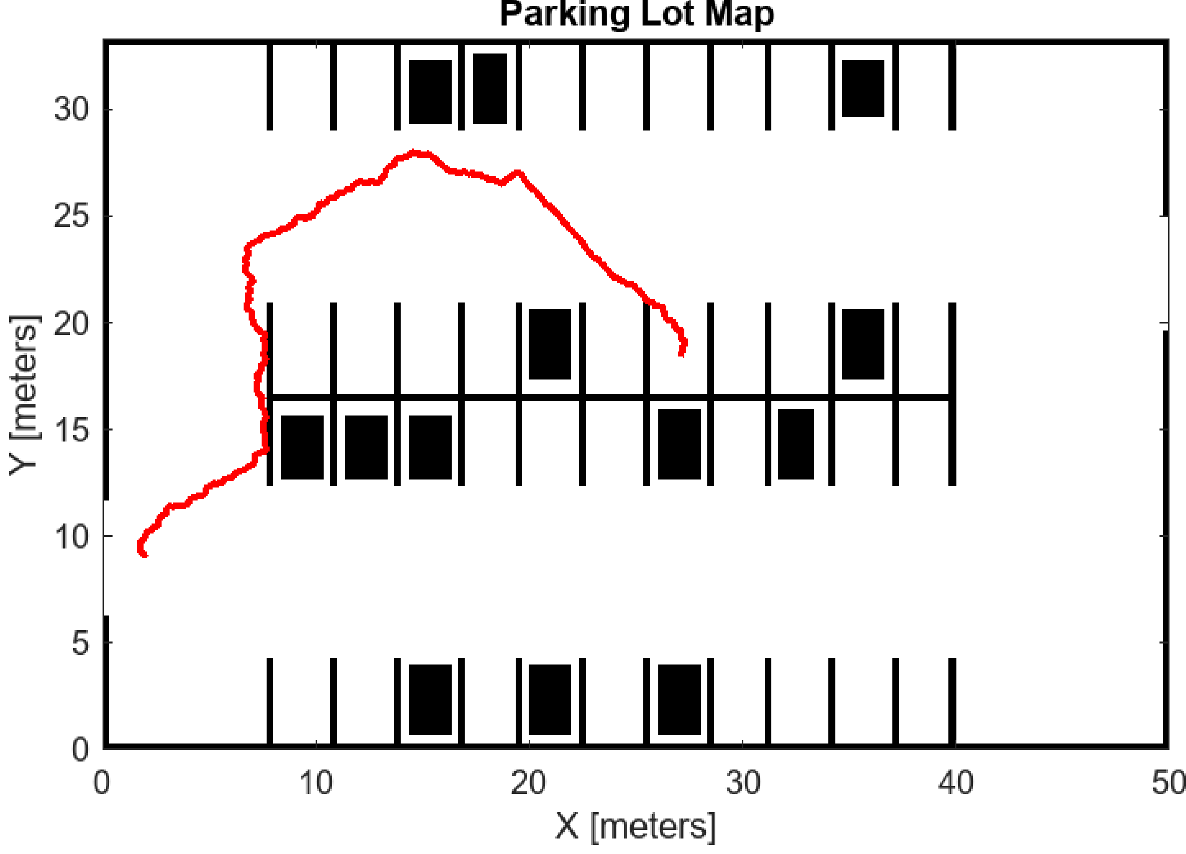
```
headingToNextPose = headingFromXY(refpath(:,1:2));
```

Align the orientation to the path, except for at the start and goal states.

```
refpath(2:end-1,3) = headingToNextPose(2:end-1);
```

Visualize the path.

```
plot(refpath(:,1),refpath(:,2),"r-",LineWidth=2)
hold off
```




### Set Up and Run Local Planner

Create a local `occupancyMap` object with a width and height of 15 meters and the same resolution as the global map.

```
localmap = occupancyMap(15,15,map.Resolution);
```

Create a `controllerTEB` object by using the reference path generated by the global planner and the local map.

```
teb = controllerTEB(refpath,localmap);
```

Specify the properties of the `controllerTEB` object.

```
teb.LookAheadTime = 10;         % sec
teb.ObstacleSafetyMargin = 0.4; % meters

% To generate time-optimal trajectories, specify a larger weight value,
% like 100, for the cost function, Time. To follow the reference path
% closely, keep the weight to a smaller value like 1e-3.
teb.CostWeights.Time = 100;
```

Create a deep clone of the `controllerTEB` object.

```
teb2 = clone(teb);
```

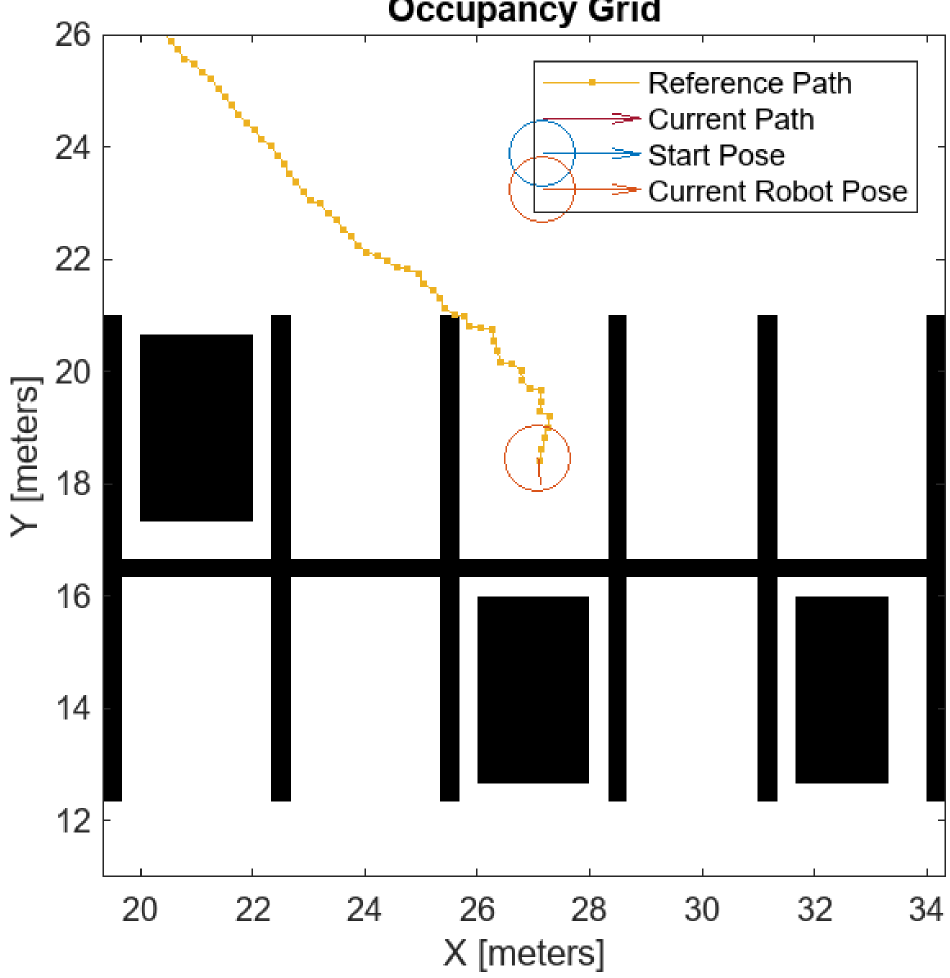
Initialize parameters.

```
curpose = refpath(1,:);
curvel = [0 0];
simtime = 0;
% Reducing timestep can lead to more accurate path tracking.
timestep = 0.1;
itr = 0;
goalReached = false;
```

Compute velocity commands and optimal trajectory.

```
while ~goalReached && simtime < 200
    % Update map to keep robot in the center of the map. Also update the
    % map with new information from the global map or sensor measurements.
    moveMapBy = curpose(1:2) - localmap.XLocalLimits(end)/2;
    localmap.move(moveMapBy,FillValue=0.5)
    syncWith(localmap,map)

    if mod(itr,10) == 0 % every 1 sec
        % Generate new vel commands with teb
        [velcmds,tstamps,curpath,info] = step(teb,curpose,curvel);
        goalReached = info.HasReachedGoal;
        feasibleDriveDuration = tstamps(info.LastFeasibleIdx);
        % If robot is far from goal and only less than third of trajectory
        % is feasible, then an option is to re-plan the path to follow to
        % reach the goal.
        if info.LastFeasibleIdx ~= height(tstamps) && ...
                feasibleDriveDuration < (teb.LookAheadTime/3)
            route = plan(rrtstar,curpose,[27 18 -pi/2]);
            refpath = route.States;
            headingToNextPose = headingFromXY(refpath(:,1:2));
            refpath(2:end-1,3) = headingToNextPose(2:end-1);
            teb.ReferencePath = refpath;
        end
        timestamps = tstamps + simtime;

        % Show the updated information input to or output
```

```
            % from controllerTEB
            clf
            show(localmap)
            hold on
            plot(refpath(:,1),refpath(:,2),".-",Color="#EDB120", ...
                 DisplayName="Reference Path")
            quiver(curpath(:,1),curpath(:,2), ...
                   cos(curpath(:,3)),sin(curpath(:,3)), ...
                   0.2,Color="#A2142F",DisplayName="Current Path")
            quiver(curpose(:,1),curpose(:,2), ...
                   cos(curpose(:,3)),sin(curpose(:,3)), ...
                   0.5,"o",MarkerSize=20,ShowArrowHead="off", ...
                   Color="#0072BD",DisplayName="Start Pose")
        end

        simtime = simtime+timestep;
        % Compute the instantaneous velocity to be sent to the robot from the
        % series of timestamped commands generated by controllerTEB
        velcmd = velocityCommand(velcmds,timestamps,simtime);
        % Very basic robot model, should be replaced by simulator.
        statedot = [velcmd(1)*cos(curpose(3)) ...
                    velcmd(1)*sin(curpose(3)) ...
                    velcmd(2)];
        curpose = curpose + statedot*timestep;

        if exist("hndl","var")
            delete(hndl)
        end
        hndl = quiver(curpose(:,1),curpose(:,2), ...
                      cos(curpose(:,3)),sin(curpose(:,3)), ...
                      0.5,"o",MarkerSize=20,ShowArrowHead="off", ...
                      Color="#D95319",DisplayName="Current Robot Pose");
        itr = itr + 1;
        drawnow
    end
    legend
```




## Version History

**Introduced in R2023a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Objects

`controllerPurePursuit` | `plannerAStarGrid`

### Functions

`step` | `clone` | `headingFromXY` | `velocityCommand`

# dubinsConnection

Dubins path connection type

## Description

The `dubinsConnection` object holds information for computing a `dubinsPathSegment` path segment to connect between poses. A Dubins path segment connects two poses as a sequence of three motions. The motion options are:

- Straight
- Left turn at maximum steer
- Right turn at maximum steer

A Dubins path segment only allows motion in the forward direction.

Use this connection object to define parameters for a robot motion model, including the minimum turning radius and options for path types. To generate a path segment between poses using this connection type, call the `connect` function.

## Creation

### Syntax

```
dubConnObj = dubinsConnection
dubConnObj = dubinsConnection(Name,Value)
```

#### Description

`dubConnObj = dubinsConnection` creates an object using default property values.

`dubConnObj = dubinsConnection(Name,Value)` specifies property values using name-value pairs. To set multiple properties, specify multiple name-value pairs.

### Properties

**`MinTurningRadius` — Minimum turning radius of the vehicle**
`1` (default) | positive scalar in meters

Minimum turning radius of the vehicle, specified as a positive scalar in meters. The minimum turning radius is for the smallest circle the vehicle can make with maximum steer in a single direction.

Data Types: `double`

**`DisabledPathTypes` — Path types to disable**
`{}` (default) | cell array of three-element character vectors | vector of three-element string scalars

Dubins path types to disable, specified as a cell array of three-element character vectors or vector of string scalars. The cell array defines three sequences of motions that are prohibited by the vehicle motion model.

| Motion Type | Description |
| --- | --- |
| "S" | Straight |
| "L" | Left turn at the maximum steering angle of the vehicle |
| "R" | Right turn at the maximum steering angle of the vehicle |

To see all available path types, see the `AllPathTypes` property.

For Dubins connections, the available path types are: `{"LSL"} {"LSR"} {"RSL"} {"RSR"} {"RLR"} {"LRL"}`.

Example: `["LSL","LSR"]`

Data Types: `string` | `cell`

**`AllPathTypes` — All possible path types**
cell array of character vectors

This property is read-only.

All possible path types, returned as a cell array of character vectors. This property lists all types. To disable certain types, specify types from this list in `DisabledPathTypes`.

For Dubins connections, the available path types are: `{'LSL'} {'LSR'} {'RSL'} {'RSR'} {'RLR'} {'LRL'}`.

Data Types: `cell`

## Object Functions

connect Connect poses for given connection type

## Examples

### Connect Poses Using Dubins Connection Path

Create a `dubinsConnection` object.

```
dubConnObj = dubinsConnection;
```

Define start and goal poses as `[x y theta]` vectors.

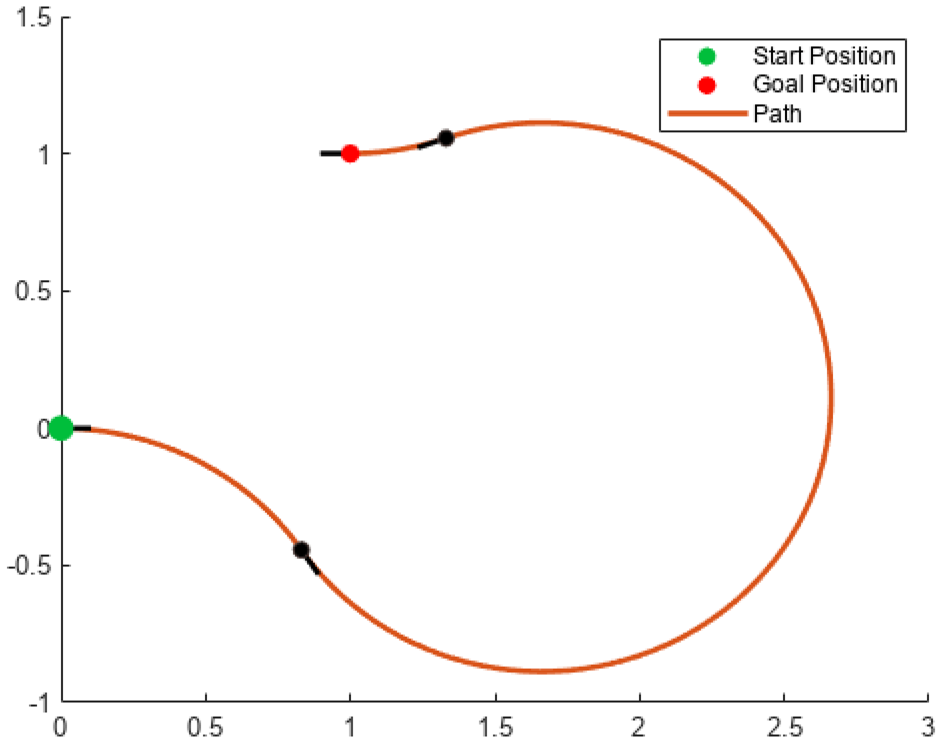
```
startPose = [0 0 0];
goalPose = [1 1 pi];
```

Calculate a valid path segment to connect the poses.

```
[pathSegObj, pathCosts] = connect(dubConnObj,startPose,goalPose);
```

Show the generated path.

```
show(pathSegObj{1})
```




#### Modify Connection Types for Dubins Path

Create a `dubinsConnection` object.

```
dubConnObj = dubinsConnection;
```

Define start and goal poses as `[x y theta]` vectors.

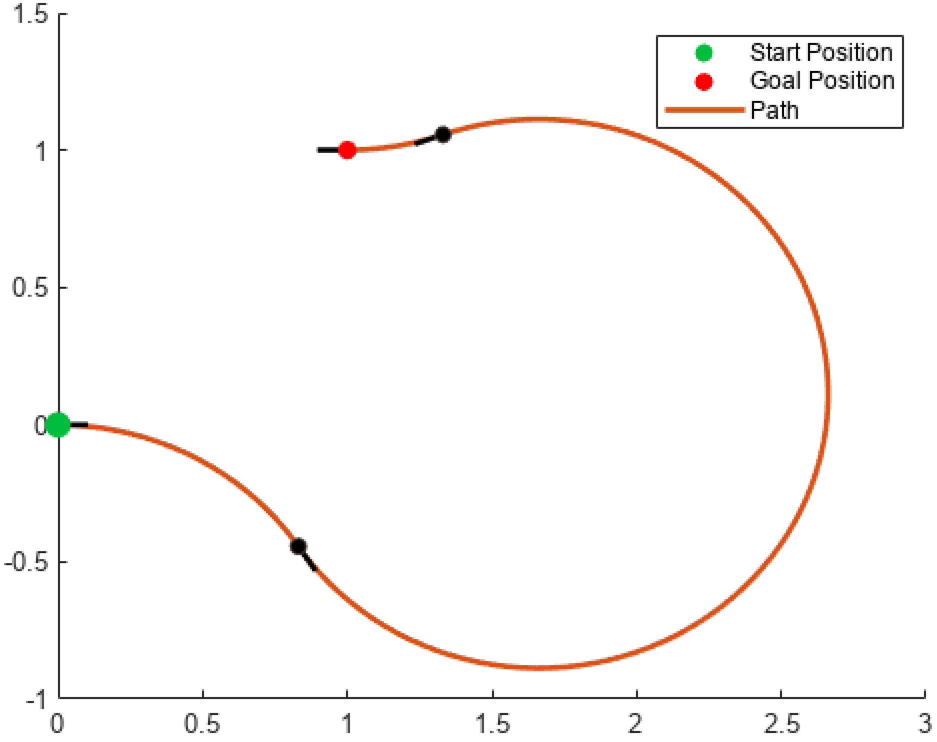
```
startPose = [0 0 0];
goalPose = [1 1 pi];
```

Calculate a valid path segment to connect the poses.

```
pathSegObj = connect(dubConnObj,startPose,goalPose);
```

Show the generated path. Notice the direction of the turns.

```
show(pathSegObj{1})
```




```
pathSegObj{1}.MotionTypes
```

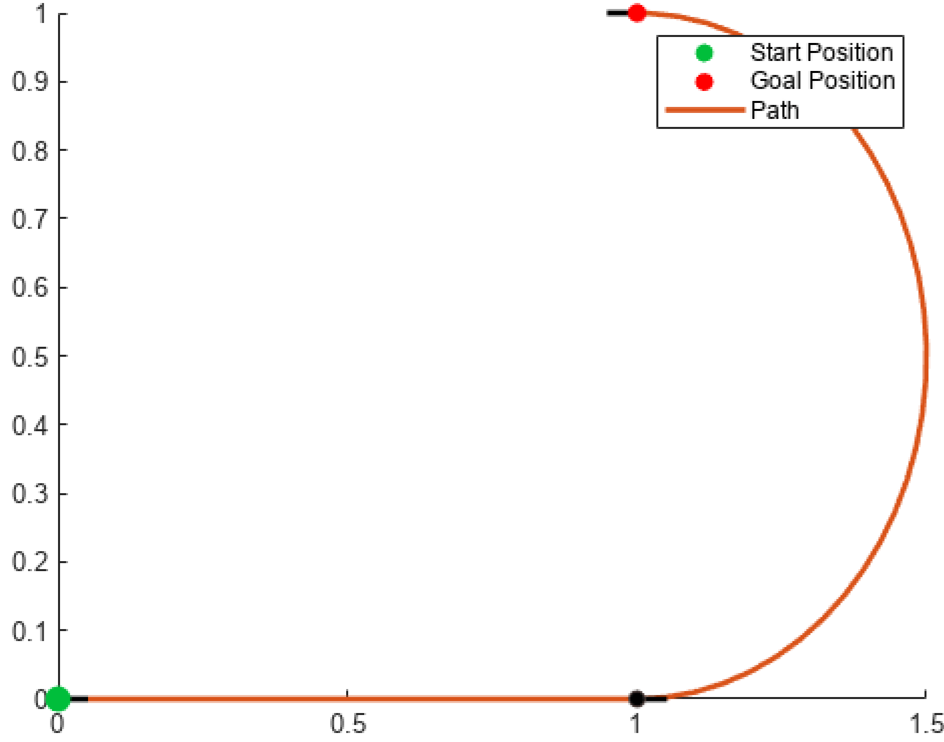
```
ans = 1x3 cell
    {'R'}    {'L'}    {'R'}
```

Disable this specific motion sequence in a new connection object. Reduce the `MinTurningRadius` if the robot is more maneuverable. Connect the poses again to get a different path.

```
dubConnObj = dubinsConnection('DisabledPathTypes',{'RLR'});
dubConnObj.MinTurningRadius = 0.5;

[pathSegObj, pathCosts] = connect(dubConnObj,startPose,goalPose);
pathSegObj{1}.MotionTypes
```

```
ans = 1x3 cell
    {'L'}    {'S'}    {'L'}
```

```
show(pathSegObj{1})
```




# Version History

**Introduced in R2019b**

## References

[1] Shkel, Andrei M., and Vladimir Lumelsky. "Classification of the Dubins set." *Robotics and Autonomous Systems*. Vol. 34, No. 4, 2001, pp. 179–202.

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
`dubinsPathSegment` | `reedsSheppConnection` | `reedsSheppPathSegment`

**Functions**
`connect` | `interpolate` | `show`

# dubinsPathSegment

Dubins path segment connecting two poses

## Description

The `dubinsPathSegment` object holds information for a Dubins path segment that connects two poses as a sequence of three motions. The motion options are:

- Straight
- Left turn at maximum steer
- Right turn at maximum steer

## Creation

To generate a `dubinsPathSegment` object, use the `connect` function with a `dubinsConnection` object:

`dubPathSeg = connect(connectionObj,start,goal)` connects the start and goal pose using the specified connection type object.

To specifically define a path segment:

`dubPathSeg = dubinsPathSegment(connectionObj,start,goal,motionLengths, motionTypes)` specifies the Dubins connection type, the start and goal poses, and the corresponding motion lengths and types. These values are set to the corresponding properties in the object.

### Properties

**`MinTurningRadius` — Minimum turning radius of vehicle**
positive scalar

This property is read-only.

Minimum turning radius of the vehicle, specified as a positive scalar in meters. This value corresponds to the radius of the turning circle at the maximum steering angle of the vehicle.

Data Types: `double`

**`StartPose` — Initial pose of the vehicle**
[$x$, $y$, $\Theta$] vector

This property is read-only.

Initial pose of the vehicle at the start of the path segment, specified as an [$x$, $y$, $\Theta$] vector. $x$ and $y$ are in meters. $\Theta$ is in radians.

Data Types: `double`

**GoalPose — Goal pose of the vehicle**
[$x$, $y$, $\Theta$] vector

This property is read-only.

Goal pose of the vehicle at the end of the path segment, specified as an [$x$, $y$, $\Theta$] vector. $x$ and $y$ are in meters. $\Theta$ is in radians.

Data Types: `double`

**MotionLengths — Length of each motion**
three-element numeric vector

This property is read-only.

Length of each motion in the path segment, in world units, specified as a three-element numeric vector. Each motion length corresponds to a motion type specified in `MotionTypes`.

Data Types: `double`

**MotionTypes — Type of each motion**
three-element string cell array

This property is read-only.

Type of each motion in the path segment, specified as a three-element string cell array.

| Motion Type | Description |
| --- | --- |
| "S" | Straight |
| "L" | Left turn at the maximum steering angle of the vehicle |
| "R" | Right turn at the maximum steering angle of the vehicle |

Each motion type corresponds to a motion length specified in `MotionLengths`.

For Dubins connections, the available path types are: `{"LSL"} {"LSR"} {"RSL"} {"RSR"} {"RLR"} {"LRL"}`.

Example: `{"R" "S" "R"}`

Data Types: `cell`

**Length — Length of path segment**
positive scalar

This property is read-only.

Length of the path segment, specified as a positive scalar in meters. This length is just a sum of the elements in `MotionLengths`.

Data Types: `double`

## Object Functions

interpolate    Interpolate poses along path segment

| | |
|---|---|
| show | Visualize path segment |

## Examples

### Connect Poses Using Dubins Connection Path

Create a `dubinsConnection` object.

```
dubConnObj = dubinsConnection;
```

Define start and goal poses as `[x y theta]` vectors.

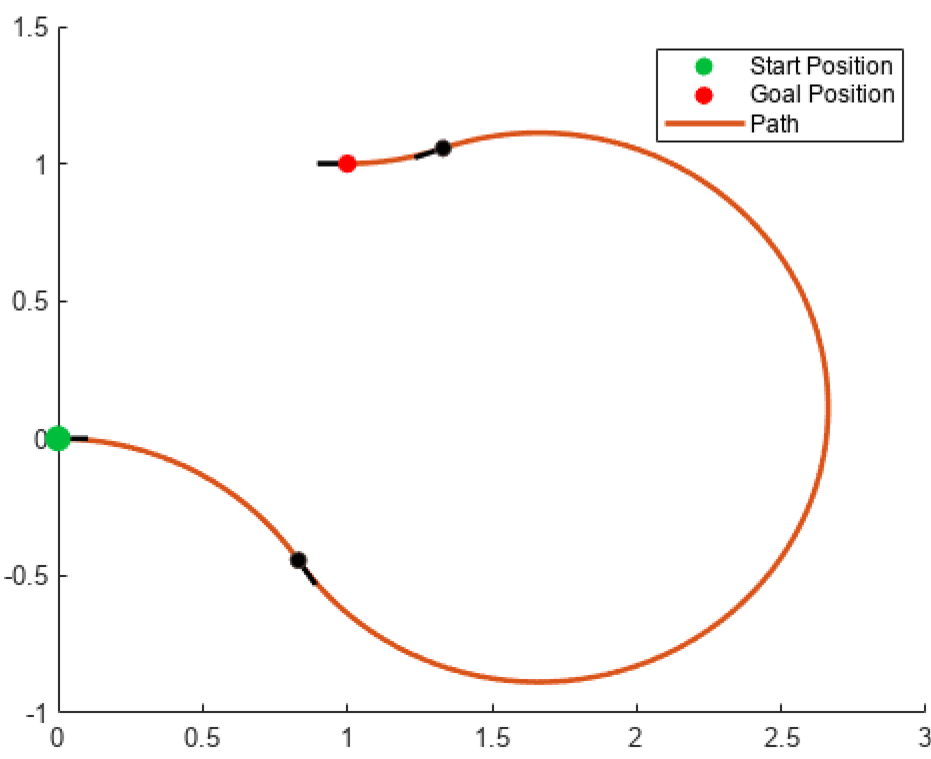
```
startPose = [0 0 0];
goalPose = [1 1 pi];
```

Calculate a valid path segment to connect the poses.

```
[pathSegObj, pathCosts] = connect(dubConnObj,startPose,goalPose);
```

Show the generated path.

```
show(pathSegObj{1})
```



## Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Objects

`dubinsConnection` | `reedsSheppConnection` | `reedsSheppPathSegment`

### Functions

`connect` | `interpolate` | `show`

# dynamicCapsuleList

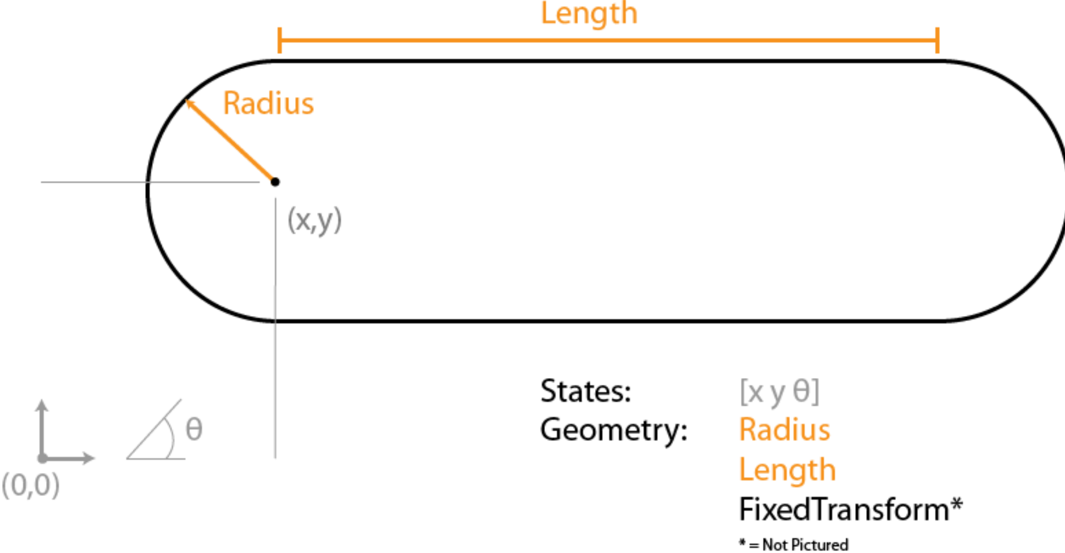
Dynamic capsule-based obstacle list

## Description

The `dynamicCapsuleList` object manages two lists of capsule-based collision objects in 2-D space. Collision objects are separated into two lists, ego bodies and obstacles. For ego bodies and obstacles in 3-D, see the `dynamicCapsuleList3D` object.

Each collision object in the two lists has three key elements:

- **ID** –– Integer that identifies each object, stored in the `EgoIDs` property for ego bodies and the `ObstacleIDs` property for obstacles.
- **States** –– Location and orientation of the object as an *M*-by-3 matrix, where each row is of form `[x y theta]` and *M* is the number of states along the path of the object in the world frame. The list of states assumes each state is separated by a fixed time interval. *xy*-positions are in meters, and `theta` is in radians. The default local origin is located at the center of the left semicircle of the capsule.
- **Geometry** –– Size of the capsule-based object based on a specified length and radius. The radius applies to the semicircle end caps, and the length applies to the central rectangle length. To shift the capsule geometry and local origin relative to the default origin point, specify a fixed transform relative to the local frame of the capsule.




Use the object functions to dynamically add, remove, and update the geometries and states of the various objects in your environment. To add an ego body, see the `addEgo` object function. To add an obstacle, see the `addObstacle` object function.

After specifying all of the object states, validate the ego-body paths and check for collisions with obstacles at every step using the `checkCollision` object function. The function only checks if an ego body collides with an obstacle, ignoring collisions between only obstacles or only ego bodies.

# Creation

## Syntax

`obstacleList = dynamicCapsuleList`

### Description

`obstacleList = dynamicCapsuleList` creates a dynamic capsule-based obstacle list with no ego bodies or obstacles. To begin building an obstacle list, use the `addEgo` or `addObstacle` object functions.

# Properties

**`MaxNumSteps` — Maximum number of time steps in obstacle list**
`31` (default) | positive integer

Maximum number of time steps in the obstacle list, specified as a positive integer. The number of steps determines to the maximum length of the `States` field for a specific ego body or obstacle.

Data Types: `double`

**`EgoIDs` — List of IDs for ego bodies**
vector of positive integers

This property is read-only.

List of identifiers for ego bodies, returned as a vector of positive integers.

Data Types: `double`

**`ObstacleIDs` — IDs for obstacles**
vector of positive integers

This property is read-only.

List of identifiers for obstacles, returned as a vector of positive integers.

Data Types: `double`

**`NumObstacles` — Number of obstacles in list**
integer

This property is read-only.

Number of obstacles in list, returned as an integer.

Data Types: `double`

**`NumEgos` — Number of ego bodies in list**
integer

This property is read-only.

Number of ego bodies in list, returned as an integer.

Data Types: `double`

## Object Functions

| | |
|---|---|
| addEgo | Add ego bodies to capsule list |
| addObstacle | Add obstacles to 2-D capsule list |
| checkCollision | Check for collisions between ego bodies and obstacles |
| egoGeometry | Geometric properties of ego bodies |
| egoPose | Poses of ego bodies |
| obstacleGeometry | Geometric properties of obstacles |
| obstaclePose | Poses of obstacles |
| removeEgo | Remove ego bodies from capsule list |
| removeObstacle | Remove obstacles from capsule list |
| show | Display ego bodies and obstacles in environment |
| updateEgoGeometry | Update geometric properties of ego bodies |
| updateEgoPose | Update states of ego bodies |
| updateObstacleGeometry | Update geometric properties of obstacles |
| updateObstaclePose | Update states of obstacles |

## Examples

### Build Ego Body Paths and Check for Collisions with Obstacles

Build an ego body path and maintain obstacle states using the `dynamicCapsuleList` object. Visualize the states of all objects in the environment at different timestamps. Validate the path of the ego body by checking for collisions with obstacles in the environment.

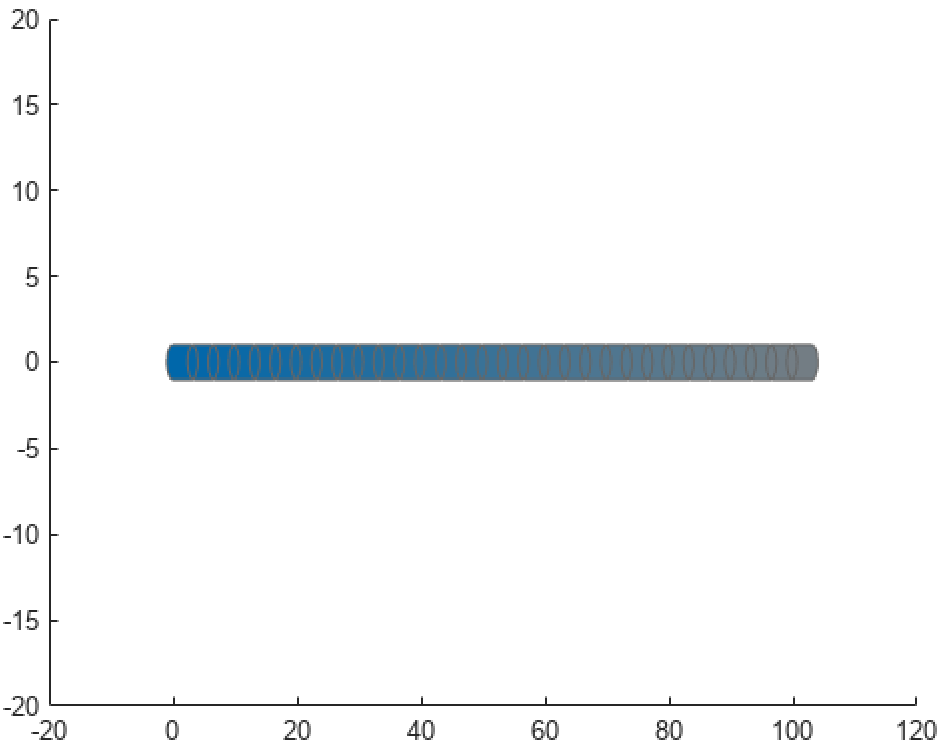
Create the `dynamicCapsuleList` object. Extract the maximum number of steps to use as the number of time stamps for your object paths.

```
obsList = dynamicCapsuleList;
numSteps = obsList.MaxNumSteps;
```

#### Add Ego Body

Define an ego body by specifying the ID, geometry, and state together in a structure. The capsule geometry has a length of 3 m and radius of 1 m. Specify the state as a linear path from $x$ = 0m to $x$ = 100m.

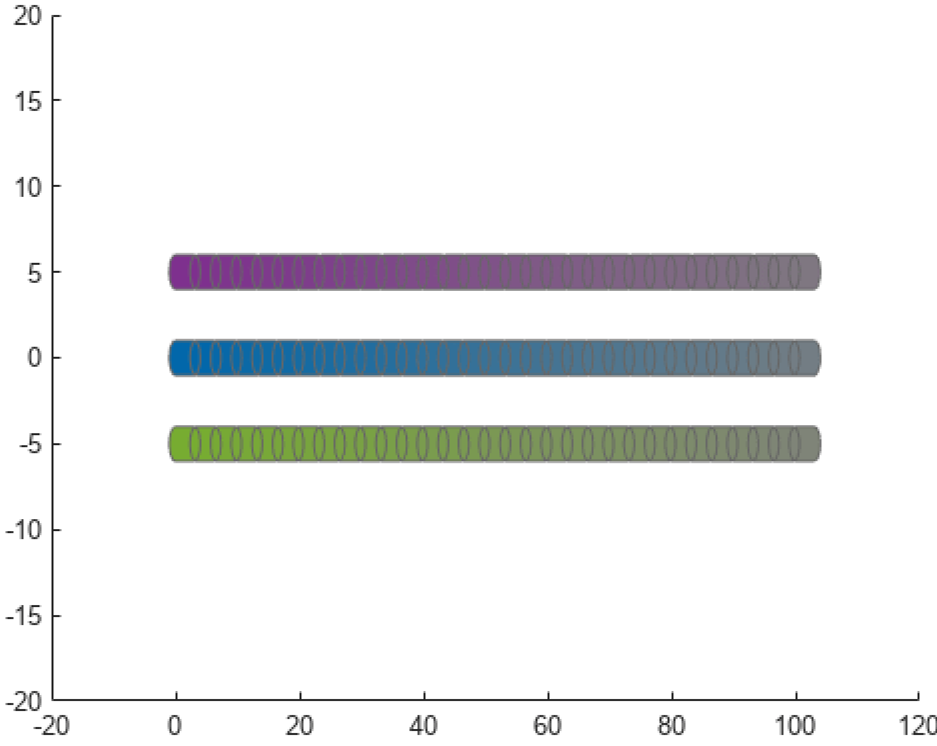
```
egoID1 = 1;
geom = struct("Length",3,"Radius",1,"FixedTransform",eye(3));
states = linspace(0,1,obsList.MaxNumSteps)'.*[100 0 0];

egoCapsule1 = struct('ID',egoID1,'States',states,'Geometry',geom);
addEgo(obsList,egoCapsule1);

show(obsList,"TimeStep",[1:numSteps]);
ylim([-20 20])
```




#### Add Obstacles

Specify states for two obstacles that are separated from the ego body by 5 m in opposite directions on the *y*-axis.. Assume the obstacles have the same geometry `geom` as the ego body.

```
obsState1 = states + [0 5 0];
obsState2 = states + [0 -5 0];

obsCapsule1 = struct('ID',1,'States',obsState1,'Geometry',geom);
obsCapsule2 = struct('ID',2,'States',obsState2,'Geometry',geom);

addObstacle(obsList,obsCapsule1);
addObstacle(obsList,obsCapsule2);

show(obsList,"TimeStep",[1:numSteps]);
ylim([-20 20])
```




### Update Obstacles

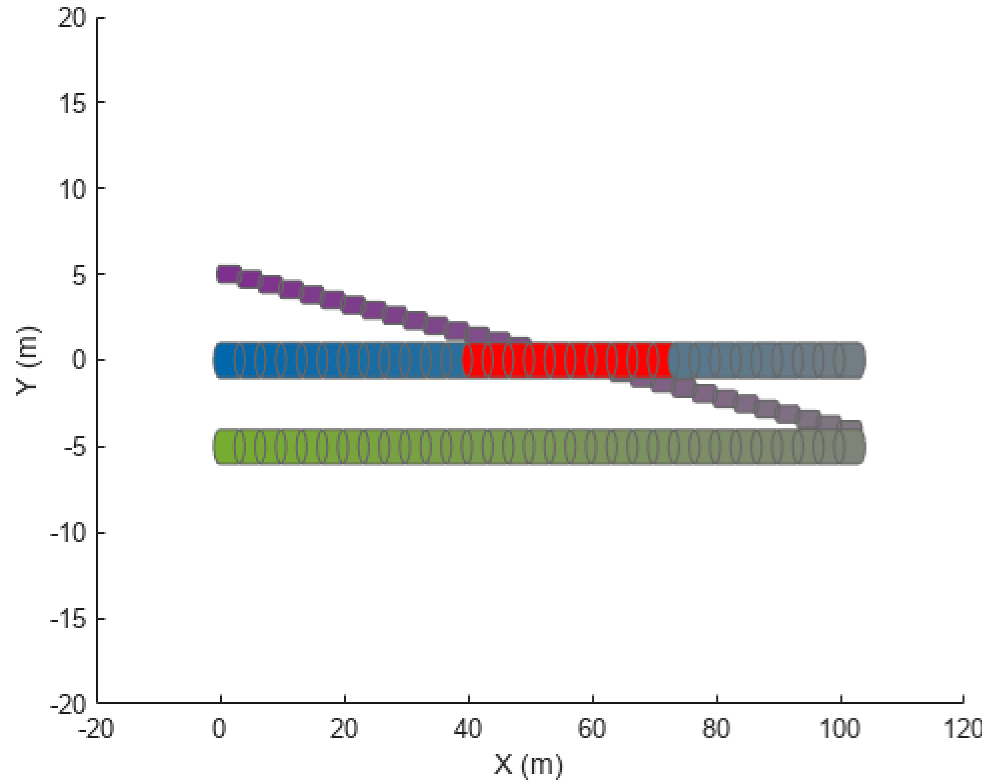
Alter your obstacle locations and geometry dimensions over time. Use the previously generated structure, modify the fields, and update the obstacles using the `updateObstacleGeometry` and `updateObstaclePose` object functions. Reduces the radius of the first obstacle to 0.5 m, and change the path to move it towards the ego body.

```
obsCapsule1.Geometry.Radius = 0.5;

obsCapsule1.States = ...
    [linspace(0,100,numSteps)' ... % x
     linspace(5,-4,numSteps)' ... % y
     zeros(numSteps,1)]; % theta

updateObstacleGeometry(obsList,1,obsCapsule1);
updateObstaclePose(obsList,1,obsCapsule1);
```

### Check for Collisions

Visualize the new paths. Show where collisions between the ego body and an obstacle, which the display highlights in red. Notice that collisions between the obstacles are not checked.

```
show(obsList,"TimeStep",[1:numSteps],"ShowCollisions",1);
ylim([-20 20])
xlabel("X (m)")
ylabel("Y (m)")
```




Programmatically check for collisions by using the `checkCollision` object function. The function returns a vector of logical values that indicates the status of each time step. The vector is transposed for display purposes.

```
collisions = checkCollision(obsList)'
```

```
collisions = 1x31 logical array

   0   0   0   0   0   0   0   0   0   0   0   0   1   1   1   1   1   1   1   1   1   1   0   0
```

To validate paths with a large number of steps, use the `any` function on the vector of collision values.

```
if any(collisions)
    disp("Collision detected.")
end
```

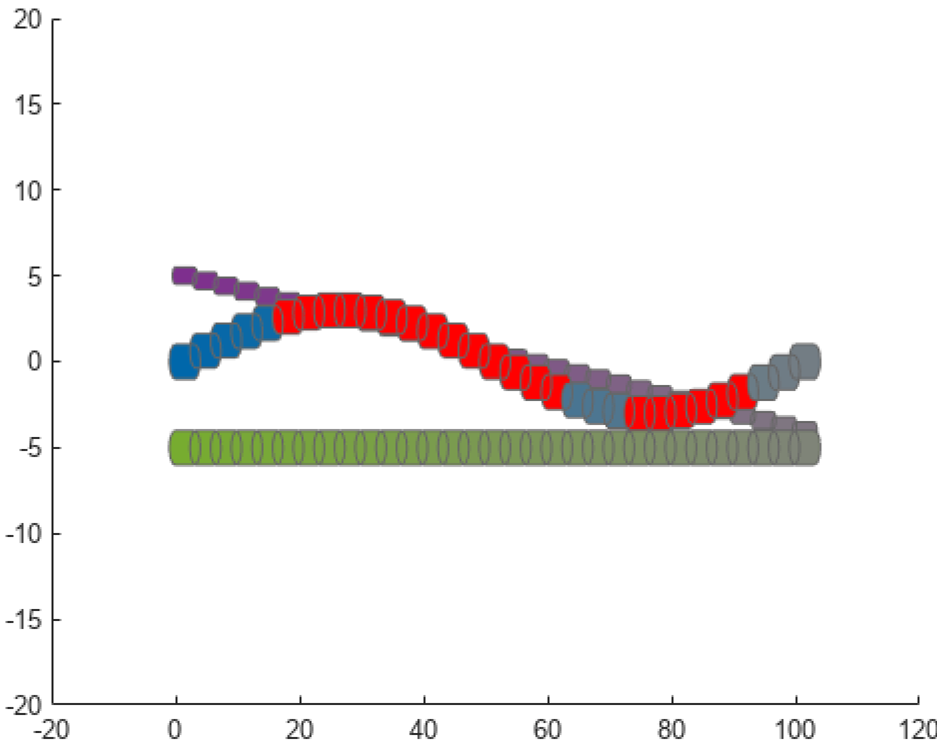
```
Collision detected.
```

### Update Ego Path

Specify a new path for the ego body. Visualize the paths again, displaying collisions.

```
egoCapsule1.States = ...
    [linspace(0,100,numSteps)' ... % x
    3*sin(linspace(0,2*pi,numSteps))' ... % y
    zeros(numSteps,1)]; % theta
```

```
updateEgoPose(obsList,1,egoCapsule1);

show(obsList,"TimeStep",[1:numSteps],"ShowCollisions",1);
ylim([-20 20])
```




# Version History

**Introduced in R2020b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Objects

`dynamicCapsuleList3D`

### Functions

`addEgo` | `addObstacle` | `checkCollision` | `egoGeometry` | `egoPose` | `obstacleGeometry` | `obstaclePose` | `removeEgo` | `removeObstacle` | `show` | `updateEgoGeometry` | `updateEgoPose` | `updateObstacleGeometry` | `updateObstaclePose`

**Topics**

"Highway Trajectory Planning Using Frenet Reference Path"

# addEgo

Add ego bodies to capsule list

## Syntax

```
addEgo(capsuleListObj,egoStruct)
status = addEgo(capsuleListObj,egoStruct)
```

## Description

`addEgo(capsuleListObj,egoStruct)` adds one or more ego bodies to the 2-D dynamic capsule list with the specified ID, state, and geometry values given in `egoStruct`.

`status = addEgo(capsuleListObj,egoStruct)` additionally returns an indicator of whether each specified ego body was added, updated, or a duplicate.

## Examples

#### Build Ego Body Paths and Check for Collisions with Obstacles

Build an ego body path and maintain obstacle states using the `dynamicCapsuleList` object. Visualize the states of all objects in the environment at different timestamps. Validate the path of the ego body by checking for collisions with obstacles in the environment.

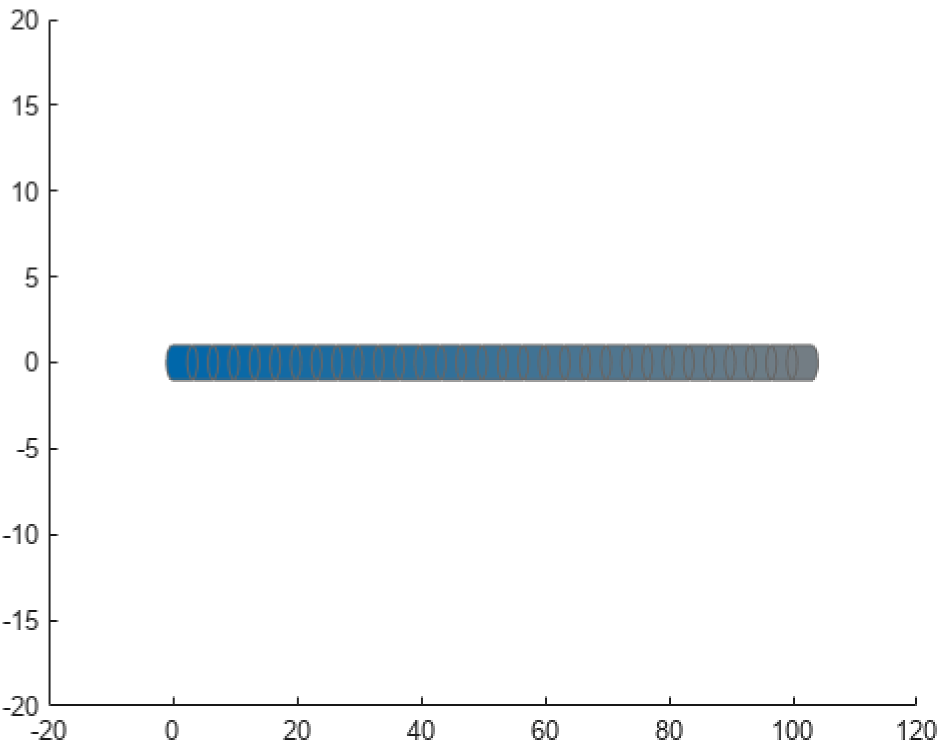
Create the `dynamicCapsuleList` object. Extract the maximum number of steps to use as the number of time stamps for your object paths.

```
obsList = dynamicCapsuleList;
numSteps = obsList.MaxNumSteps;
```

#### Add Ego Body

Define an ego body by specifying the ID, geometry, and state together in a structure. The capsule geometry has a length of 3 m and radius of 1 m. Specify the state as a linear path from $x$ = 0m to $x$ = 100m.

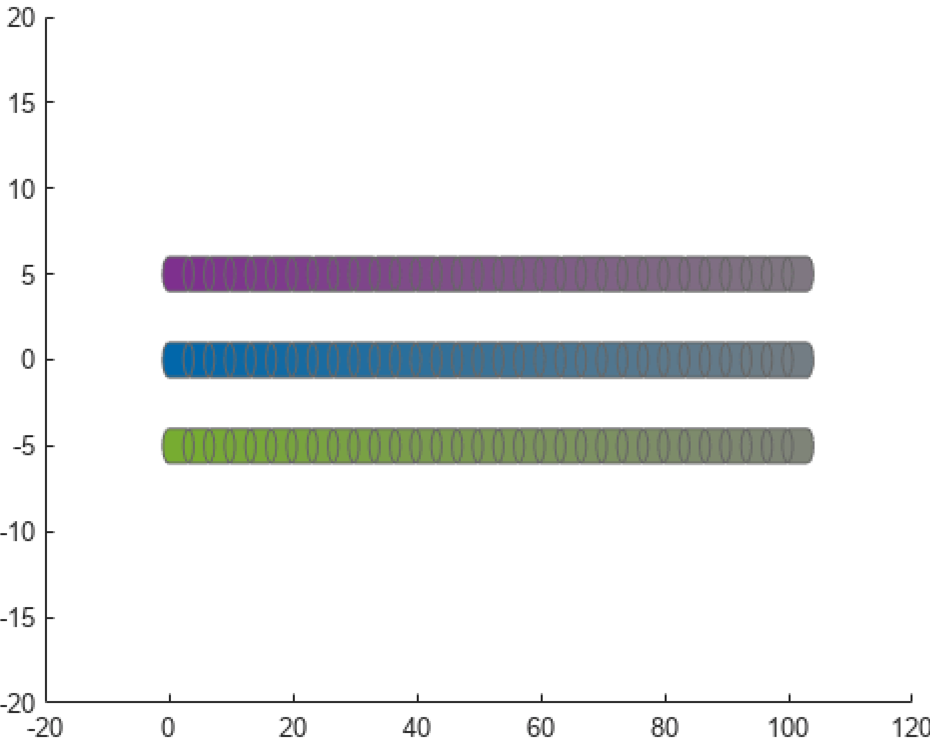
```
egoID1 = 1;
geom = struct("Length",3,"Radius",1,"FixedTransform",eye(3));
states = linspace(0,1,obsList.MaxNumSteps)'.*[100 0 0];

egoCapsule1 = struct('ID',egoID1,'States',states,'Geometry',geom);
addEgo(obsList,egoCapsule1);

show(obsList,"TimeStep",[1:numSteps]);
ylim([-20 20])
```




#### Add Obstacles

Specify states for two obstacles that are separated from the ego body by 5 m in opposite directions on the *y*-axis.. Assume the obstacles have the same geometry `geom` as the ego body.

```
obsState1 = states + [0 5 0];
obsState2 = states + [0 -5 0];

obsCapsule1 = struct('ID',1,'States',obsState1,'Geometry',geom);
obsCapsule2 = struct('ID',2,'States',obsState2,'Geometry',geom);

addObstacle(obsList,obsCapsule1);
addObstacle(obsList,obsCapsule2);

show(obsList,"TimeStep",[1:numSteps]);
ylim([-20 20])
```




### Update Obstacles

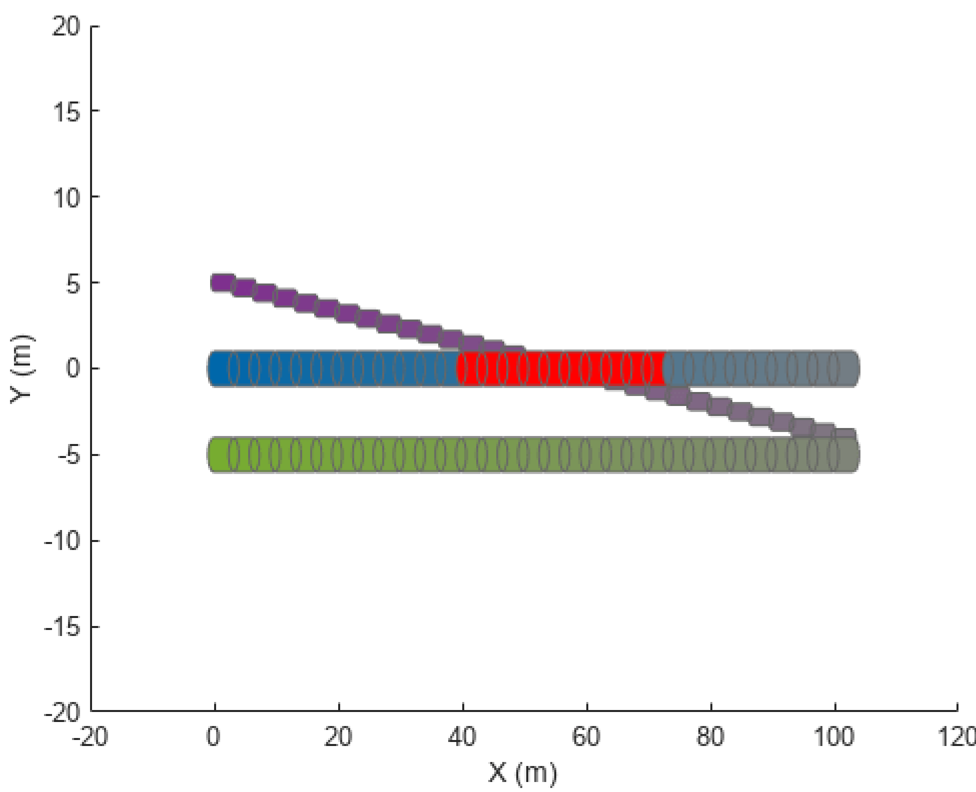
Alter your obstacle locations and geometry dimensions over time. Use the previously generated structure, modify the fields, and update the obstacles using the `updateObstacleGeometry` and `updateObstaclePose` object functions. Reduces the radius of the first obstacle to 0.5 m, and change the path to move it towards the ego body.

```
obsCapsule1.Geometry.Radius = 0.5;

obsCapsule1.States = ...
    [linspace(0,100,numSteps)' ... % x
     linspace(5,-4,numSteps)' ... % y
     zeros(numSteps,1)]; % theta

updateObstacleGeometry(obsList,1,obsCapsule1);
updateObstaclePose(obsList,1,obsCapsule1);
```

### Check for Collisions

Visualize the new paths. Show where collisions between the ego body and an obstacle, which the display highlights in red. Notice that collisions between the obstacles are not checked.

```
show(obsList,"TimeStep",[1:numSteps],"ShowCollisions",1);
ylim([-20 20])
xlabel("X (m)")
ylabel("Y (m)")
```




Programmatically check for collisions by using the `checkCollision` object function. The function returns a vector of logical values that indicates the status of each time step. The vector is transposed for display purposes.

```
collisions = checkCollision(obsList)'
```

```
collisions = 1x31 logical array

   0   0   0   0   0   0   0   0   0   0   0   0   1   1   1   1   1   1   1   1   1   1   0   0
```

To validate paths with a large number of steps, use the `any` function on the vector of collision values.

```
if any(collisions)
    disp("Collision detected.")
end
```

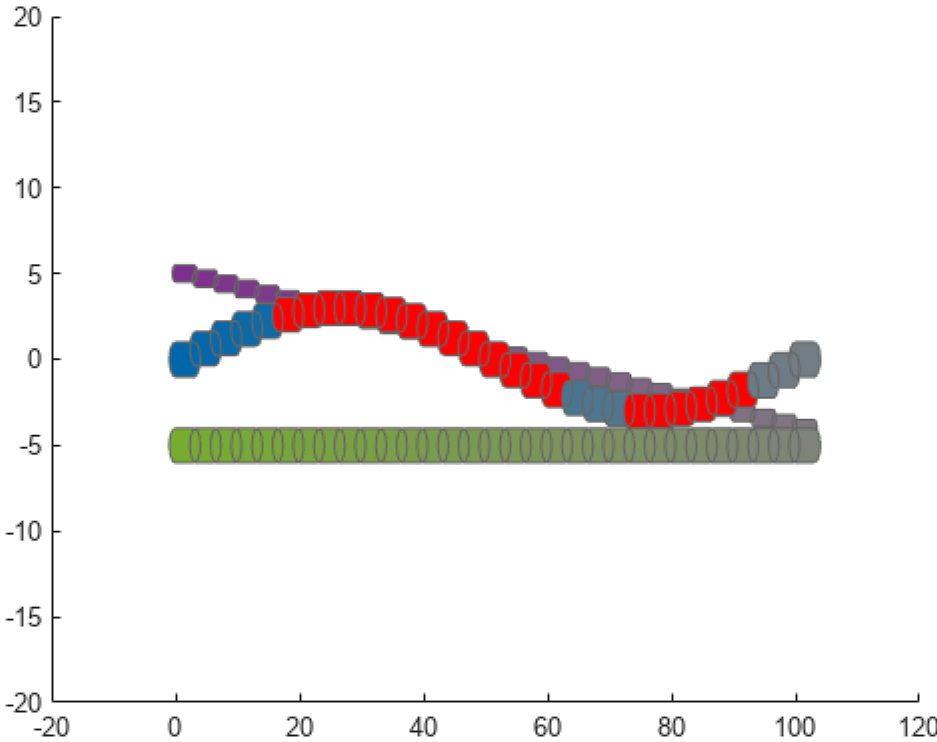
```
Collision detected.
```

### Update Ego Path

Specify a new path for the ego body. Visualize the paths again, displaying collisions.

```
egoCapsule1.States = ...
    [linspace(0,100,numSteps)' ... % x
    3*sin(linspace(0,2*pi,numSteps))' ... % y
    zeros(numSteps,1)]; % theta
```

```
updateEgoPose(obsList,1,egoCapsule1);

show(obsList,"TimeStep",[1:numSteps],"ShowCollisions",1);
ylim([-20 20])
```




## Input Arguments

**capsuleListObj — Dynamic capsule list**
dynamicCapsuleList object

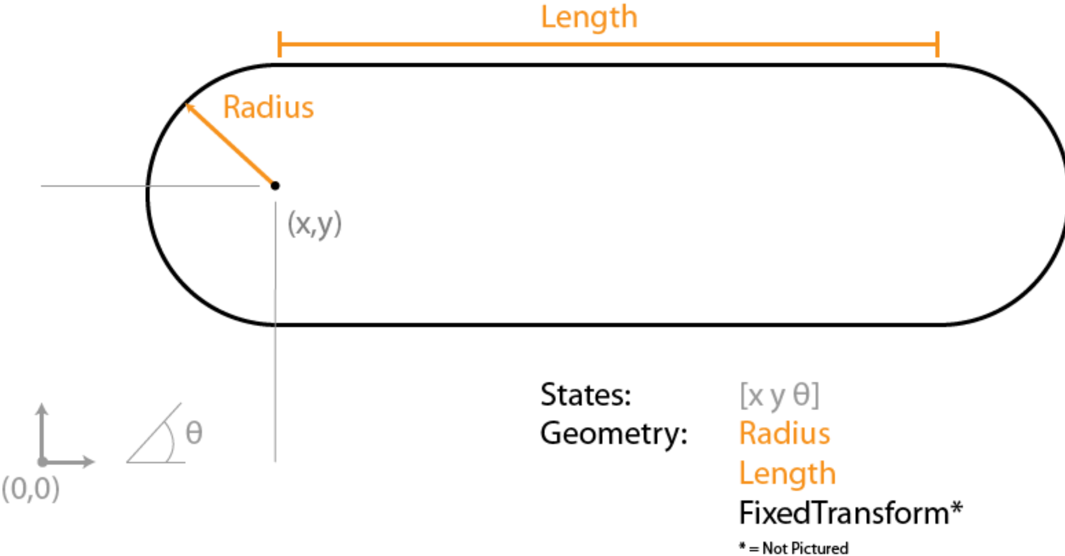
Dynamic capsule list, specified as a `dynamicCapsuleList` object.

**egoStruct — Ego body parameters**
structure | *N*-element structure array

Ego body parameters, specified as an *N*-element structure or a structure array, where *N* is the number of added ego bodies. The fields of each structure define the ID, geometry, and states of an ego body:

- `ID` -- Integer that identifies each object. Stored in the `EgoIDs` property of the `dynamicCapsuleList` object specified by the `capsuleListObj` argument.
- `States` -- Location and orientation of the object as an *M*-by-3 matrix, where each row is of form `[x y theta]`, and *M* is the number of states for the specified ego body in the world frame. The list of states assumes each state is separated by a fixed time interval. *xy*-positions are in meters and `theta` is in radians.

- `Geometry` -- Structure with fields `Length`, `Radius`, and `FixedTransform`. These fields define the size of the capsule-based object using the specified length for the cylinder and semicircle radius for the end caps. To shift the capsule geometry from the default origin, specify the `FixedTransform` field as a fixed transform relative to the local frame of the capsule. To keep the default capsule origin, specify the transform as `eye(3)`.




## Output Arguments

**`status` — Result of adding ego bodies**
*N*-element column vector

Result of adding ego bodies, returned as a *N*-element column vector of ones, zeros, and negative ones. *N* is the number of ego bodies specified in the `egoStruct` argument. Each value indicates whether the associated body is added (`1`), updated (`0`), or a duplicate (`-1`). While adding ego bodies, if multiple structures with the same body ID are found in the structure array `egoStruct`, then the function marks the previous entry as duplicate and ignores it.

# Version History

**Introduced in R2020b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
dynamicCapsuleList | dynamicCapsuleList3D

**Functions**
addObstacle | checkCollision | egoGeometry | egoPose | obstacleGeometry | obstaclePose | removeEgo | removeObstacle | show | updateEgoGeometry | updateEgoPose | updateObstacleGeometry | updateObstaclePose

**Topics**
"Highway Trajectory Planning Using Frenet Reference Path"

# addObstacle

Add obstacles to 2-D capsule list

## Syntax

```
addObstacle(capsuleListObj,obstacleStruct)
status = addObstacle(capsuleListObj,obstacleStruct)
```

## Description

`addObstacle(capsuleListObj,obstacleStruct)` adds one or more obstacles to the 2-D dynamic capsule list with the specified ID, state, and geometry values given in `obstacleStruct`.

`status = addObstacle(capsuleListObj,obstacleStruct)` additionally returns an indicator of whether each specified obstacle was added, updated, or a duplicate.

## Examples

### Build Ego Body Paths and Check for Collisions with Obstacles

Build an ego body path and maintain obstacle states using the `dynamicCapsuleList` object. Visualize the states of all objects in the environment at different timestamps. Validate the path of the ego body by checking for collisions with obstacles in the environment.

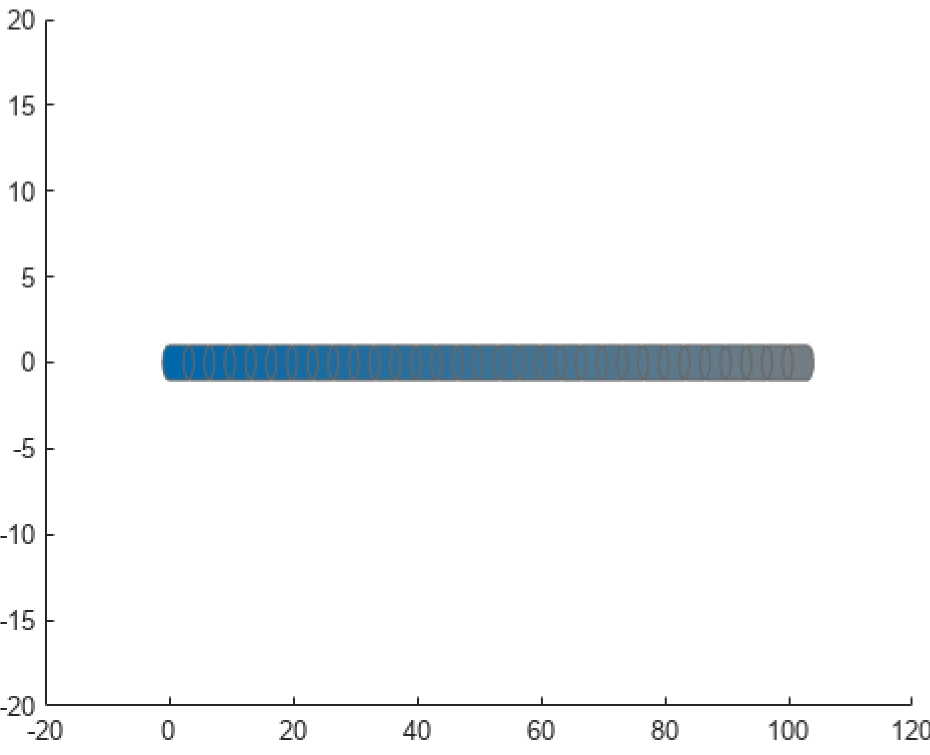
Create the `dynamicCapsuleList` object. Extract the maximum number of steps to use as the number of time stamps for your object paths.

```
obsList = dynamicCapsuleList;
numSteps = obsList.MaxNumSteps;
```

#### Add Ego Body

Define an ego body by specifying the ID, geometry, and state together in a structure. The capsule geometry has a length of 3 m and radius of 1 m. Specify the state as a linear path from $x$ = 0m to $x$ = 100m.

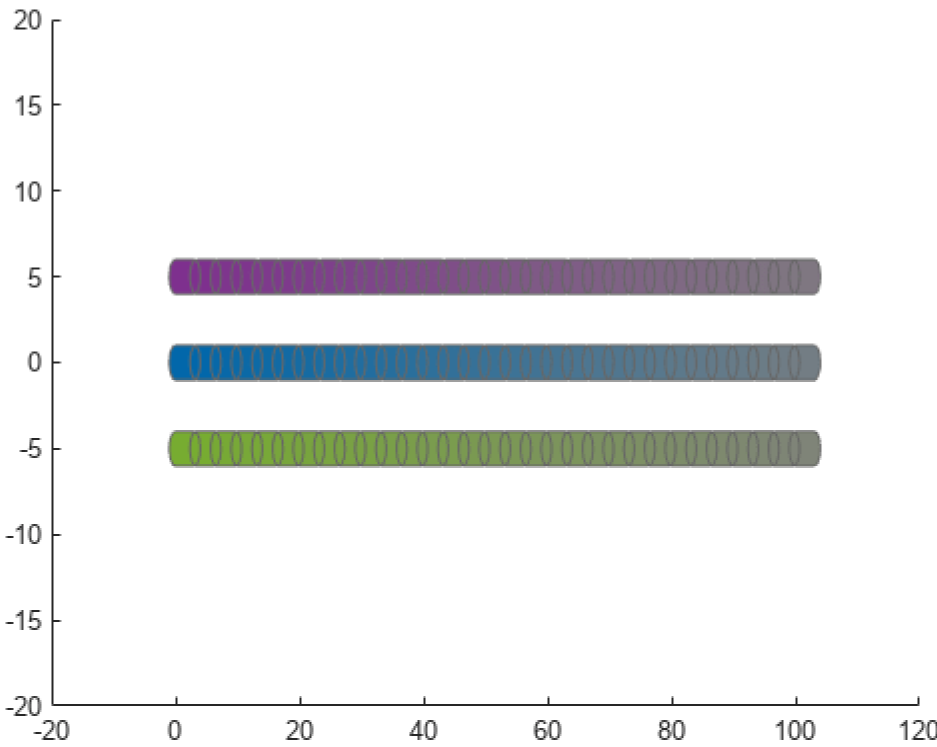
```
egoID1 = 1;
geom = struct("Length",3,"Radius",1,"FixedTransform",eye(3));
states = linspace(0,1,obsList.MaxNumSteps)'.*[100 0 0];

egoCapsule1 = struct('ID',egoID1,'States',states,'Geometry',geom);
addEgo(obsList,egoCapsule1);

show(obsList,"TimeStep",[1:numSteps]);
ylim([-20 20])
```




#### Add Obstacles

Specify states for two obstacles that are separated from the ego body by 5 m in opposite directions on the *y*-axis.. Assume the obstacles have the same geometry `geom` as the ego body.

```
obsState1 = states + [0 5 0];
obsState2 = states + [0 -5 0];

obsCapsule1 = struct('ID',1,'States',obsState1,'Geometry',geom);
obsCapsule2 = struct('ID',2,'States',obsState2,'Geometry',geom);

addObstacle(obsList,obsCapsule1);
addObstacle(obsList,obsCapsule2);

show(obsList,"TimeStep",[1:numSteps]);
ylim([-20 20])
```




#### Update Obstacles

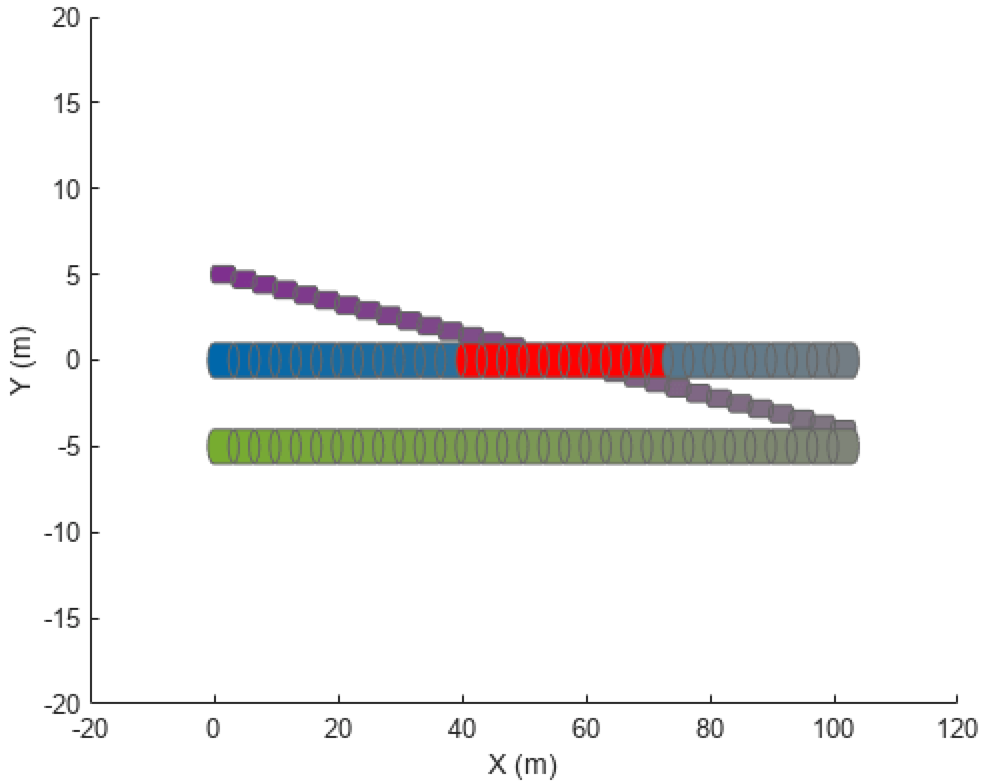
Alter your obstacle locations and geometry dimensions over time. Use the previously generated structure, modify the fields, and update the obstacles using the `updateObstacleGeometry` and `updateObstaclePose` object functions. Reduces the radius of the first obstacle to 0.5 m, and change the path to move it towards the ego body.

```
obsCapsule1.Geometry.Radius = 0.5;

obsCapsule1.States = ...
    [linspace(0,100,numSteps)' ... % x
     linspace(5,-4,numSteps)' ... % y
     zeros(numSteps,1)]; % theta

updateObstacleGeometry(obsList,1,obsCapsule1);
updateObstaclePose(obsList,1,obsCapsule1);
```

#### Check for Collisions

Visualize the new paths. Show where collisions between the ego body and an obstacle, which the display highlights in red. Notice that collisions between the obstacles are not checked.

```
show(obsList,"TimeStep",[1:numSteps],"ShowCollisions",1);
ylim([-20 20])
xlabel("X (m)")
ylabel("Y (m)")
```




Programmatically check for collisions by using the `checkCollision` object function. The function returns a vector of logical values that indicates the status of each time step. The vector is transposed for display purposes.

```
collisions = checkCollision(obsList)'
```

```
collisions = 1x31 logical array

   0   0   0   0   0   0   0   0   0   0   0   0   1   1   1   1   1   1   1   1   1   1   0   0
```

To validate paths with a large number of steps, use the `any` function on the vector of collision values.

```
if any(collisions)
    disp("Collision detected.")
end
```

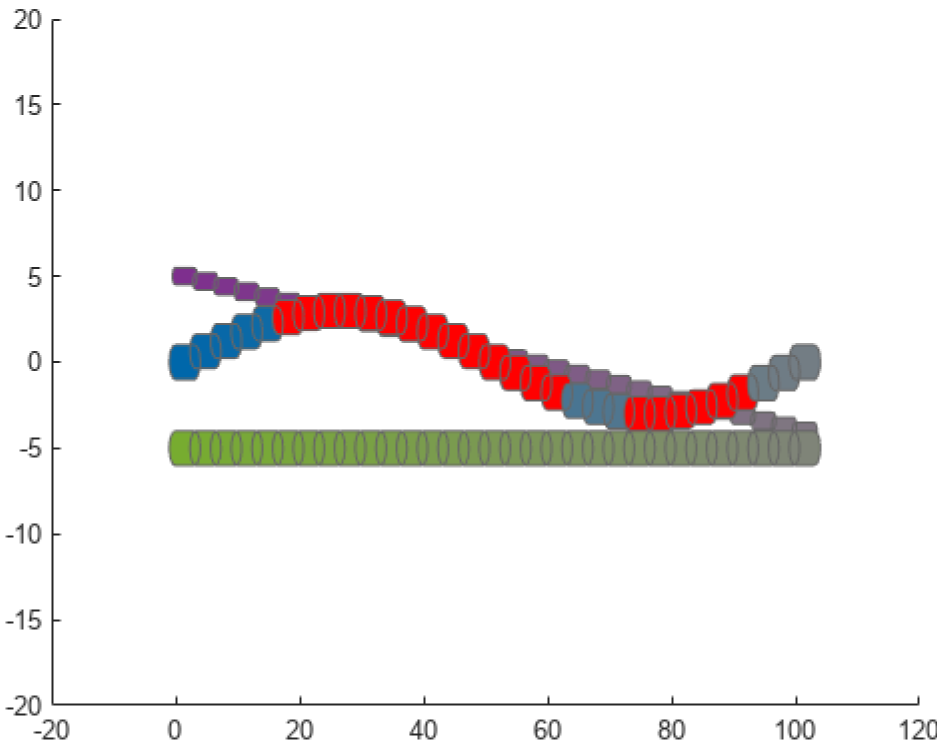
```
Collision detected.
```

### Update Ego Path

Specify a new path for the ego body. Visualize the paths again, displaying collisions.

```
egoCapsule1.States = ...
    [linspace(0,100,numSteps)' ... % x
    3*sin(linspace(0,2*pi,numSteps))' ... % y
    zeros(numSteps,1)]; % theta
```

```
updateEgoPose(obsList,1,egoCapsule1);

show(obsList,"TimeStep",[1:numSteps],"ShowCollisions",1);
ylim([-20 20])
```



## Input Arguments

**capsuleListObj — Dynamic capsule list**
dynamicCapsuleList object

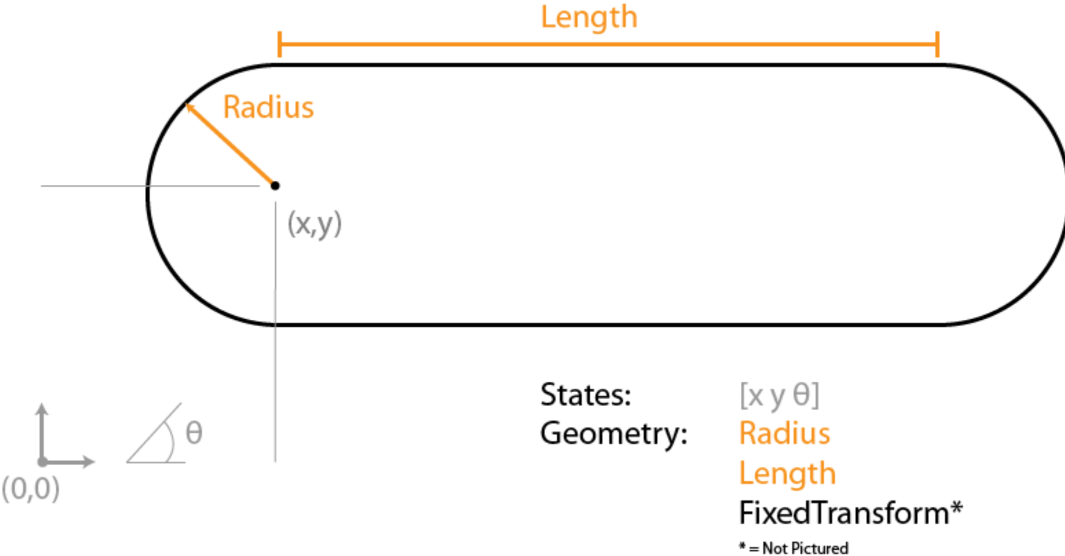
Dynamic capsule list, specified as a dynamicCapsuleList object.

**obstacleStruct — Obstacle parameters**
structure | *N*-element structure array

Obstacle parameters, specified as an *N*-element structure or a structure array, where *N* is the number of added obstacles. The fields of each structure define the ID, geometry, and states of an obstacle:

- ID -- Integer that identifies each object. Stored in the ObstacleIDs property of the dynamicCapsuleList object specified by the capsuleListObj argument.
- States -- Location and orientation of the object as an *M*-by-3 matrix, where each row is of form [x y theta], and *M* is the number of states for the specified obstacle in the world frame. The list of states assumes each state is separated by a fixed time interval. *xy*-positions are in meters and theta is in radians.

- `Geometry` -- Structure with fields `Length`, `Radius`, and `FixedTransform`. These fields define the size of the capsule-based object using the specified length for the cylinder and semicircle radius for the end caps. To shift the capsule geometry from the default origin, specify the `FixedTransform` field as a fixed transform relative to the local frame of the capsule. To keep the default capsule origin, specify the transform as `eye(3)`.




## Output Arguments

**`status` — Result of adding obstacles**
*N*-element column vector

Result of adding obstacles, returned as a *N*-element column vector of ones, zeros, and negative ones. *N* is the number of obstacles specified in the `obstacleStruct` argument. Each value indicates whether the associated body is added (`1`), updated (`0`), or a duplicate (`-1`). While adding obstacles, if multiple structures with the same body ID are found in the structure array `obstaclesStruct`, then the function marks the previous entry as duplicate and ignores it.

# Version History

**Introduced in R2020b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
`dynamicCapsuleList` | `dynamicCapsuleList3D`

**Functions**
`addEgo` | `checkCollision` | `egoGeometry` | `egoPose` | `obstacleGeometry` | `obstaclePose` | `removeEgo` | `removeObstacle` | `show` | `updateEgoGeometry` | `updateEgoPose` | `updateObstacleGeometry` | `updateObstaclePose`

**Topics**
"Highway Trajectory Planning Using Frenet Reference Path"

# checkCollision

Check for collisions between ego bodies and obstacles

## Syntax

```
collisionFound = checkCollision(capsuleListObj)
[fullResults,distance] = checkCollision(capsuleListObj,options)
```

## Description

`collisionFound = checkCollision(capsuleListObj)` checks each ego body for collisions with obstacles in the environment. The function indicates whether each ego body is in collision at each time step..

`[fullResults,distance] = checkCollision(capsuleListObj,options)` checks each ego body for collisions with obstacles in the environment, and returns the results using additional specified collision detection options `options`.

## Examples

### Build Ego Body Paths and Check for Collisions with Obstacles

Build an ego body path and maintain obstacle states using the `dynamicCapsuleList` object. Visualize the states of all objects in the environment at different timestamps. Validate the path of the ego body by checking for collisions with obstacles in the environment.

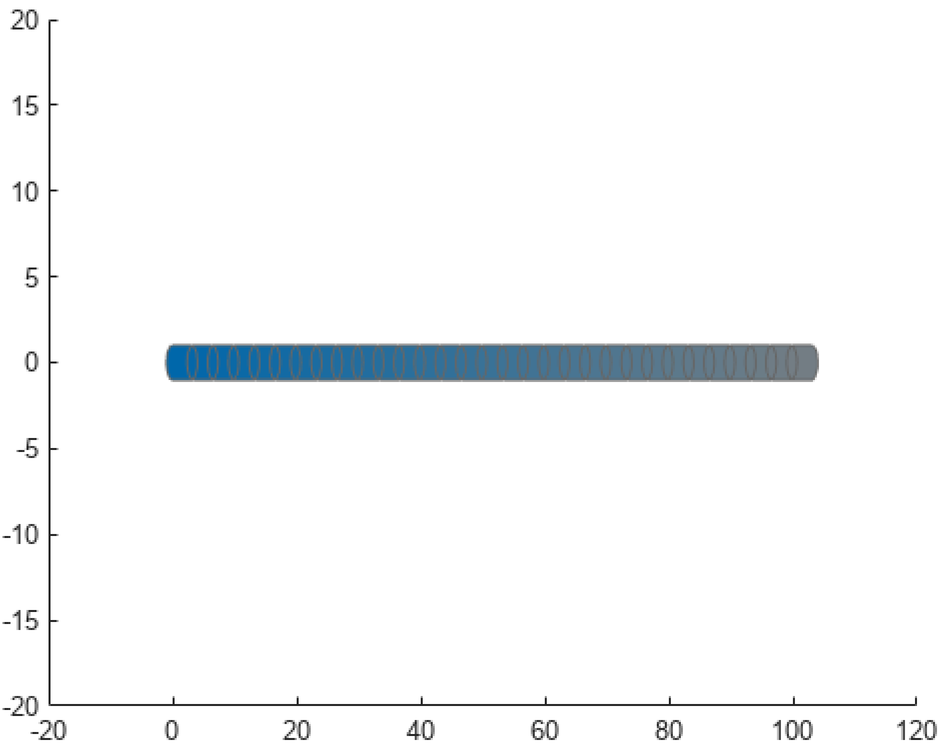
Create the `dynamicCapsuleList` object. Extract the maximum number of steps to use as the number of time stamps for your object paths.

```
obsList = dynamicCapsuleList;
numSteps = obsList.MaxNumSteps;
```

#### Add Ego Body

Define an ego body by specifying the ID, geometry, and state together in a structure. The capsule geometry has a length of 3 m and radius of 1 m. Specify the state as a linear path from $x$ = 0m to $x$ = 100m.

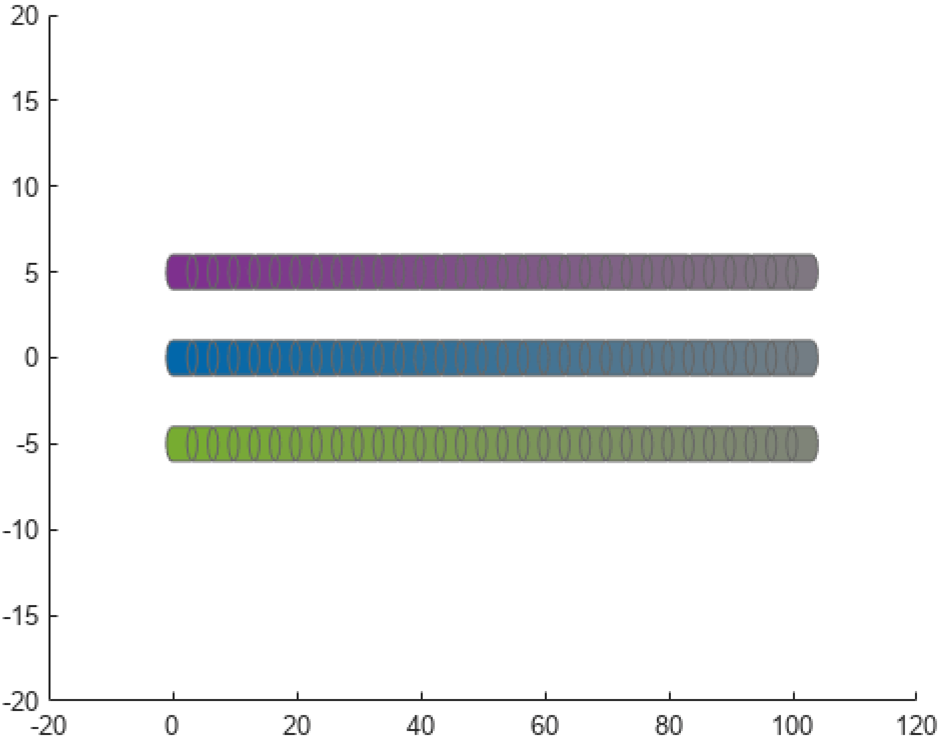
```
egoID1 = 1;
geom = struct("Length",3,"Radius",1,"FixedTransform",eye(3));
states = linspace(0,1,obsList.MaxNumSteps)'.*[100 0 0];

egoCapsule1 = struct('ID',egoID1,'States',states,'Geometry',geom);
addEgo(obsList,egoCapsule1);

show(obsList,"TimeStep",[1:numSteps]);
ylim([-20 20])
```




#### Add Obstacles

Specify states for two obstacles that are separated from the ego body by 5 m in opposite directions on the *y*-axis.. Assume the obstacles have the same geometry `geom` as the ego body.

```
obsState1 = states + [0 5 0];
obsState2 = states + [0 -5 0];

obsCapsule1 = struct('ID',1,'States',obsState1,'Geometry',geom);
obsCapsule2 = struct('ID',2,'States',obsState2,'Geometry',geom);

addObstacle(obsList,obsCapsule1);
addObstacle(obsList,obsCapsule2);

show(obsList,"TimeStep",[1:numSteps]);
ylim([-20 20])
```




#### Update Obstacles

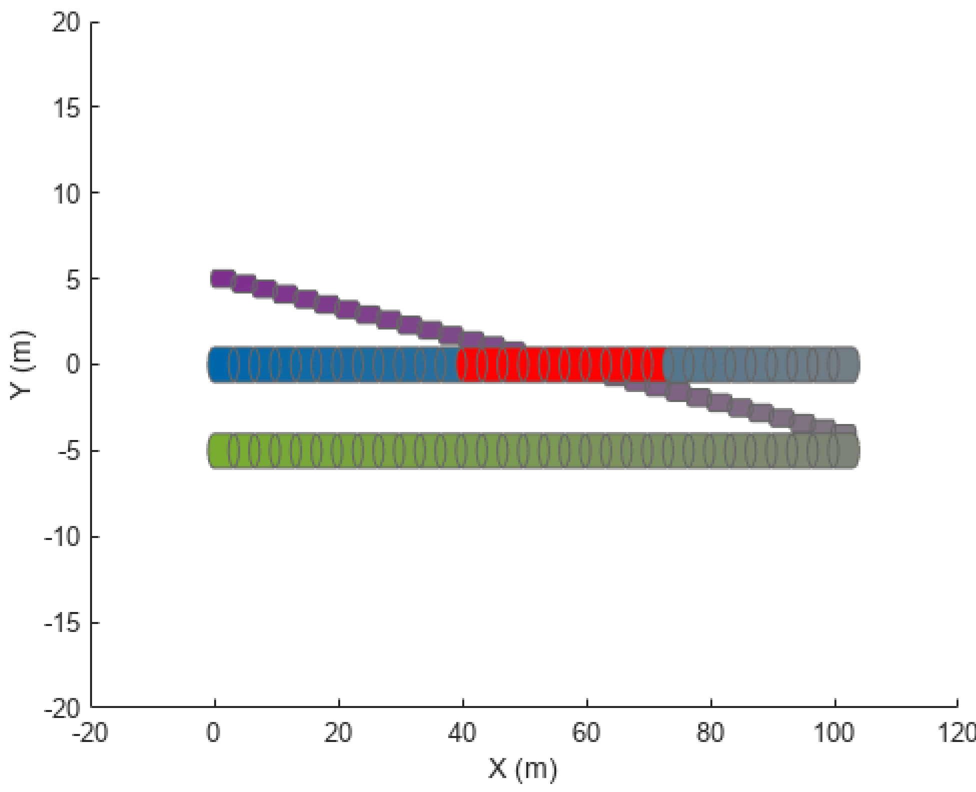
Alter your obstacle locations and geometry dimensions over time. Use the previously generated structure, modify the fields, and update the obstacles using the `updateObstacleGeometry` and `updateObstaclePose` object functions. Reduces the radius of the first obstacle to 0.5 m, and change the path to move it towards the ego body.

```
obsCapsule1.Geometry.Radius = 0.5;

obsCapsule1.States = ...
    [linspace(0,100,numSteps)' ... % x
     linspace(5,-4,numSteps)' ... % y
     zeros(numSteps,1)]; % theta

updateObstacleGeometry(obsList,1,obsCapsule1);
updateObstaclePose(obsList,1,obsCapsule1);
```

#### Check for Collisions

Visualize the new paths. Show where collisions between the ego body and an obstacle, which the display highlights in red. Notice that collisions between the obstacles are not checked.

```
show(obsList,"TimeStep",[1:numSteps],"ShowCollisions",1);
ylim([-20 20])
xlabel("X (m)")
ylabel("Y (m)")
```




Programmatically check for collisions by using the `checkCollision` object function. The function returns a vector of logical values that indicates the status of each time step. The vector is transposed for display purposes.

```
collisions = checkCollision(obsList)'
```

```
collisions = 1x31 logical array

   0   0   0   0   0   0   0   0   0   0   0   0   1   1   1   1   1   1   1   1   1   1   0   0
```

To validate paths with a large number of steps, use the `any` function on the vector of collision values.

```
if any(collisions)
    disp("Collision detected.")
end
```

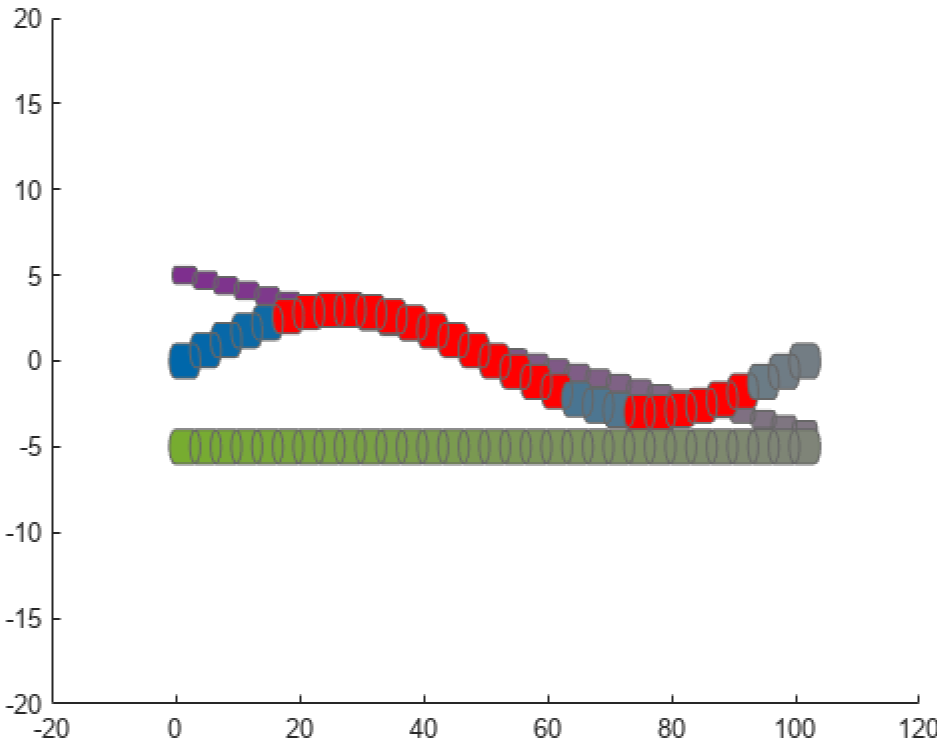
```
Collision detected.
```

### Update Ego Path

Specify a new path for the ego body. Visualize the paths again, displaying collisions.

```
egoCapsule1.States = ...
    [linspace(0,100,numSteps)' ... % x
    3*sin(linspace(0,2*pi,numSteps))' ... % y
    zeros(numSteps,1)]; % theta
```

```
updateEgoPose(obsList,1,egoCapsule1);

show(obsList,"TimeStep",[1:numSteps],"ShowCollisions",1);
ylim([-20 20])
```




## Input Arguments

**capsuleListObj — Dynamic capsule list**
`dynamicCapsuleList` object | `dynamicCapsuleList3D` object

Dynamic capsule list, specified as a `dynamicCapsuleList` or `dynamicCapsuleList3D` object.

**options — Collision detection options**
structure

Collision detection options, specified as a structure with these fields:

- `FullResults` –– Return the collision results for each obstacle separately , specified as a logical `0` (`false`) or `1` (`true`). See the `fullResults` output argument.
- `ReturnDistance` –– Return the distance calculation from collision checking, specified as a logical `0` (`false`) or `1` (`true`). See the `distance` output argument.

Data Types: `struct`

## Output Arguments

**`collisionFound` — Collision checking results**
*n*-by-*e* matrix of logical values

Collision checking results, returned as an *n*-by-*e* matrix of logical values. By default, the function checks for any collision between any object, which returns an *n*-by-*e* matrix, where *n* is the maximum number of states for ego bodies in the specified `capsuleListobj` object, and *e* is the number of ego bodies.

Data Types: `logical`

**`fullResults` — Full collision checking results for each obstacle**
*n*-by-*o*-by-*e* array of logical values

Full collision checking results for each obstacle, returned as an *n*-by-*o*-by-*e* array of logical values. *n* is the maximum number of states for ego bodies in the specified `capsuleListobj` argument, *o* is the number of obstacles, and *e* is the number of ego bodies.

**Dependencies**

To return the `fullResults` output argument, specify the `options` input argument with the `FullResults` field set to `true`.

Data Types: `logical`

**`distance` — Distance from obstacles**
*n*-by-*e* numeric matrix | *n*-by-*o*by-*e* numeric array

Distance from obstacles, returned as an *n*-by-*e* numeric matrix or *n*-by-*o*by-*e* numeric array. The dimensions and behavior of the distance argument depend on the value of the `FullResults` field of the options argument

| `distance` Dimensions | `FullResults` Value | Behavior |
| --- | --- | --- |
| *n*-by-*e* numeric matrix | `false` | Returns the distance between each ego body and the closest obstacle at each time step. *n* is the maximum number of states for ego bodies specified in the `capsuleListObj` argument, and *e* is the number of ego bodies. |
| *n*-by-*o*by-*e* numeric array | `true` | Returns the distance between each ego body and each obstacle at each time step. *o* is the number of obstacles. |

**Dependencies**

To return the `distance` output argument, specify the `options` input argument with the `ReturnDistance` field set to `true`.

Data Types: `single` | `double`

# Version History

**Introduced in R2020b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
`dynamicCapsuleList` | `dynamicCapsuleList3D`

**Functions**
`addEgo` | `addObstacle` | `egoGeometry` | `egoPose` | `obstacleGeometry` | `obstaclePose` | `removeEgo` | `removeObstacle` | `show` | `updateEgoGeometry` | `updateEgoPose` | `updateObstacleGeometry` | `updateObstaclePose`

**Topics**
"Highway Trajectory Planning Using Frenet Reference Path"

# egoGeometry

Geometric properties of ego bodies

## Syntax

```
[egoIDs,geomStruct] = egoGeometry(capsuleListObj)
[egoIDs,geomStruct] = egoGeometry(capsuleListObj,selectEgoIDs)
[egoIDs,geomStruct,status] = egoGeometry(capsuleListObj,selectEgoIDs)
```

## Description

`[egoIDs,geomStruct] = egoGeometry(capsuleListObj)` returns the ego ID and the geometry parameters for each ego body in the capsule list.

`[egoIDs,geomStruct] = egoGeometry(capsuleListObj,selectEgoIDs)` specifies which ego bodies to return the ID and geometry parameters for.

`[egoIDs,geomStruct,status] = egoGeometry(capsuleListObj,selectEgoIDs)` returns an indicator of whether each ID in `selectEgoIDs` exists.

## Examples

### Create and Modify Capsule-Based Ego Bodies

Add ego bodies to an environment using the `dynamicCapsuleList` object. Modify the properties of the ego bodies. Remove an ego body from the environment. Visualize the states of all objects in the environment at different timestamps.

Create the `dynamicCapsuleList` object. Extract the maximum number of steps to use as the number of time stamps for the object paths.

```
capsuleList = dynamicCapsuleList;
numSteps = capsuleList.MaxNumSteps;
```

#### Add Ego Bodies

Specify the states for the two ego bodies as a linear path from $x = 0$ m to $x = 100$ m. The two ego bodies are separated by 5 m in opposite directions on the *y*-axis.

```
egoState = linspace(0,1,numSteps)'.*[100 0 0];
egoState1 = egoState+[0 5 0];
egoState2 = egoState+[0 -5 0];
```

Generate default poses and geometric structures for the two ego bodies using ego IDs.

```
[egoIDs,egoPoseStruct] = egoPose(capsuleList,[1 2]);
[egoIDs,egoGeomStruct] = egoGeometry(capsuleList,egoIDs);
```

#### Update Ego Bodies

Assign the states to the ego bodies.

```
egoPoseStruct(1).States = egoState1;
egoPoseStruct(2).States = egoState2;
```

Increase the radius of the first ego body to 2 m.

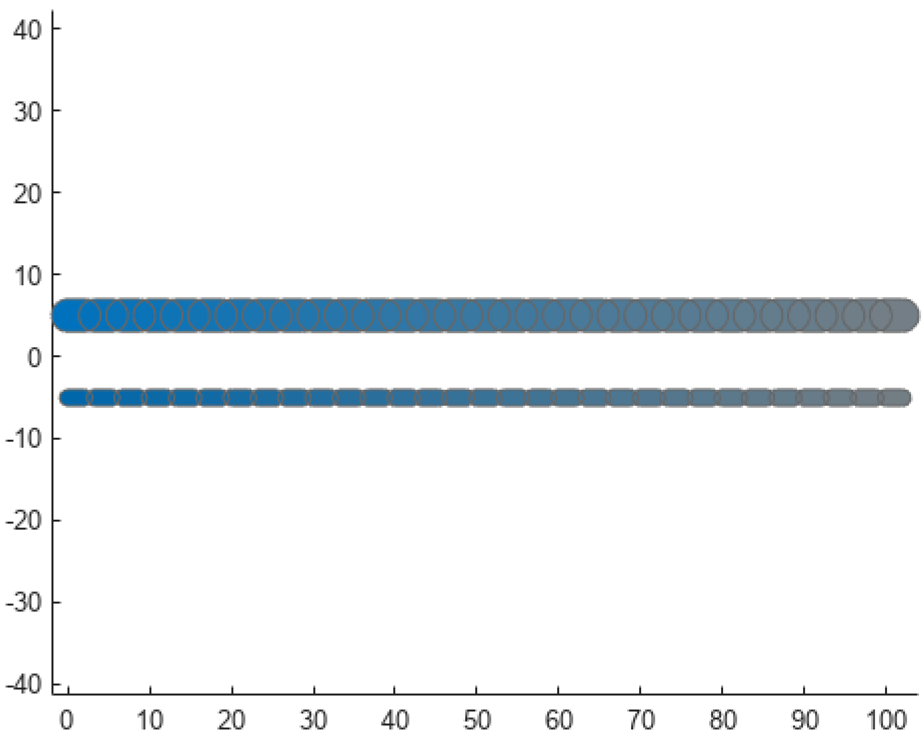
```
egoGeomStruct(1).Geometry.Radius = 2;
```

update the ego bodies using the `updateEgoPose` and `updateEgoGeometry` object functions.

```
updateEgoPose(capsuleList,egoIDs,egoPoseStruct);
updateEgoGeometry(capsuleList,egoIDs,egoGeomStruct);
```

Visualize the ego bodies.

```
show(capsuleList,'TimeStep',1:numSteps);
axis equal
```



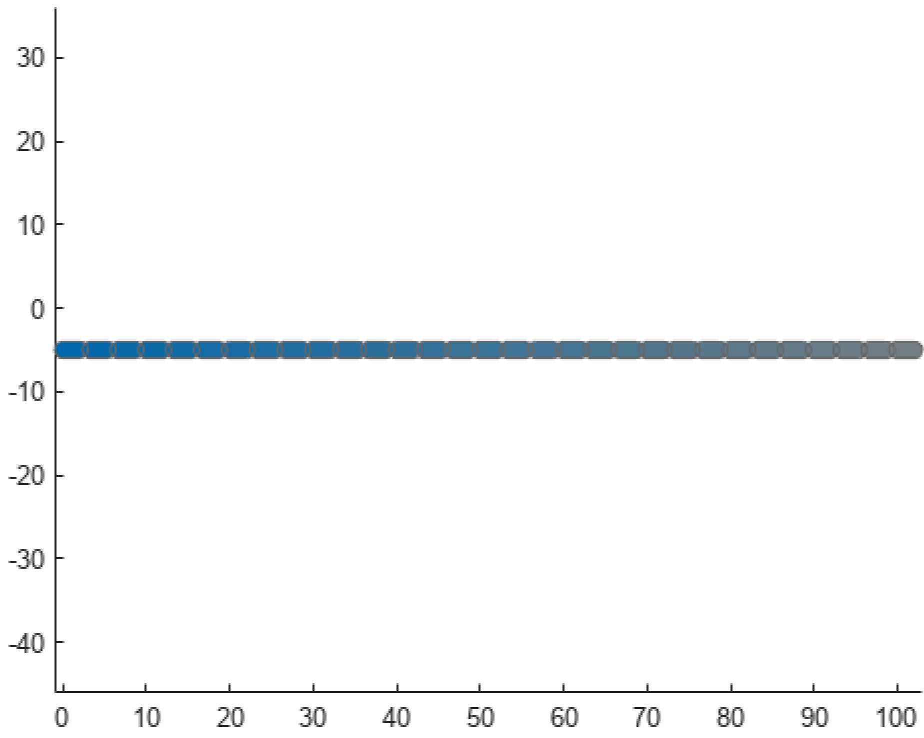

### Remove Ego Body

Remove the first ego body from the capsule list by specifying its ID.

```
removeEgo(capsuleList,1);
```

Visualize the ego bodies again.

```
show(capsuleList,'TimeStep',1:numSteps);
axis equal
```




## Input Arguments

**`capsuleListObj` — Dynamic capsule list**
`dynamicCapsuleList` object | `dynamicCapsuleList3D` object

Dynamic capsule list, specified as a `dynamicCapsuleList` or `dynamicCapsuleList3D` object.

**`selectEgoIDs` — Ego body IDs**
vector of positive integers

Ego body IDs, specified as a vector of positive integers. The function returns the ego IDs and geometry parameters for only the ego bodies specified in this vector.

## Output Arguments

**`egoIDs` — IDs of ego bodies**
vector of positive integers

IDs of ego bodies, returned as a vector of positive integers.

**`geomStruct` — Geometry parameters for ego bodies**
structure | structure array

Geometry parameters for ego bodies, returned as a structure or structure array where each structure contains the fields from the structure in the `Geometry` field of the associated ego body. The fields of

this structure depend on whether you are using a `dynamicCapsuleList` or `dynamicCapsuleList3D` object.

**`status` — Indication of ego body existence**
*N*-element column vector

Indication of ego body existence, returned as a *N*-element column vector of ones, zeros, and negative ones. Each value indicates whether the associated body exists (`1`), updated (`0`), or a duplicate (`-1`). If you specify the same ego body ID more than once in the `selectEgoIDs` argument, then the function marks all instances of that ID after the first as duplicates and ignores them.

# Version History

**Introduced in R2020b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Objects

`dynamicCapsuleList` | `dynamicCapsuleList3D`

### Functions

`addEgo` | `addObstacle` | `checkCollision` | `egoPose` | `obstacleGeometry` | `obstaclePose` | `removeEgo` | `removeObstacle` | `show` | `updateEgoGeometry` | `updateEgoPose` | `updateObstacleGeometry` | `updateObstaclePose`

### Topics

“Highway Trajectory Planning Using Frenet Reference Path”

# egoPose

Poses of ego bodies

## Syntax

```
[egoIDs,poseStruct] = egoPose(capsuleListObj)
[egoIDs,poseStruct] = egoPose(capsuleListObj,selectEgoIDs)
[egoIDs,poseStruct,status] = egoPose(capsuleListObj,selectEgoIDs)
```

## Description

`[egoIDs,poseStruct] = egoPose(capsuleListObj)` returns the ego ID and the states for each ego body in the specified capsule list.

`[egoIDs,poseStruct] = egoPose(capsuleListObj,selectEgoIDs)` specifies which ego bodies to return the ID and states for.

`[egoIDs,poseStruct,status] = egoPose(capsuleListObj,selectEgoIDs)` returns an indicator of whether each ID in `selectEgoIDs` exists.

## Examples

### Create and Modify Capsule-Based Ego Bodies

Add ego bodies to an environment using the `dynamicCapsuleList` object. Modify the properties of the ego bodies. Remove an ego body from the environment. Visualize the states of all objects in the environment at different timestamps.

Create the `dynamicCapsuleList` object. Extract the maximum number of steps to use as the number of time stamps for the object paths.

```
capsuleList = dynamicCapsuleList;
numSteps = capsuleList.MaxNumSteps;
```

#### Add Ego Bodies

Specify the states for the two ego bodies as a linear path from $x = 0$ m to $x = 100$ m. The two ego bodies are separated by 5 m in opposite directions on the $y$-axis.

```
egoState = linspace(0,1,numSteps)'.*[100 0 0];
egoState1 = egoState+[0 5 0];
egoState2 = egoState+[0 -5 0];
```

Generate default poses and geometric structures for the two ego bodies using ego IDs.

```
[egoIDs,egoPoseStruct] = egoPose(capsuleList,[1 2]);
[egoIDs,egoGeomStruct] = egoGeometry(capsuleList,egoIDs);
```

#### Update Ego Bodies

Assign the states to the ego bodies.

```
egoPoseStruct(1).States = egoState1;
egoPoseStruct(2).States = egoState2;
```

Increase the radius of the first ego body to 2 m.

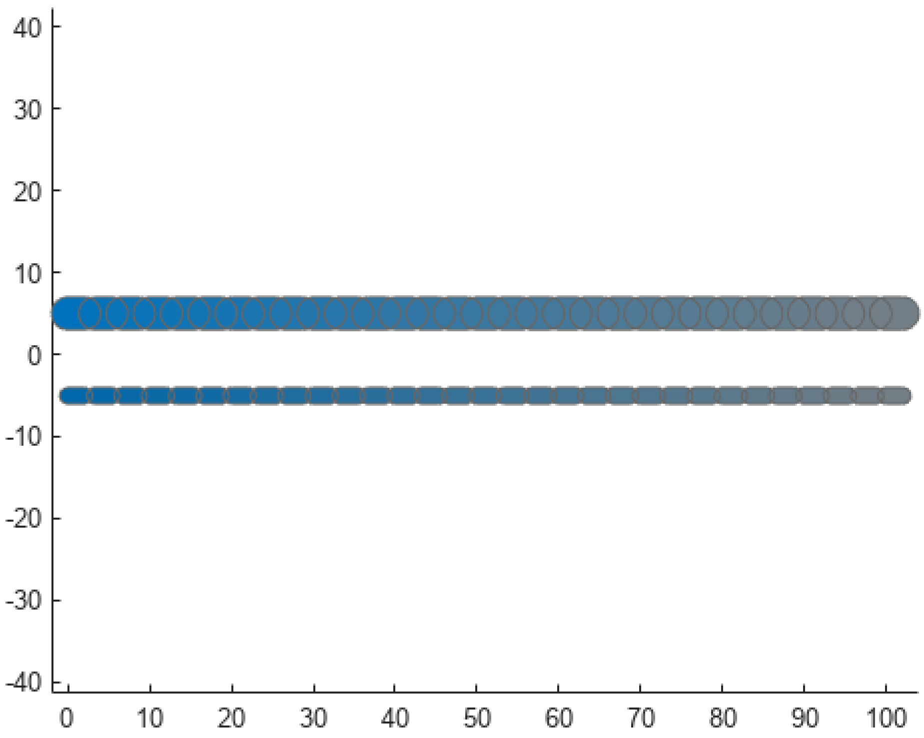
```
egoGeomStruct(1).Geometry.Radius = 2;
```

update the ego bodies using the `updateEgoPose` and `updateEgoGeometry` object functions.

```
updateEgoPose(capsuleList,egoIDs,egoPoseStruct);
updateEgoGeometry(capsuleList,egoIDs,egoGeomStruct);
```

Visualize the ego bodies.

```
show(capsuleList,'TimeStep',1:numSteps);
axis equal
```



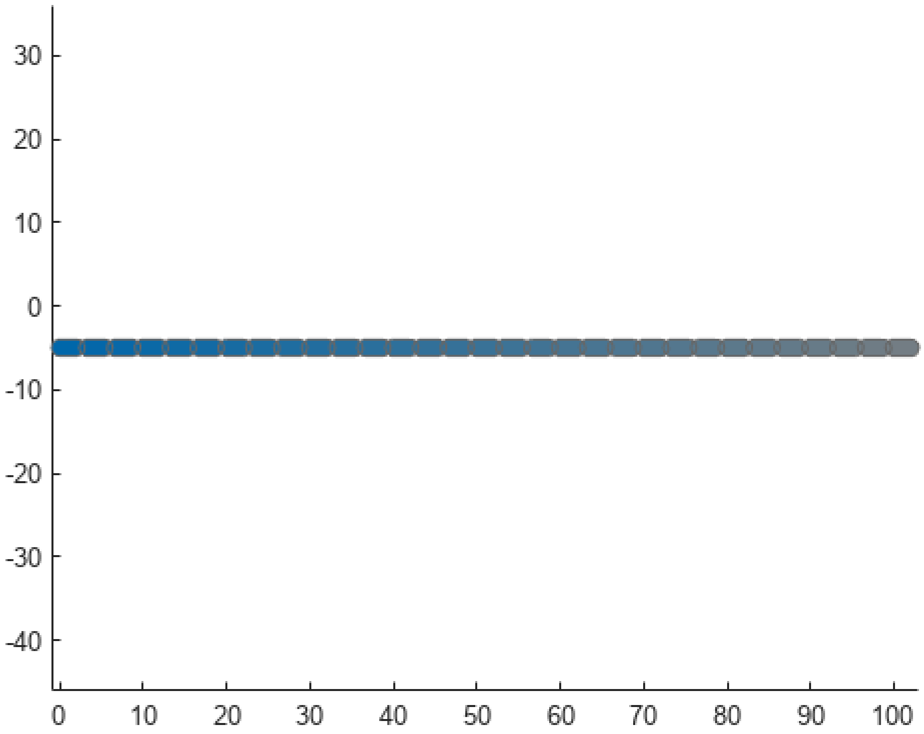

### Remove Ego Body

Remove the first ego body from the capsule list by specifying its ID.

```
removeEgo(capsuleList,1);
```

Visualize the ego bodies again.

```
show(capsuleList,'TimeStep',1:numSteps);
axis equal
```




## Input Arguments

**`capsuleListObj` — Dynamic capsule list**
`dynamicCapsuleList` object | `dynamicCapsuleList3D` object

Dynamic capsule list, specified as a `dynamicCapsuleList` or `dynamicCapsuleList3D` object.

**`selectEgoIDs` — Ego body IDs**
vector of positive integers

Ego body IDs, specified as a vector of positive integers. The function returns the ego IDs and states for only the ego bodies specified in this vector.

## Output Arguments

**`egoIDs` — IDs of ego bodies**
vector of positive integers

IDs of ego bodies, returned as a vector of positive integers.

**`poseStruct` — States for ego bodies**
structure | structure array

States for ego bodies, returned as a structure or structure array. Each structure contains a matrix of states for each ego body. The state matrix size depends on whether you are using a `dynamicCapsuleList` or `dynamicCapsuleList3D` object.

Data Types: `struct`

**`status` — Indication of ego body existence**
*N*-element column vector

Indication of ego body existence, returned as a *N*-element column vector of ones, zeros, and negative ones. Each value indicates whether the associated body exists (`1`), updated (`0`), or a duplicate (`-1`). If you specify the same ego body ID more than once in the `selectEgoIDs` argument, then the function marks all instances of that ID after the first as duplicates and ignores them.

# Version History

**Introduced in R2020b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Objects

`dynamicCapsuleList` | `dynamicCapsuleList3D`

### Functions

`addEgo` | `addObstacle` | `checkCollision` | `egoGeometry` | `obstaclePose` | `removeEgo` | `removeObstacle` | `show` | `updateEgoGeometry` | `updateEgoPose` | `updateObstacleGeometry` | `updateObstaclePose`

### Topics

"Highway Trajectory Planning Using Frenet Reference Path"

# obstacleGeometry

Geometric properties of obstacles

## Syntax

```
[obstacleIDs,geomStruct] = obstacleGeometry(capsuleListObj)
[obstacleIDs,geomStruct] = obstacleGeometry(capsuleListObj,selectObstacleIDs)
[obstacleIDs,geomStruct,status] = obstacleGeometry(capsuleListObj,
selectObstacleIDs)
```

## Description

`[obstacleIDs,geomStruct] = obstacleGeometry(capsuleListObj)` returns the obstacle ID and the geometry parameters for each obstacle in the capsule list.

`[obstacleIDs,geomStruct] = obstacleGeometry(capsuleListObj,selectObstacleIDs)` specifies which obstacle to return the ID and geometry parameters for.

`[obstacleIDs,geomStruct,status] = obstacleGeometry(capsuleListObj, selectObstacleIDs)` returns an indicator of whether each ID in `selectobstacleIDs` exists.

## Examples

### Create and Modify Capsule-Based Obstacles

Add obstacles to an environment using the `dynamicCapsuleList` object. Modify the properties of the obstacles. Remove an obstacle from the environment. Visualize the states of all objects in the environment at different timestamps.

Create the `dynamicCapsuleList` object. Extract the maximum number of steps to use as the number of time stamps for the object paths.

```
capsuleList = dynamicCapsuleList;
numSteps = capsuleList.MaxNumSteps;
```

#### Add Obstacles

Specify the states for the two obstacles as a linear path from $x = 0$ m to $x = 100$ m. The two obstacles are separated by 10 m in opposite directions on the $y$-axis.

```
obsState = linspace(0,1,numSteps)'.*[100 0 0];
obsState1 = obsState+[0 10 0];
obsState2 = obsState+[0 -10 0];
```

Generate default poses and geometric structures for the two obstacles using obstacle IDs.

```
[obsIDs,obsPoseStruct] = obstaclePose(capsuleList,[1 2]);
[obsIDs,obsGeomStruct] = obstacleGeometry(capsuleList,obsIDs);
```

### Update Obstacles

Assign the states to the obstacles.

```
obsPoseStruct(1).States = obsState1;
obsPoseStruct(2).States = obsState2;
```

Increase the radius of the first obstacle to 2 m.

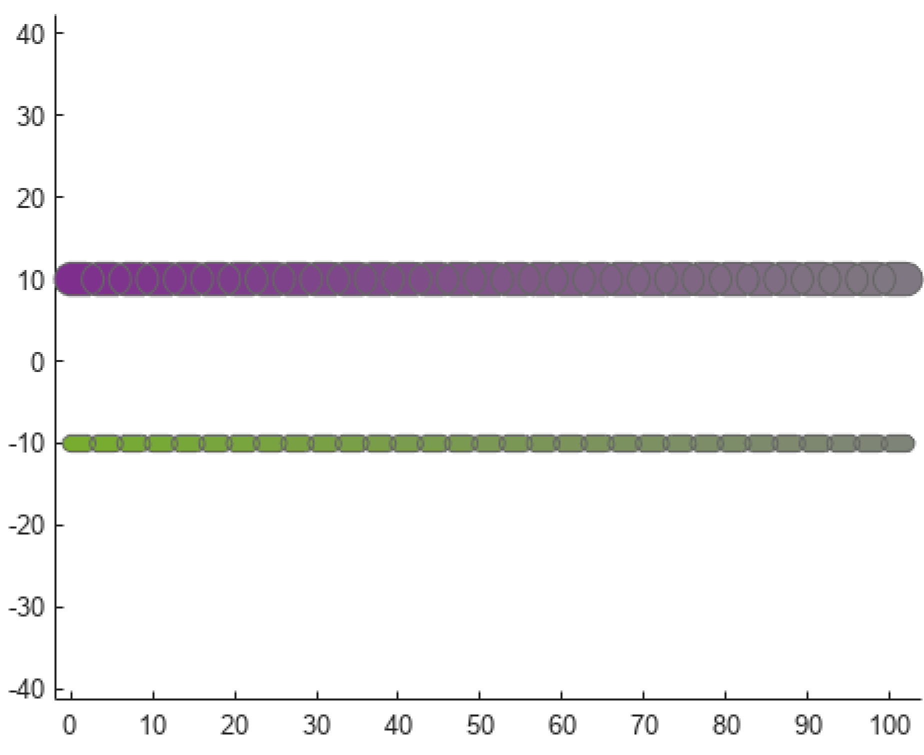
```
obsGeomStruct(1).Geometry.Radius = 2;
```

update the obstacles using the `updateObstaclePose` and `updateObstacleGeometry` object functions.

```
updateObstaclePose(capsuleList,obsIDs,obsPoseStruct);
updateObstacleGeometry(capsuleList,obsIDs,obsGeomStruct);
```

Visualize the obstacles.

```
show(capsuleList,'TimeStep',1:numSteps);
axis equal
```



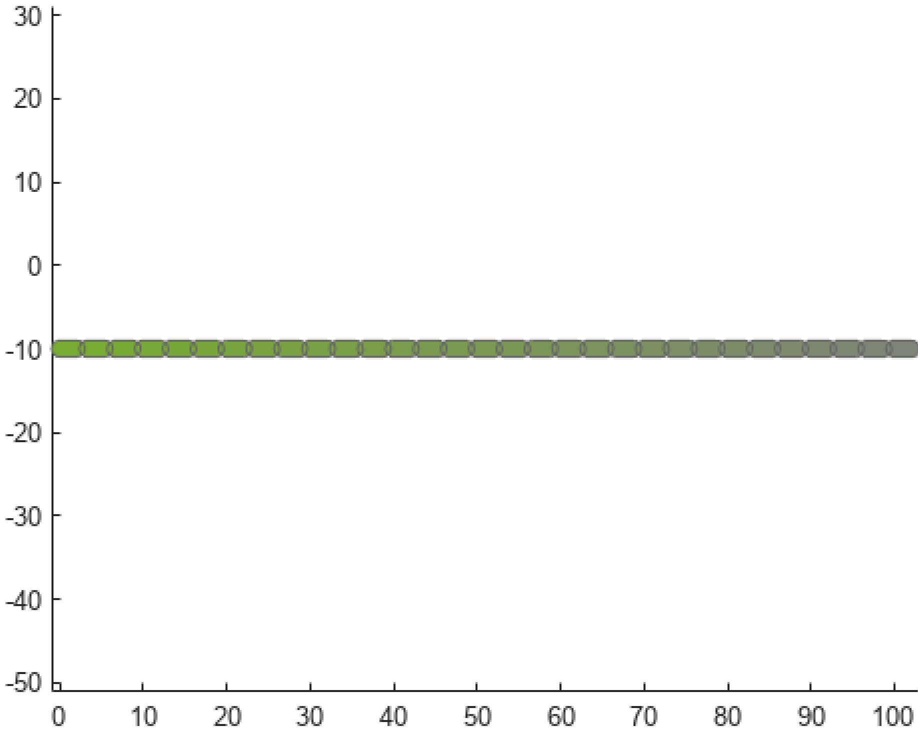

### Remove Obstacles

Remove the first obstacle from the capsule list by specifying its ID.

```
removeObstacle(capsuleList,1);
```

Visualize the obstacles again.

```
show(capsuleList,'TimeStep',1:numSteps);
axis equal
```




## Input Arguments

**capsuleListObj — Dynamic capsule list**
dynamicCapsuleList object | dynamicCapsuleList3D object

Dynamic capsule list, specified as a dynamicCapsuleList or dynamicCapsuleList3D object.

**selectObstacleIDs — Obstacle IDs**
vector of positive integers

Obstacle IDs, specified as a vector of positive integers. The function returns the obstacle IDs and geometry parameters for only the obstacles specified in this vector.

## Output Arguments

**obstacleIDs — IDs of obstacles**
vector of positive integers

IDs of obstacles, returned as a vector of positive integers.

**geomStruct — Geometry parameters for obstacles**
structure | structure array

Geometry parameters for obstacles, returned as a structure or structure array where each structure contains the fields from the structure in the `Geometry` field of the associated obstacle. The fields of this structure depend on whether you are using a `dynamicCapsuleList` or `dynamicCapsuleList3D` object.

**`status` — Indication of obstacle existence**
vector of ones, zeros, and negative ones

Indication of obstacle existence, returned as a *N*-element column vector of ones, zeros, and negative ones. Each value indicates whether the associated obstacle exists (`1`), updated (`0`), or a duplicate (`-1`). If you specify the same ego body ID more than once in the `selectObstacleIDs` argument, then the function marks all instances of that ID after the first as duplicates and ignores them.

# Version History

**Introduced in R2020b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Objects

`dynamicCapsuleList` | `dynamicCapsuleList3D`

### Functions

`addEgo` | `addObstacle` | `checkCollision` | `egoGeometry` | `egoPose` | `obstaclePose` | `removeEgo` | `removeObstacle` | `show` | `updateEgoGeometry` | `updateEgoPose` | `updateObstacleGeometry` | `updateObstaclePose`

### Topics

"Highway Trajectory Planning Using Frenet Reference Path"

# obstaclePose

Poses of obstacles

## Syntax

```
[obstacleIDs,poseStruct] = obstaclePose(capsuleListObj)
[obstacleIDs,poseStruct] = obstaclePose(capsuleListObj,selectObstacleIDs)
[obstacleIDs,poseStruct,status] = obstaclePose(capsuleListObj,
selectObstacleIDs)
```

## Description

`[obstacleIDs,poseStruct] = obstaclePose(capsuleListObj)` returns the obstacle ID and states for each obstacle in the specified capsule list.

`[obstacleIDs,poseStruct] = obstaclePose(capsuleListObj,selectObstacleIDs)` specifies which obstacles to return the ID and states for.

`[obstacleIDs,poseStruct,status] = obstaclePose(capsuleListObj, selectObstacleIDs)` returns an indicator of whether each ID in `selectObstacleIDs` exists.

## Examples

### Create and Modify Capsule-Based Obstacles

Add obstacles to an environment using the `dynamicCapsuleList` object. Modify the properties of the obstacles. Remove an obstacle from the environment. Visualize the states of all objects in the environment at different timestamps.

Create the `dynamicCapsuleList` object. Extract the maximum number of steps to use as the number of time stamps for the object paths.

```
capsuleList = dynamicCapsuleList;
numSteps = capsuleList.MaxNumSteps;
```

#### Add Obstacles

Specify the states for the two obstacles as a linear path from $x$ = 0 m to $x$ = 100 m. The two obstacles are separated by 10 m in opposite directions on the $y$-axis.

```
obsState = linspace(0,1,numSteps)'.*[100 0 0];
obsState1 = obsState+[0 10 0];
obsState2 = obsState+[0 -10 0];
```

Generate default poses and geometric structures for the two obstacles using obstacle IDs.

```
[obsIDs,obsPoseStruct] = obstaclePose(capsuleList,[1 2]);
[obsIDs,obsGeomStruct] = obstacleGeometry(capsuleList,obsIDs);
```

#### Update Obstacles

Assign the states to the obstacles.

```
obsPoseStruct(1).States = obsState1;
obsPoseStruct(2).States = obsState2;
```

Increase the radius of the first obstacle to 2 m.

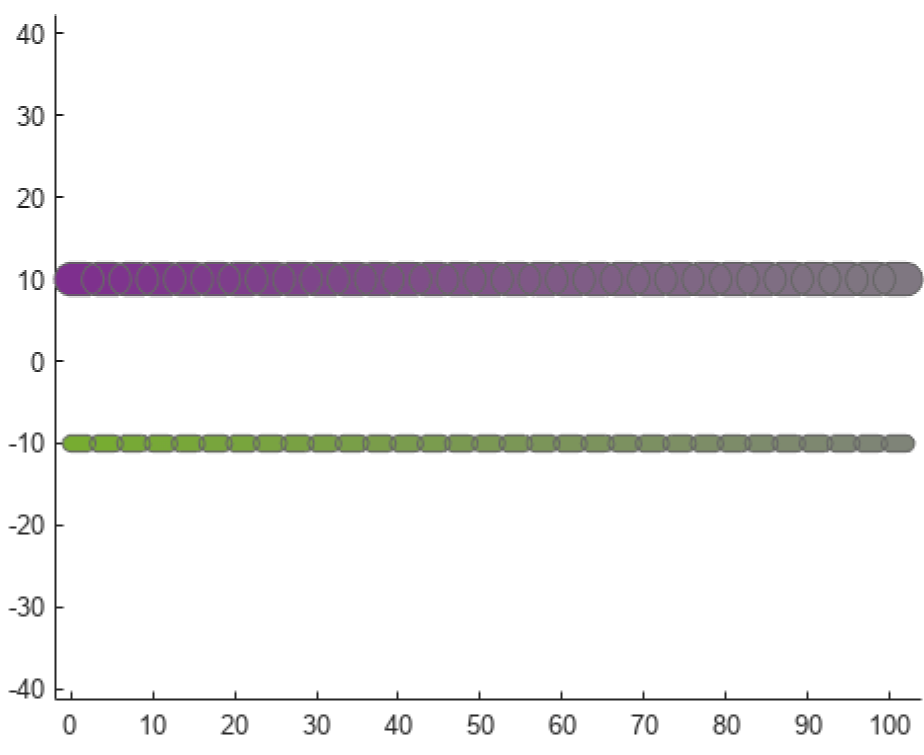
```
obsGeomStruct(1).Geometry.Radius = 2;
```

update the obstacles using the `updateObstaclePose` and `updateObstacleGeometry` object functions.

```
updateObstaclePose(capsuleList,obsIDs,obsPoseStruct);
updateObstacleGeometry(capsuleList,obsIDs,obsGeomStruct);
```

Visualize the obstacles.

```
show(capsuleList,'TimeStep',1:numSteps);
axis equal
```



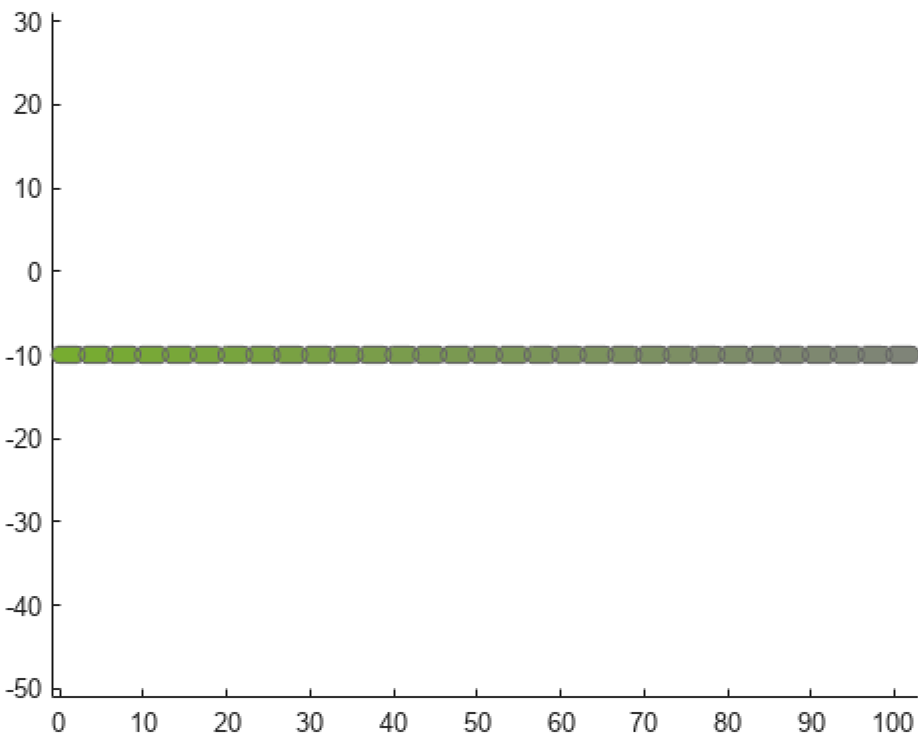

#### Remove Obstacles

Remove the first obstacle from the capsule list by specifying its ID.

```
removeObstacle(capsuleList,1);
```

Visualize the obstacles again.

```
show(capsuleList,'TimeStep',1:numSteps);
axis equal
```




## Input Arguments

**capsuleListObj — Dynamic capsule list**
dynamicCapsuleList object | dynamicCapsuleList3D object

Dynamic capsule list, specified as a `dynamicCapsuleList` or `dynamicCapsuleList3D` object.

**selectObstacleIDs — Obstacle IDs**
vector of positive integers

Obstacle IDs, specified as a vector of positive integers. The function returns the obstacle IDs and states for only the obstacles specified in this vector.

## Output Arguments

**obstacleIDs — IDs of obstacles**
vector of positive integers

IDs of obstacles, specified as a vector of positive integers.

**poseStruct — States for ego bodies**
structure | structure array

States for obstacles, returned as a structure or structure array. Each structure contains a matrix of states for each obstacle. The state matrix size depends on whether you are using a `dynamicCapsuleList` or `dynamicCapsuleList3D` object.

Data Types: `struct`

**`status` — Indication of obstacle existence**
*N*-element column vector

Indication of obstacle existence, returned as a *N*-element column vector of ones, zeros, and negative ones. Each value indicates whether the associated obstacle exists (`1`), updated (`0`), or a duplicate (`-1`). If you specify the same obstacle ID more than once in the `selectObstacleIDs` argument, then the function marks all instances of that ID after the first as duplicates and ignores them.

# Version History

**Introduced in R2020b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Objects

`dynamicCapsuleList` | `dynamicCapsuleList3D`

### Functions

`addEgo` | `addObstacle` | `checkCollision` | `egoGeometry` | `egoPose` | `obstacleGeometry` | `removeEgo` | `removeObstacle` | `show` | `updateEgoGeometry` | `updateEgoPose` | `updateObstacleGeometry` | `updateObstaclePose`

### Topics

"Highway Trajectory Planning Using Frenet Reference Path"

# removeEgo

Remove ego bodies from capsule list

## Syntax

```
removeEgo(capsuleListObj,egoIDs)
status = removeEgo(capsuleListObj,egoIDs)
```

## Description

`removeEgo(capsuleListObj,egoIDs)` removes ego bodies with the specified IDs from the dynamic capsule list.

`status = removeEgo(capsuleListObj,egoIDs)` additionally returns an indicator of whether an ego body is removed, not found, or a duplicate.

## Examples

### Create and Modify Capsule-Based Ego Bodies

Add ego bodies to an environment using the `dynamicCapsuleList` object. Modify the properties of the ego bodies. Remove an ego body from the environment. Visualize the states of all objects in the environment at different timestamps.

Create the `dynamicCapsuleList` object. Extract the maximum number of steps to use as the number of time stamps for the object paths.

```
capsuleList = dynamicCapsuleList;
numSteps = capsuleList.MaxNumSteps;
```

#### Add Ego Bodies

Specify the states for the two ego bodies as a linear path from $x = 0$ m to $x = 100$ m. The two ego bodies are separated by 5 m in opposite directions on the $y$-axis.

```
egoState = linspace(0,1,numSteps)'.*[100 0 0];
egoState1 = egoState+[0 5 0];
egoState2 = egoState+[0 -5 0];
```

Generate default poses and geometric structures for the two ego bodies using ego IDs.

```
[egoIDs,egoPoseStruct] = egoPose(capsuleList,[1 2]);
[egoIDs,egoGeomStruct] = egoGeometry(capsuleList,egoIDs);
```

#### Update Ego Bodies

Assign the states to the ego bodies.

```
egoPoseStruct(1).States = egoState1;
egoPoseStruct(2).States = egoState2;
```

Increase the radius of the first ego body to 2 m.

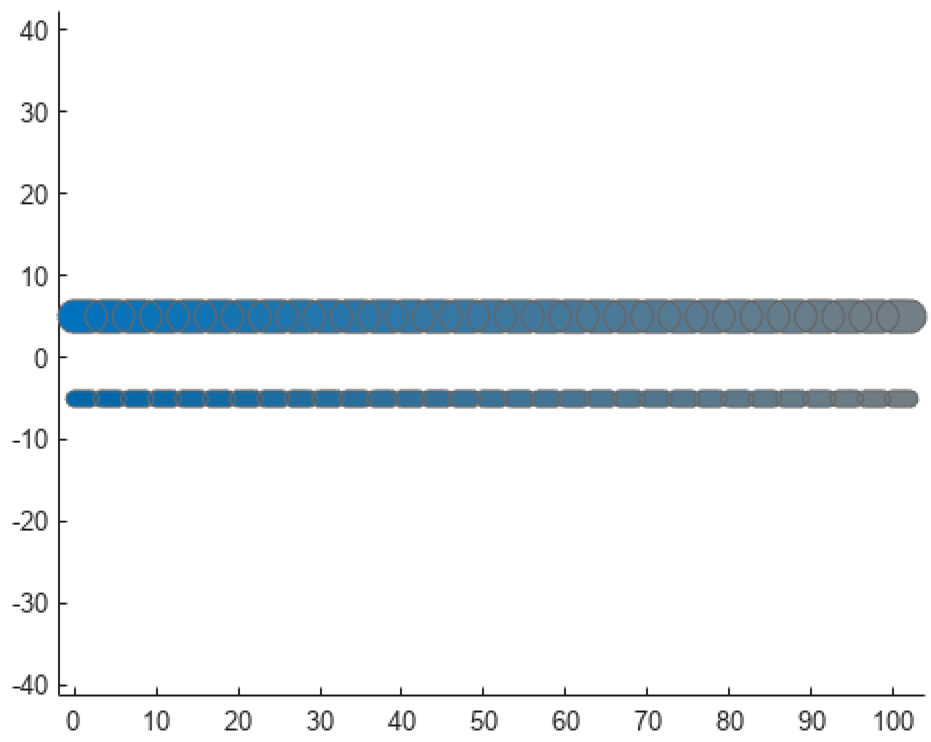
```
egoGeomStruct(1).Geometry.Radius = 2;
```

update the ego bodies using the `updateEgoPose` and `updateEgoGeometry` object functions.

```
updateEgoPose(capsuleList,egoIDs,egoPoseStruct);
updateEgoGeometry(capsuleList,egoIDs,egoGeomStruct);
```

Visualize the ego bodies.

```
show(capsuleList,'TimeStep',1:numSteps);
axis equal
```



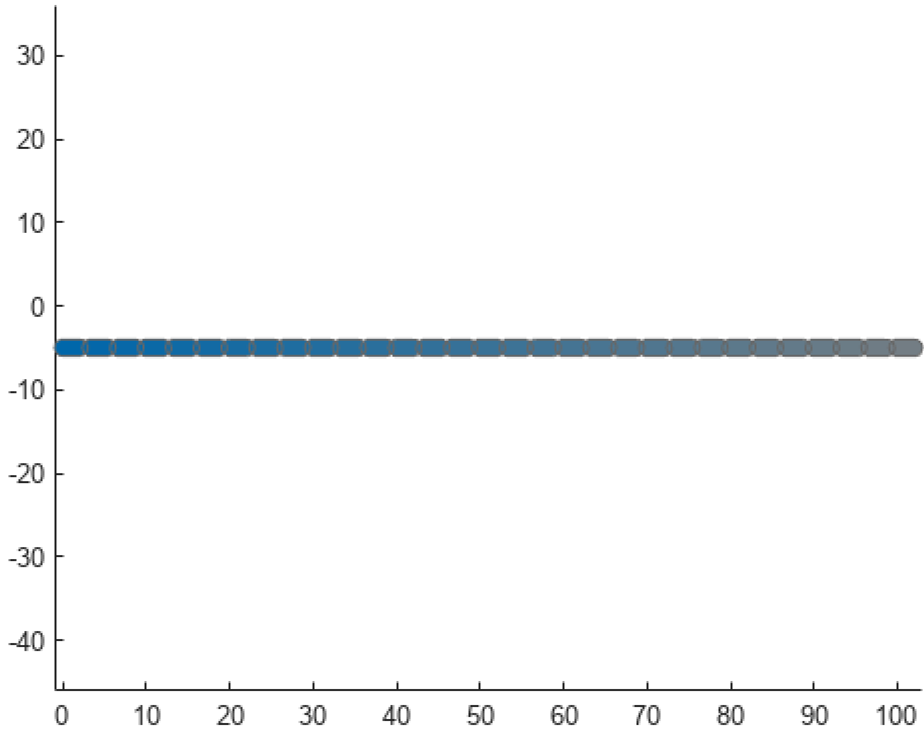

#### Remove Ego Body

Remove the first ego body from the capsule list by specifying its ID.

```
removeEgo(capsuleList,1);
```

Visualize the ego bodies again.

```
show(capsuleList,'TimeStep',1:numSteps);
axis equal
```




## Input Arguments

**`capsuleListObj` — Dynamic capsule list**
`dynamicCapsuleList` object | `dynamicCapsuleList3D` object

Dynamic capsule list, specified as a `dynamicCapsuleList` or `dynamicCapsuleList3D` object.

**`egoIDs` — IDs of ego bodies**
vector of positive integers

IDs of ego bodies to remove, specified as a vector of positive integers.

## Output Arguments

**`status` — Result of removing ego bodies**
*N*-element column vector

Result of removing ego bodies, specified as *N*-element column vector of ones, zeros, and negative ones. *N* is the number of ego bodies specified in the `egoIDs` argument. Each value indicates whether the body is removed (`1`), not found (`0`), or a duplicate (`-1`). If you specify the same ego ID multiple times in the `egoIDs` input argument, then all entries besides the last are marked as a duplicate.

# Version History

**Introduced in R2020b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Objects

`dynamicCapsuleList` | `dynamicCapsuleList3D`

### Functions

`addEgo` | `addObstacle` | `checkCollision` | `egoGeometry` | `egoPose` | `obstacleGeometry` | `obstaclePose` | `removeObstacle` | `show` | `updateEgoGeometry` | `updateEgoPose` | `updateObstacleGeometry` | `updateObstaclePose`

### Topics

"Highway Trajectory Planning Using Frenet Reference Path"

# removeObstacle

Remove obstacles from capsule list

## Syntax

```
removeObstacle(capsuleListObj,obstacleIDs)
status = removeObstacle(capsuleListObj,obstacleIDs)
```

## Description

`removeObstacle(capsuleListObj,obstacleIDs)` removes obstacles with the specified IDs from the dynamic capsule list.

`status = removeObstacle(capsuleListObj,obstacleIDs)` additionally returns an indicator of whether an obstacles is removed, not found, or a duplicate.

## Examples

### Create and Modify Capsule-Based Obstacles

Add obstacles to an environment using the `dynamicCapsuleList` object. Modify the properties of the obstacles. Remove an obstacle from the environment. Visualize the states of all objects in the environment at different timestamps.

Create the `dynamicCapsuleList` object. Extract the maximum number of steps to use as the number of time stamps for the object paths.

```
capsuleList = dynamicCapsuleList;
numSteps = capsuleList.MaxNumSteps;
```

### Add Obstacles

Specify the states for the two obstacles as a linear path from $x = 0$ m to $x = 100$ m. The two obstacles are separated by 10 m in opposite directions on the $y$-axis.

```
obsState = linspace(0,1,numSteps)'.*[100 0 0];
obsState1 = obsState+[0 10 0];
obsState2 = obsState+[0 -10 0];
```

Generate default poses and geometric structures for the two obstacles using obstacle IDs.

```
[obsIDs,obsPoseStruct] = obstaclePose(capsuleList,[1 2]);
[obsIDs,obsGeomStruct] = obstacleGeometry(capsuleList,obsIDs);
```

### Update Obstacles

Assign the states to the obstacles.

```
obsPoseStruct(1).States = obsState1;
obsPoseStruct(2).States = obsState2;
```

Increase the radius of the first obstacle to 2 m.

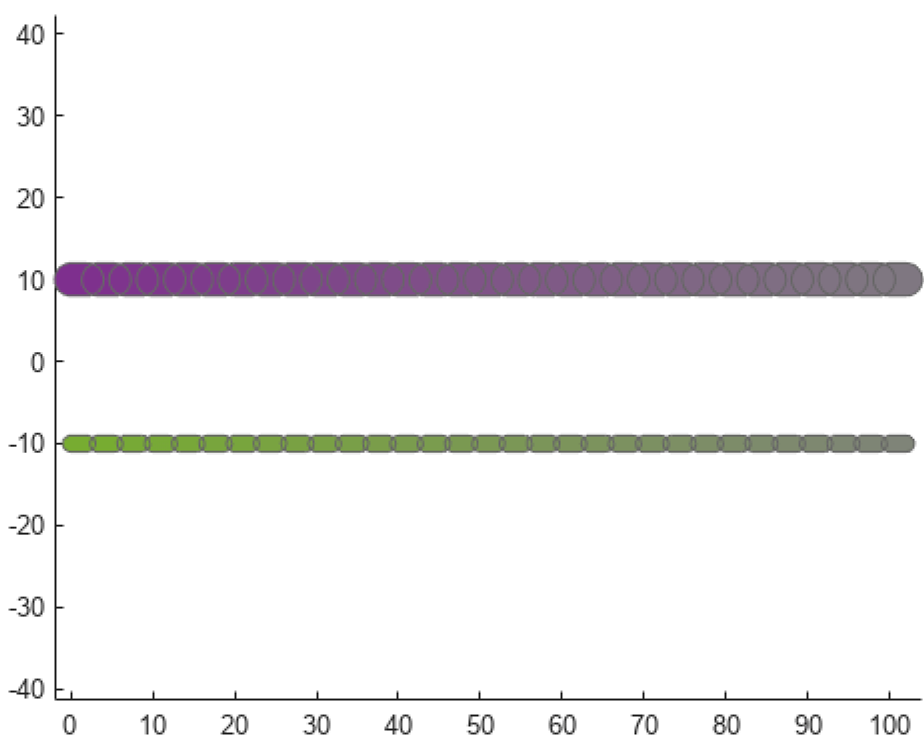
```
obsGeomStruct(1).Geometry.Radius = 2;
```

update the obstacles using the `updateObstaclePose` and `updateObstacleGeometry` object functions.

```
updateObstaclePose(capsuleList,obsIDs,obsPoseStruct);
updateObstacleGeometry(capsuleList,obsIDs,obsGeomStruct);
```

Visualize the obstacles.

```
show(capsuleList,'TimeStep',1:numSteps);
axis equal
```



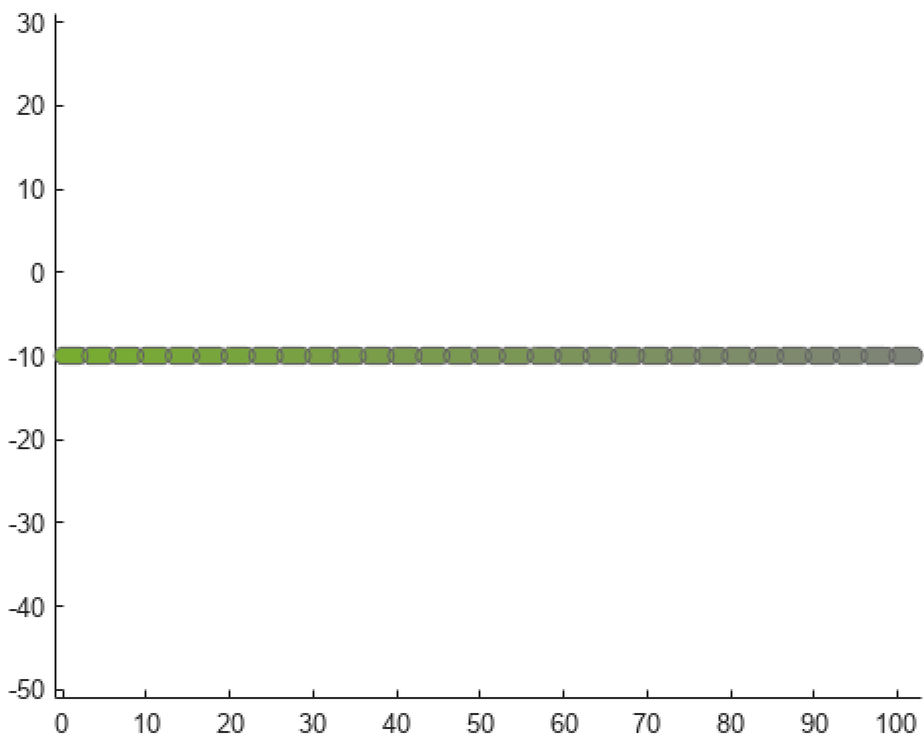

#### Remove Obstacles

Remove the first obstacle from the capsule list by specifying its ID.

```
removeObstacle(capsuleList,1);
```

Visualize the obstacles again.

```
show(capsuleList,'TimeStep',1:numSteps);
axis equal
```




## Input Arguments

**`capsuleListObj` — Dynamic capsule list**
`dynamicCapsuleList` object | `dynamicCapsuleList3D` object

Dynamic capsule list, specified as a `dynamicCapsuleList` or `dynamicCapsuleList3D` object.

**`obstacleIDs` — IDs of obstacles**
vector of positive integers

IDs of obstacles to remove, specified as a vector of positive integers.

## Output Arguments

**`status` — Result of removing obstacles**
*N*-element column vector

Result of removing obstacles, specified as *N*-element column vector of ones, zeros, and negative ones. *N* is the number of obstacles specified in the `obstacleIDs` argument. Each value indicates whether the obstacle is removed (`1`), not found (`0`), or a duplicate (`-1`). If you specify the same obstacle ID multiple times in the `obstacleIDs` input argument, then all entries besides the last are marked as a duplicate.

## Version History

**Introduced in R2020b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Objects

`dynamicCapsuleList` | `dynamicCapsuleList3D`

### Functions

`addEgo` | `addObstacle` | `checkCollision` | `egoGeometry` | `egoPose` | `obstacleGeometry` | `obstaclePose` | `removeEgo` | `show` | `updateEgoGeometry` | `updateEgoPose` | `updateObstacleGeometry` | `updateObstaclePose`

### Topics

"Highway Trajectory Planning Using Frenet Reference Path"

# show

Display ego bodies and obstacles in environment

## Syntax

```
ax = show(capsuleListObj)
ax = show(capsuleListObj,Name,Value)
```

## Description

`ax = show(capsuleListObj)` displays the initial state of all ego bodies and obstacles in the specified capsule list, and returns the axes handle of the plot.

`ax = show(capsuleListObj,Name,Value)` specifies options using name-value pair arguments on page 2-290. For example, `'FastUpdate',true` enables fast updates to an existing plot.

## Examples

### Build Ego Body Paths and Check for Collisions with Obstacles

Build an ego body path and maintain obstacle states using the `dynamicCapsuleList` object. Visualize the states of all objects in the environment at different timestamps. Validate the path of the ego body by checking for collisions with obstacles in the environment.

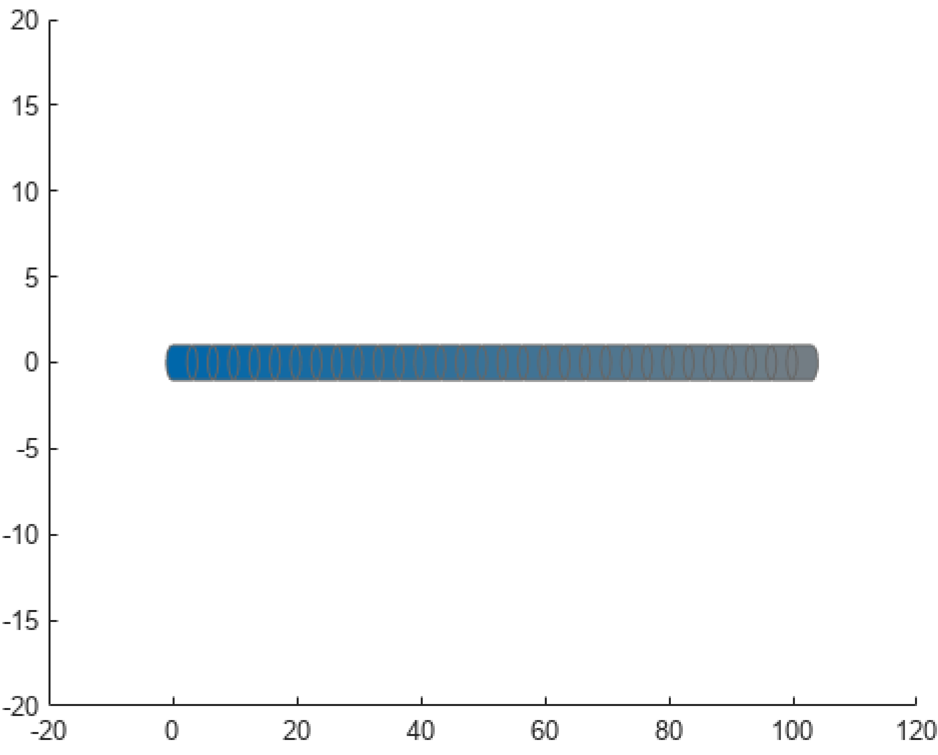
Create the `dynamicCapsuleList` object. Extract the maximum number of steps to use as the number of time stamps for your object paths.

```
obsList = dynamicCapsuleList;
numSteps = obsList.MaxNumSteps;
```

**Add Ego Body**

Define an ego body by specifying the ID, geometry, and state together in a structure. The capsule geometry has a length of 3 m and radius of 1 m. Specify the state as a linear path from $x$ = 0m to $x$ = 100m.

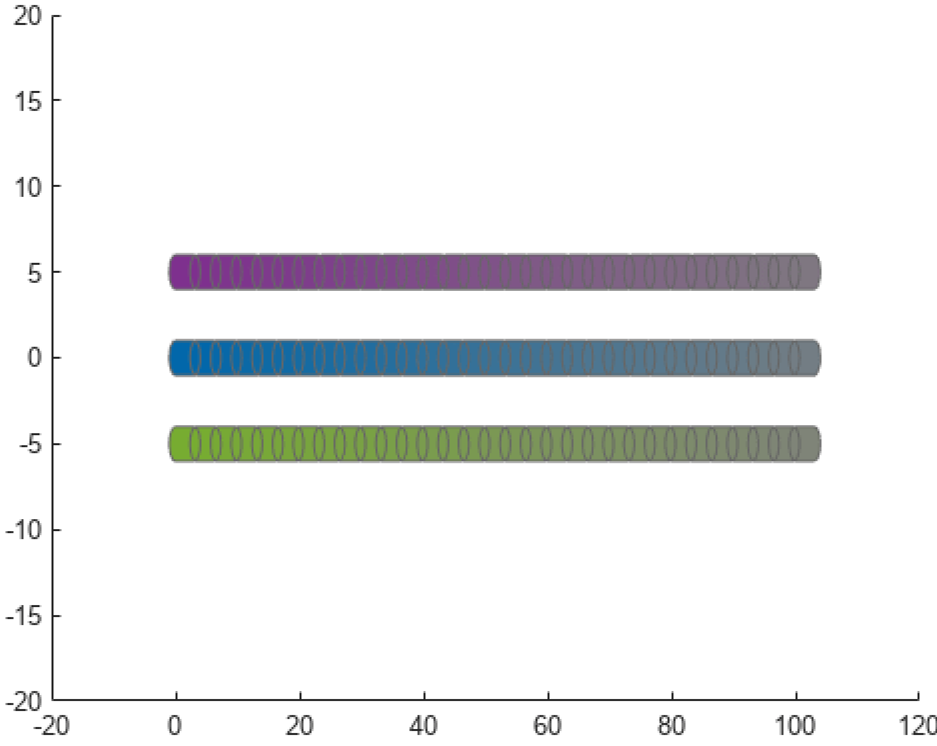
```
egoID1 = 1;
geom = struct("Length",3,"Radius",1,"FixedTransform",eye(3));
states = linspace(0,1,obsList.MaxNumSteps)'.*[100 0 0];

egoCapsule1 = struct('ID',egoID1,'States',states,'Geometry',geom);
addEgo(obsList,egoCapsule1);

show(obsList,"TimeStep",[1:numSteps]);
ylim([-20 20])
```




#### Add Obstacles

Specify states for two obstacles that are separated from the ego body by 5 m in opposite directions on the *y*-axis.. Assume the obstacles have the same geometry `geom` as the ego body.

```
obsState1 = states + [0 5 0];
obsState2 = states + [0 -5 0];

obsCapsule1 = struct('ID',1,'States',obsState1,'Geometry',geom);
obsCapsule2 = struct('ID',2,'States',obsState2,'Geometry',geom);

addObstacle(obsList,obsCapsule1);
addObstacle(obsList,obsCapsule2);

show(obsList,"TimeStep",[1:numSteps]);
ylim([-20 20])
```




### Update Obstacles

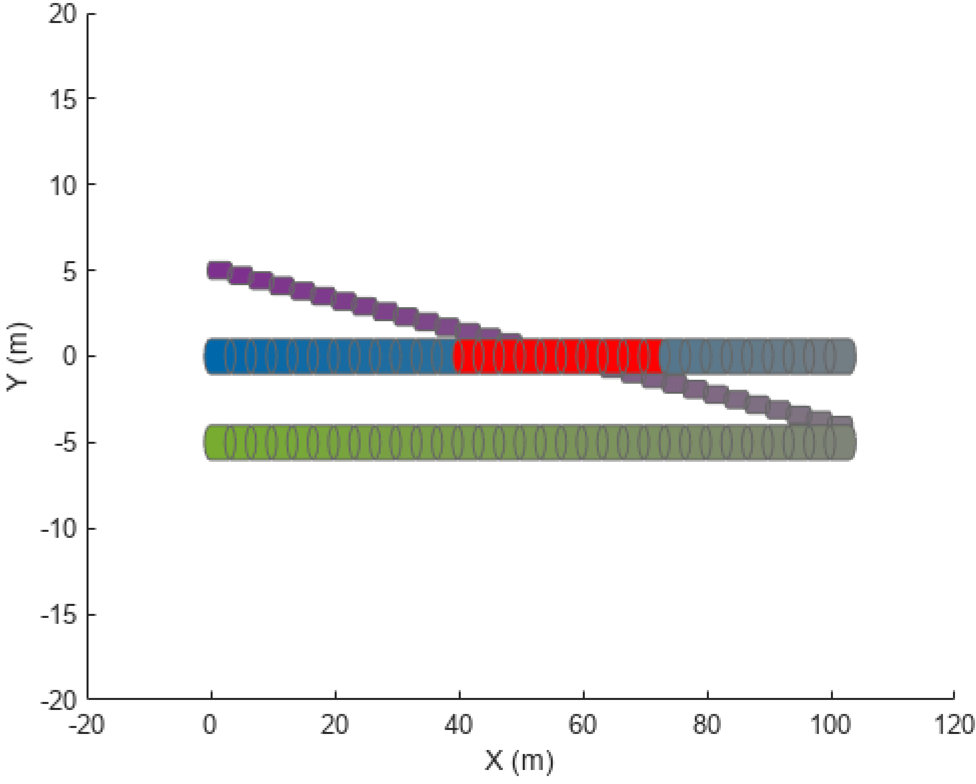
Alter your obstacle locations and geometry dimensions over time. Use the previously generated structure, modify the fields, and update the obstacles using the `updateObstacleGeometry` and `updateObstaclePose` object functions. Reduces the radius of the first obstacle to 0.5 m, and change the path to move it towards the ego body.

```
obsCapsule1.Geometry.Radius = 0.5;

obsCapsule1.States = ...
    [linspace(0,100,numSteps)' ... % x
     linspace(5,-4,numSteps)' ... % y
     zeros(numSteps,1)]; % theta

updateObstacleGeometry(obsList,1,obsCapsule1);
updateObstaclePose(obsList,1,obsCapsule1);
```

### Check for Collisions

Visualize the new paths. Show where collisions between the ego body and an obstacle, which the display highlights in red. Notice that collisions between the obstacles are not checked.

```
show(obsList,"TimeStep",[1:numSteps],"ShowCollisions",1);
ylim([-20 20])
xlabel("X (m)")
ylabel("Y (m)")
```




Programmatically check for collisions by using the `checkCollision` object function. The function returns a vector of logical values that indicates the status of each time step. The vector is transposed for display purposes.

```
collisions = checkCollision(obsList)'
```

```
collisions = 1x31 logical array

   0   0   0   0   0   0   0   0   0   0   0   0   1   1   1   1   1   1   1   1   1   1   0   0
```

To validate paths with a large number of steps, use the `any` function on the vector of collision values.

```
if any(collisions)
    disp("Collision detected.")
end
```

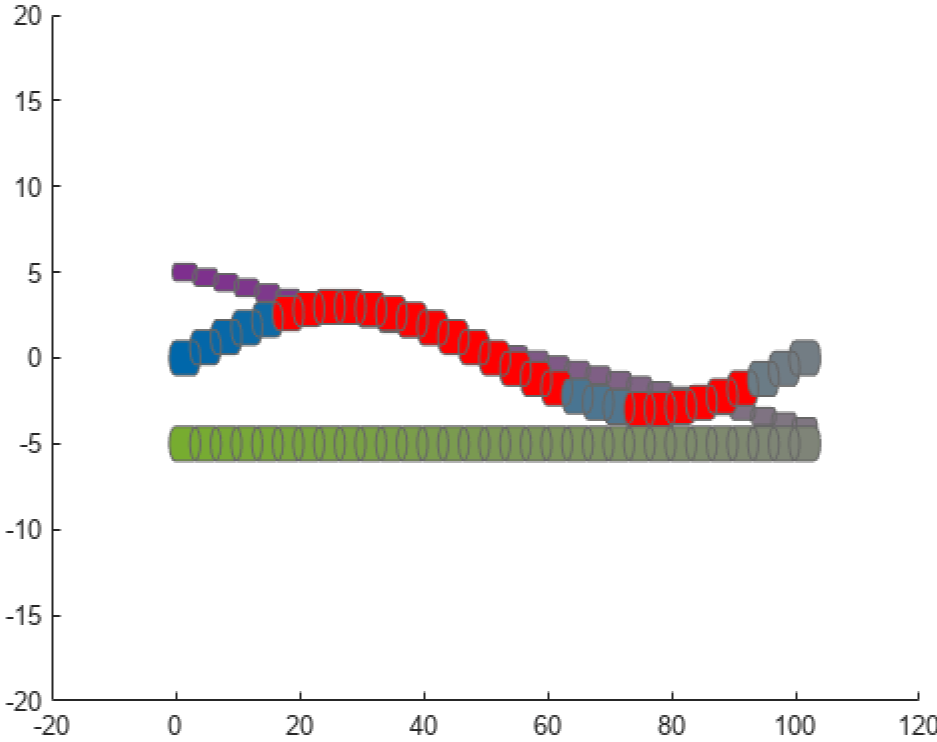
```
Collision detected.
```

### Update Ego Path

Specify a new path for the ego body. Visualize the paths again, displaying collisions.

```
egoCapsule1.States = ...
    [linspace(0,100,numSteps)' ... % x
    3*sin(linspace(0,2*pi,numSteps))' ... % y
    zeros(numSteps,1)]; % theta
```

```
updateEgoPose(obsList,1,egoCapsule1);

show(obsList,"TimeStep",[1:numSteps],"ShowCollisions",1);
ylim([-20 20])
```




## Input Arguments

**capsuleListObj — Dynamic capsule list**
dynamicCapsuleList object | dynamicCapsuleList3D object

Dynamic capsule list, specified as a dynamicCapsuleList or dynamicCapsuleList3D object.

### Name-Value Pair Arguments

Specify optional pairs of arguments as Name1=Value1,...,NameN=ValueN, where Name is the argument name and Value is the corresponding value. Name-value arguments must appear after other arguments, but the order of the pairs does not matter.

*Before R2021a, use commas to separate each name and value, and enclose* Name *in quotes.*

Example: 'FastUpdate',true enables the option for fast updates in an existing plot.

**Parent — Parent axes to plot on**
gca (default) | Axes handle

Parent axes to plot on, specified as the comma-separated pair consisting of 'Parent' and an Axes handle.

**`FastUpdate` — Perform fast update to existing plot**
`false` or `0` (default) | `true` or `1`

Perform a fast update to an existing plot, specified as the comma-separated pair consisting of `'FastUpdate'` and a logical `0` (`false`) or `1` (`true`). You must use the `show` object function to initially display your capsule list before you can specify it with this argument.

Data Types: `logical`

**`TimeStep` — Time steps to display**
`1` (default) | numeric vector

Time steps to display, specified as the comma-separated pair consisting of `'TimeStep'` and numeric vector of values in the range [1, *N*], where *N* is the value of the `MaxNumSteps` property of the object specified in the `capsuleListObj` argument. Each time step corresponds to a row of the state matrix for each ego body and obstacle.

**`ShowCollisions` — Check for and highlight collisions in display**
`false` or `0` (default) | `true` or `1`

Check for and highlight collisions in the display, specified as the comma-separated pair consisting of `'ShowCollisions'` and a logical `0` (`false`) or `1` (`true`).

Data Types: `logical`

**`EgoIDs` — Ego IDs to display**
vector of positive integers

Ego IDs to display, specified as the comma-separated pair consisting of `'EgoIDs'` and a vector of positive integers. By default, the object function displays all ego bodies.

**`ObstacleIDs` — Obstacle IDs to display**
vector of positive integers

Obstacle IDs to display, specified as the comma-separated pair consisting of `'ObstacleIDs'` and a vector of positive integers. By default, the function displays all obstacles.

## Output Arguments

**ax — Parent axes of dynamic capsule list plot**
`Axes` handle

Parent axes of the dynamic capsule list plot, returned as anAxes handle.

# Version History

**Introduced in R2020b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
dynamicCapsuleList | dynamicCapsuleList3D

**Functions**
addEgo | addObstacle | checkCollision | egoGeometry | egoPose | obstacleGeometry | obstaclePose | removeEgo | removeObstacle | updateEgoGeometry | updateEgoPose | updateObstacleGeometry | updateObstaclePose

**Topics**
"Highway Trajectory Planning Using Frenet Reference Path"

# updateEgoGeometry

Update geometric properties of ego bodies

## Syntax

```
updateEgoGeometry(capsuleListObj,egoIDs,geomStruct)
status = updateEgoGeometry(capsuleListObj,egoIDs,geomStruct)
```

## Description

`updateEgoGeometry(capsuleListObj,egoIDs,geomStruct)` updates geometry parameters for the specified ego bodies in the capsule list. If a specified ego ID does not already exist, the function adds a new ego body with that ID to the list.

`status = updateEgoGeometry(capsuleListObj,egoIDs,geomStruct)` additionally returns an indicator of whether an ego body is added, updated, or a duplicate.

## Examples

### Create and Modify Capsule-Based Ego Bodies

Add ego bodies to an environment using the `dynamicCapsuleList` object. Modify the properties of the ego bodies. Remove an ego body from the environment. Visualize the states of all objects in the environment at different timestamps.

Create the `dynamicCapsuleList` object. Extract the maximum number of steps to use as the number of time stamps for the object paths.

```
capsuleList = dynamicCapsuleList;
numSteps = capsuleList.MaxNumSteps;
```

#### Add Ego Bodies

Specify the states for the two ego bodies as a linear path from $x = 0$ m to $x = 100$ m. The two ego bodies are separated by 5 m in opposite directions on the *y*-axis.

```
egoState = linspace(0,1,numSteps)'.*[100 0 0];
egoState1 = egoState+[0 5 0];
egoState2 = egoState+[0 -5 0];
```

Generate default poses and geometric structures for the two ego bodies using ego IDs.

```
[egoIDs,egoPoseStruct] = egoPose(capsuleList,[1 2]);
[egoIDs,egoGeomStruct] = egoGeometry(capsuleList,egoIDs);
```

#### Update Ego Bodies

Assign the states to the ego bodies.

```
egoPoseStruct(1).States = egoState1;
egoPoseStruct(2).States = egoState2;
```

Increase the radius of the first ego body to 2 m.

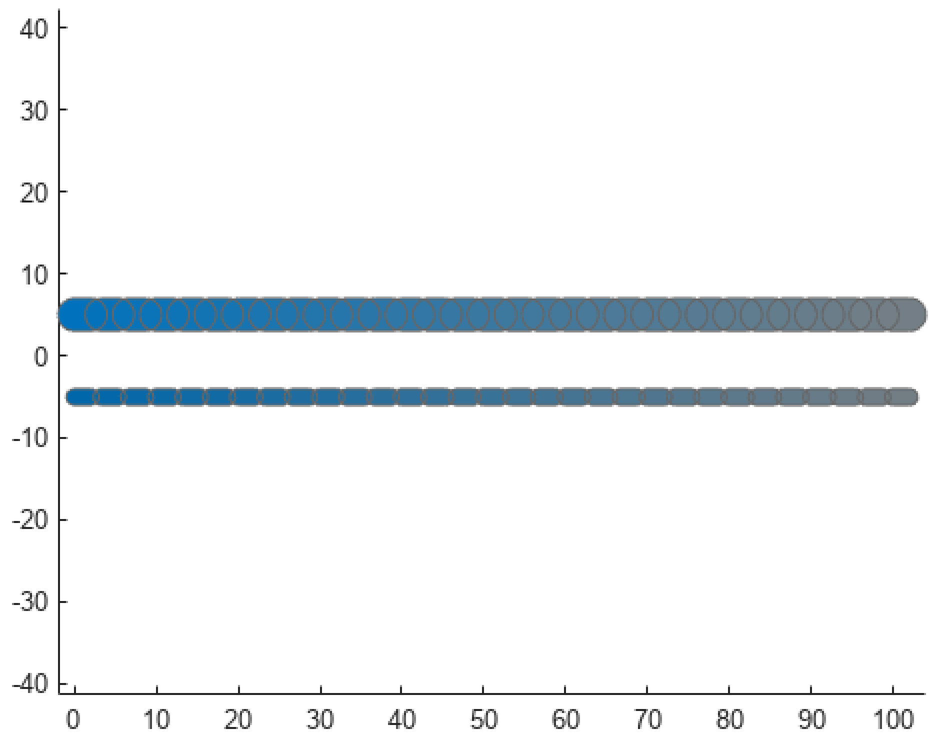
```
egoGeomStruct(1).Geometry.Radius = 2;
```

update the ego bodies using the `updateEgoPose` and `updateEgoGeometry` object functions.

```
updateEgoPose(capsuleList,egoIDs,egoPoseStruct);
updateEgoGeometry(capsuleList,egoIDs,egoGeomStruct);
```

Visualize the ego bodies.

```
show(capsuleList,'TimeStep',1:numSteps);
axis equal
```



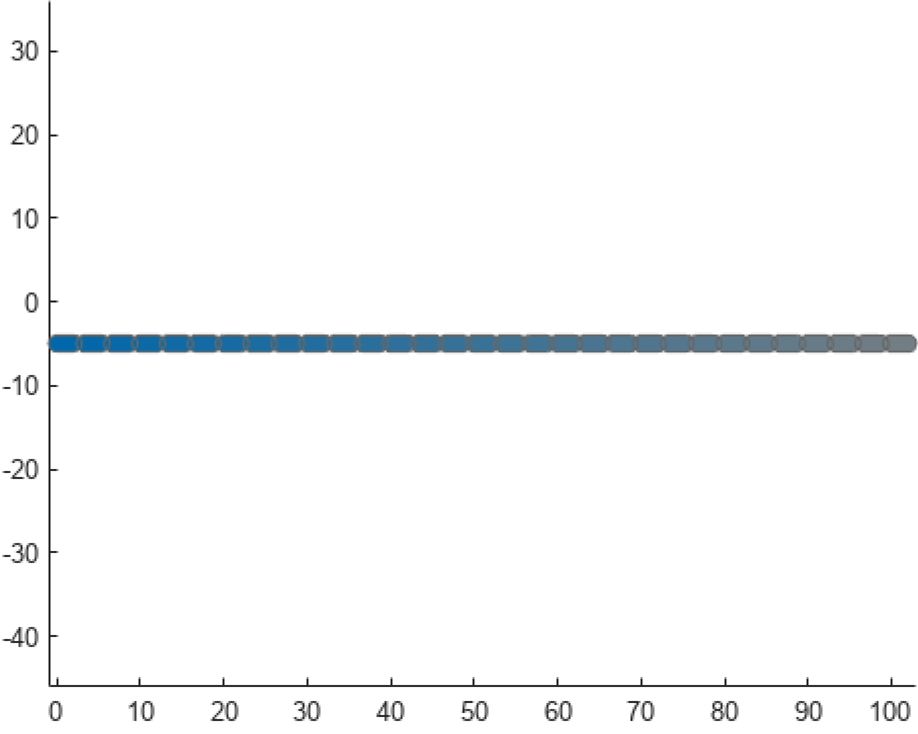

#### Remove Ego Body

Remove the first ego body from the capsule list by specifying its ID.

```
removeEgo(capsuleList,1);
```

Visualize the ego bodies again.

```
show(capsuleList,'TimeStep',1:numSteps);
axis equal
```




## Input Arguments

**`capsuleListObj` — Dynamic capsule list**
`dynamicCapsuleList` object | `dynamicCapsuleList3D` object

Dynamic capsule list, specified as a `dynamicCapsuleList` or `dynamicCapsuleList3D` object.

**`egoIDs` — IDs of ego bodies to update**
vector of positive integers

IDs of ego bodies to update, specified as a vector of positive integers.

**`geomStruct` — Geometry parameters for ego bodies**
structure | structure array

Geometry parameters for ego bodies, specified as a structure or structure array, where each structure contains the fields of the structure in the `Geometry` field of the ego body to be updated. The fields of this structure depend on whether you are using a `dynamicCapsuleList` or `dynamicCapsuleList3D` object.

Data Types: `struct`

## Output Arguments

**`status` — Result of updating ego bodies**
*N*-element column vector

Result of updating ego bodies, specified as *N*-element column vector of ones, zeros, and negative ones. *N* is the number of ego bodies specified in the `egoIDs` argument. Each value indicates whether the body is removed (`1`), not found (`0`), or a duplicate (`-1`). If you specify the same ego ID multiple times in the `egoIDs` input argument, then all entries besides the last are marked as a duplicate.

# Version History

**Introduced in R2020b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Objects

`dynamicCapsuleList` | `dynamicCapsuleList3D`

### Functions

`addEgo` | `addObstacle` | `checkCollision` | `egoGeometry` | `egoPose` | `obstacleGeometry` | `obstaclePose` | `removeEgo` | `removeObstacle` | `show` | `updateEgoPose` | `updateObstacleGeometry` | `updateObstaclePose`

### Topics

"Highway Trajectory Planning Using Frenet Reference Path"

# updateEgoPose

Update states of ego bodies

## Syntax

```
updateEgoPose(capsuleListObj,egoIDs,poseStruct)
status = updateEgoPose(capsuleListObj,egoIDs,poseStruct)
```

## Description

`updateEgoPose(capsuleListObj,egoIDs,poseStruct)` updates the states of the specified ego bodies in the capsule list. If a specified ego ID does not already exist, the function adds a new ego body with that ID to the list.

`status = updateEgoPose(capsuleListObj,egoIDs,poseStruct)` returns an indicator of whether an ego body is added, updated, or a duplicate.

## Examples

### Build Ego Body Paths and Check for Collisions with Obstacles

Build an ego body path and maintain obstacle states using the `dynamicCapsuleList` object. Visualize the states of all objects in the environment at different timestamps. Validate the path of the ego body by checking for collisions with obstacles in the environment.

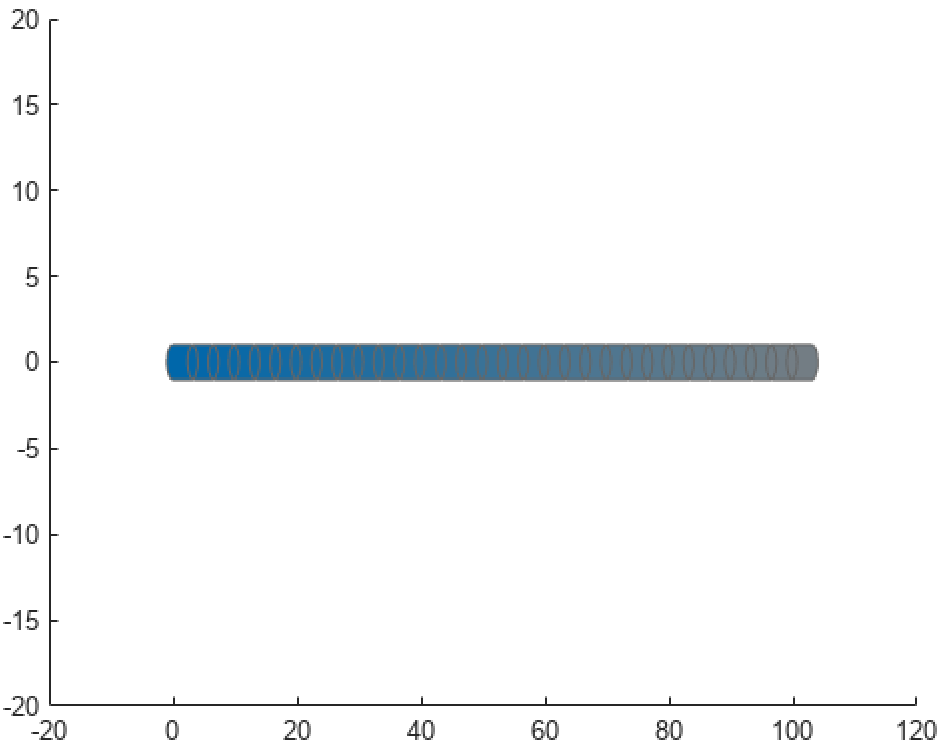
Create the `dynamicCapsuleList` object. Extract the maximum number of steps to use as the number of time stamps for your object paths.

```
obsList = dynamicCapsuleList;
numSteps = obsList.MaxNumSteps;
```

#### Add Ego Body

Define an ego body by specifying the ID, geometry, and state together in a structure. The capsule geometry has a length of 3 m and radius of 1 m. Specify the state as a linear path from $x$ = 0m to $x$ = 100m.

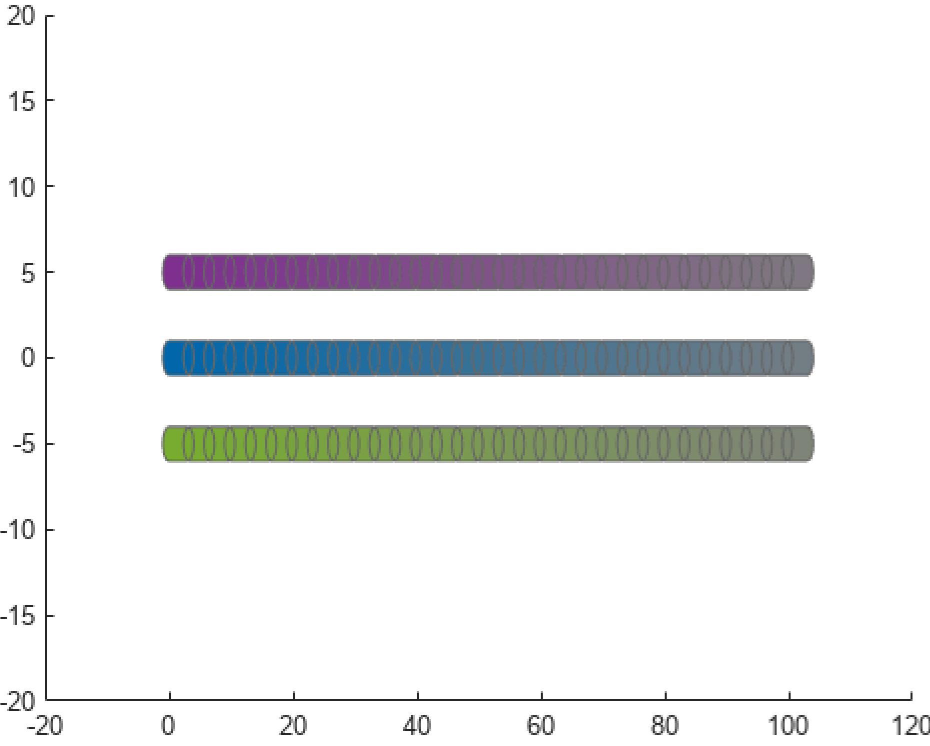
```
egoID1 = 1;
geom = struct("Length",3,"Radius",1,"FixedTransform",eye(3));
states = linspace(0,1,obsList.MaxNumSteps)'.*[100 0 0];

egoCapsule1 = struct('ID',egoID1,'States',states,'Geometry',geom);
addEgo(obsList,egoCapsule1);

show(obsList,"TimeStep",[1:numSteps]);
ylim([-20 20])
```




#### Add Obstacles

Specify states for two obstacles that are separated from the ego body by 5 m in opposite directions on the *y*-axis.. Assume the obstacles have the same geometry `geom` as the ego body.

```
obsState1 = states + [0 5 0];
obsState2 = states + [0 -5 0];

obsCapsule1 = struct('ID',1,'States',obsState1,'Geometry',geom);
obsCapsule2 = struct('ID',2,'States',obsState2,'Geometry',geom);

addObstacle(obsList,obsCapsule1);
addObstacle(obsList,obsCapsule2);

show(obsList,"TimeStep",[1:numSteps]);
ylim([-20 20])
```




### Update Obstacles

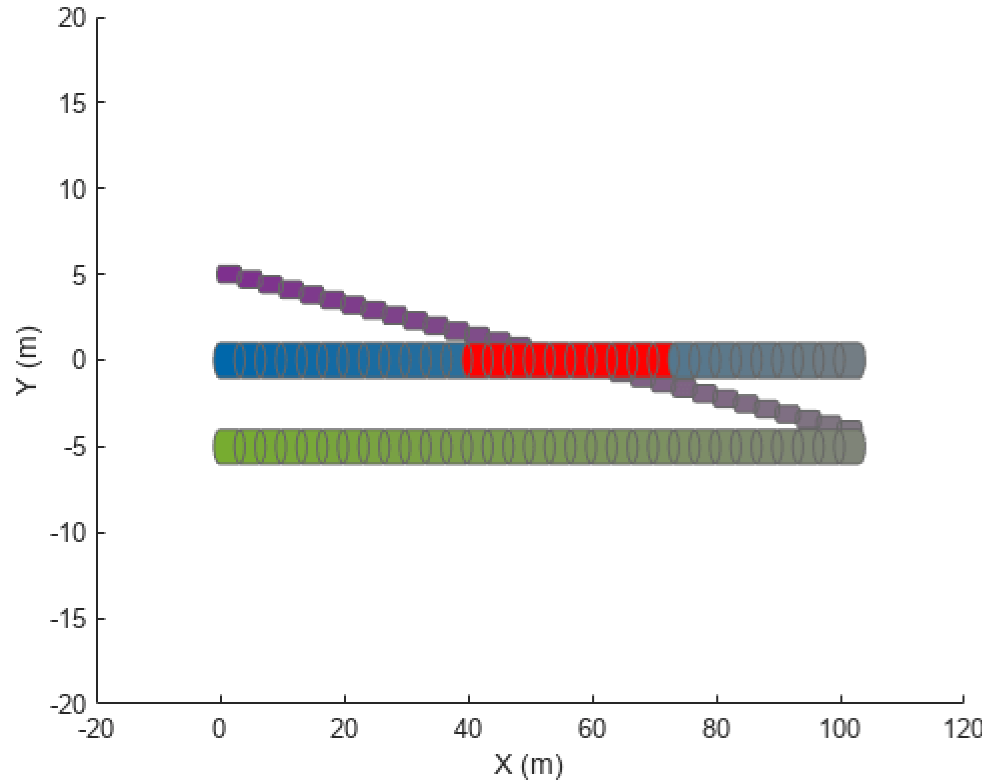
Alter your obstacle locations and geometry dimensions over time. Use the previously generated structure, modify the fields, and update the obstacles using the `updateObstacleGeometry` and `updateObstaclePose` object functions. Reduces the radius of the first obstacle to 0.5 m, and change the path to move it towards the ego body.

```
obsCapsule1.Geometry.Radius = 0.5;

obsCapsule1.States = ...
    [linspace(0,100,numSteps)' ... % x
     linspace(5,-4,numSteps)' ... % y
     zeros(numSteps,1)]; % theta

updateObstacleGeometry(obsList,1,obsCapsule1);
updateObstaclePose(obsList,1,obsCapsule1);
```

### Check for Collisions

Visualize the new paths. Show where collisions between the ego body and an obstacle, which the display highlights in red. Notice that collisions between the obstacles are not checked.

```
show(obsList,"TimeStep",[1:numSteps],"ShowCollisions",1);
ylim([-20 20])
xlabel("X (m)")
ylabel("Y (m)")
```




Programmatically check for collisions by using the `checkCollision` object function. The function returns a vector of logical values that indicates the status of each time step. The vector is transposed for display purposes.

```
collisions = checkCollision(obsList)'
```

```
collisions = 1x31 logical array

   0   0   0   0   0   0   0   0   0   0   0   0   1   1   1   1   1   1   1   1   1   1   0   0
```

To validate paths with a large number of steps, use the `any` function on the vector of collision values.

```
if any(collisions)
    disp("Collision detected.")
end
```

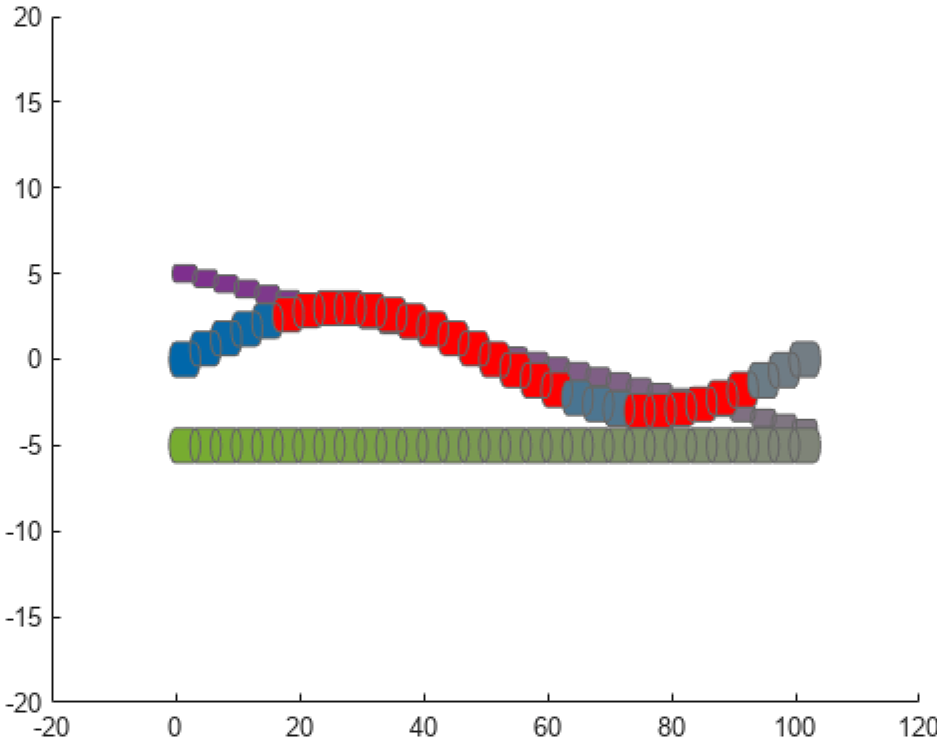
```
Collision detected.
```

### Update Ego Path

Specify a new path for the ego body. Visualize the paths again, displaying collisions.

```
egoCapsule1.States = ...
    [linspace(0,100,numSteps)' ... % x
    3*sin(linspace(0,2*pi,numSteps))' ... % y
    zeros(numSteps,1)]; % theta
```

```
updateEgoPose(obsList,1,egoCapsule1);

show(obsList,"TimeStep",[1:numSteps],"ShowCollisions",1);
ylim([-20 20])
```




## Input Arguments

**capsuleListObj — Dynamic capsule list**
dynamicCapsuleList object | dynamicCapsuleList3D object

Dynamic capsule list, specified as a dynamicCapsuleList or dynamicCapsuleList3D object.

**egoIDs — IDs of ego bodies to update**
vector of positive integers

IDs of ego bodies to update, specified as a vector of positive integers.

**poseStruct — States for ego bodies**
structure | structure array

States for ego bodies, specified as a structure array or structure array, where each structure contains the fields of the structure in the Geometry field of the ego body to be updated. Each element of the structure array contains a matrix of states for each ego body. The state matrix size depends on whether you are using a dynamicCapsuleList or dynamicCapsuleList3D object.

Data Types: struct

### Output Arguments

**`status` — Result of updating ego bodies**
*N*-element column vector

Result of updating ego bodies, specified as *N*-element column vector of ones, zeros, and negative ones. *N* is the number of ego bodies specified in the `egoIDs` argument. Each value indicates whether the body is updated (`1`), not found (`0`), or a duplicate (`-1`). If you specify the same ego ID multiple times in the `egoIDs` input argument, then all entries besides the last are marked as a duplicate.

## Version History

**Introduced in R2020b**

### Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

### See Also

**Objects**
`dynamicCapsuleList` | `dynamicCapsuleList3D`

**Functions**
`addEgo` | `addObstacle` | `checkCollision` | `egoGeometry` | `egoPose` | `obstacleGeometry` | `obstaclePose` | `removeEgo` | `removeObstacle` | `show` | `updateEgoGeometry` | `updateObstacleGeometry` | `updateObstaclePose`

**Topics**
"Highway Trajectory Planning Using Frenet Reference Path"

# updateObstacleGeometry

Update geometric properties of obstacles

## Syntax

```
updateObstacleGeometry(capsuleListObj,obstacleIDs,geomStruct)
status = updateObstacleGeometry(capsuleListObj,obstacleIDs,geomStruct)
```

## Description

`updateObstacleGeometry(capsuleListObj,obstacleIDs,geomStruct)` updates geometry parameters for the specified obstacles in the capsule list. If a specified obstacle ID does not already exist, the function adds a new obstacle with that ID to the list.

`status = updateObstacleGeometry(capsuleListObj,obstacleIDs,geomStruct)` returns an indicator of whether an obstacle is added, updated, or a duplicate.

## Examples

### Build Ego Body Paths and Check for Collisions with Obstacles

Build an ego body path and maintain obstacle states using the `dynamicCapsuleList` object. Visualize the states of all objects in the environment at different timestamps. Validate the path of the ego body by checking for collisions with obstacles in the environment.

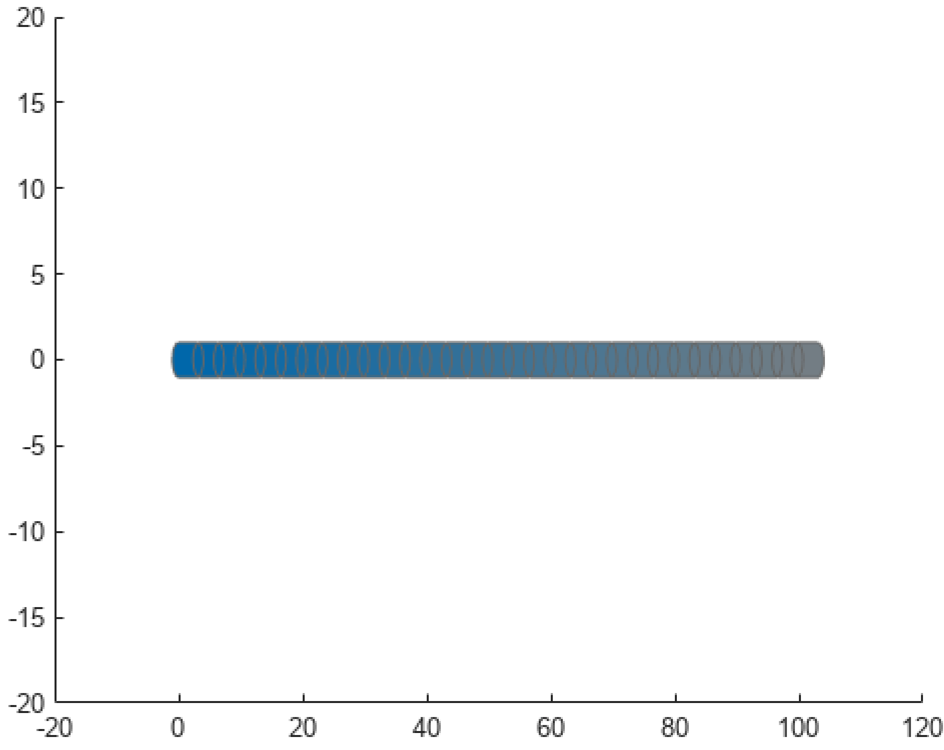
Create the `dynamicCapsuleList` object. Extract the maximum number of steps to use as the number of time stamps for your object paths.

```
obsList = dynamicCapsuleList;
numSteps = obsList.MaxNumSteps;
```

#### Add Ego Body

Define an ego body by specifying the ID, geometry, and state together in a structure. The capsule geometry has a length of 3 m and radius of 1 m. Specify the state as a linear path from $x$ = 0m to $x$ = 100m.

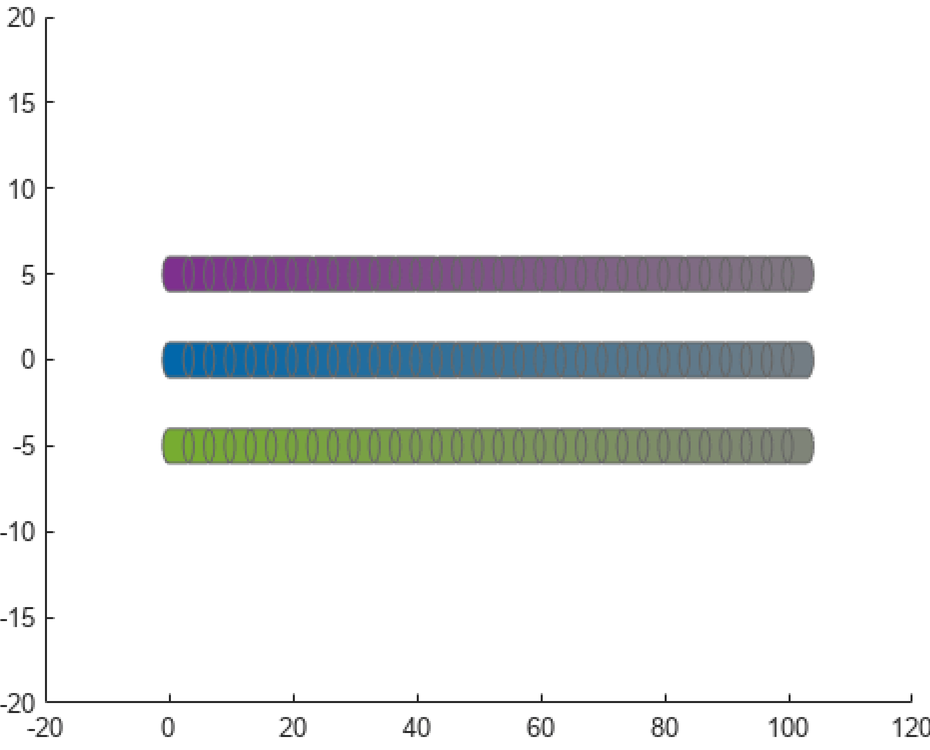
```
egoID1 = 1;
geom = struct("Length",3,"Radius",1,"FixedTransform",eye(3));
states = linspace(0,1,obsList.MaxNumSteps)'.*[100 0 0];

egoCapsule1 = struct('ID',egoID1,'States',states,'Geometry',geom);
addEgo(obsList,egoCapsule1);

show(obsList,"TimeStep",[1:numSteps]);
ylim([-20 20])
```




### Add Obstacles

Specify states for two obstacles that are separated from the ego body by 5 m in opposite directions on the *y*-axis.. Assume the obstacles have the same geometry `geom` as the ego body.

```
obsState1 = states + [0 5 0];
obsState2 = states + [0 -5 0];

obsCapsule1 = struct('ID',1,'States',obsState1,'Geometry',geom);
obsCapsule2 = struct('ID',2,'States',obsState2,'Geometry',geom);

addObstacle(obsList,obsCapsule1);
addObstacle(obsList,obsCapsule2);

show(obsList,"TimeStep",[1:numSteps]);
ylim([-20 20])
```




### Update Obstacles

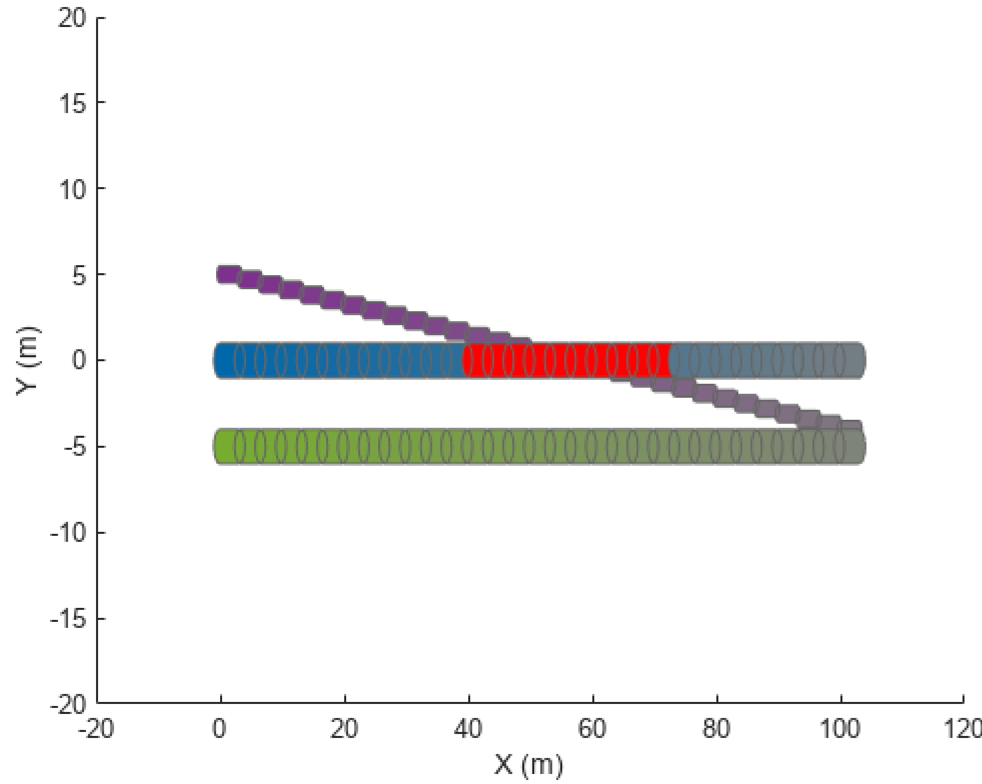
Alter your obstacle locations and geometry dimensions over time. Use the previously generated structure, modify the fields, and update the obstacles using the `updateObstacleGeometry` and `updateObstaclePose` object functions. Reduces the radius of the first obstacle to 0.5 m, and change the path to move it towards the ego body.

```
obsCapsule1.Geometry.Radius = 0.5;

obsCapsule1.States = ...
    [linspace(0,100,numSteps)' ... % x
     linspace(5,-4,numSteps)' ... % y
     zeros(numSteps,1)]; % theta

updateObstacleGeometry(obsList,1,obsCapsule1);
updateObstaclePose(obsList,1,obsCapsule1);
```

### Check for Collisions

Visualize the new paths. Show where collisions between the ego body and an obstacle, which the display highlights in red. Notice that collisions between the obstacles are not checked.

```
show(obsList,"TimeStep",[1:numSteps],"ShowCollisions",1);
ylim([-20 20])
xlabel("X (m)")
ylabel("Y (m)")
```




Programmatically check for collisions by using the `checkCollision` object function. The function returns a vector of logical values that indicates the status of each time step. The vector is transposed for display purposes.

```
collisions = checkCollision(obsList)'
```

```
collisions = 1x31 logical array

   0   0   0   0   0   0   0   0   0   0   0   0   1   1   1   1   1   1   1   1   1   1   0   0
```

To validate paths with a large number of steps, use the `any` function on the vector of collision values.

```
if any(collisions)
    disp("Collision detected.")
end
```

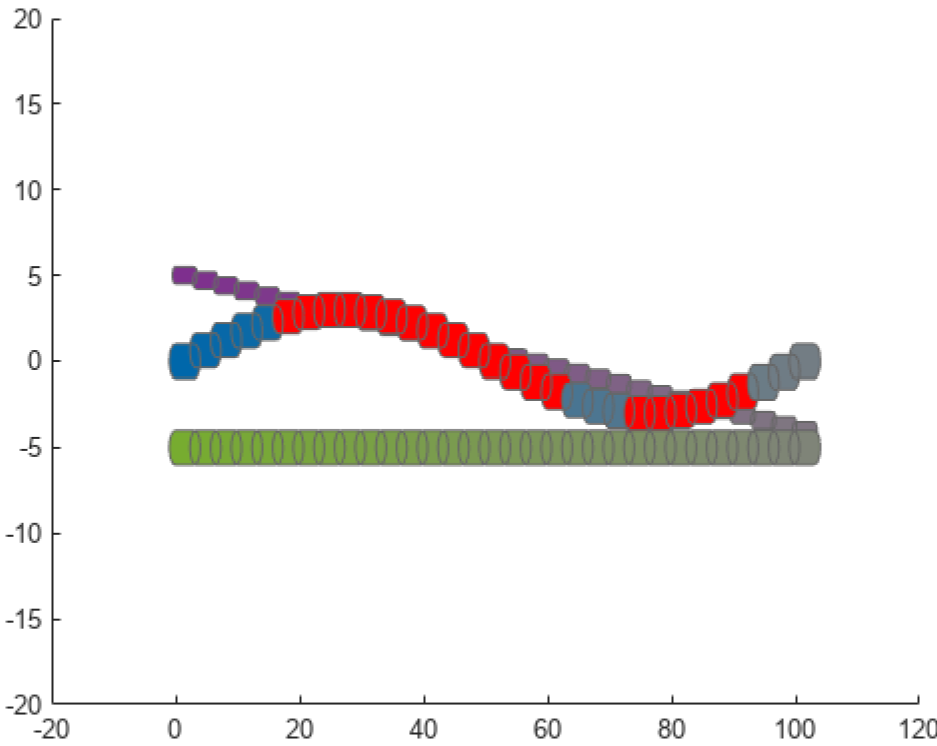
```
Collision detected.
```

### Update Ego Path

Specify a new path for the ego body. Visualize the paths again, displaying collisions.

```
egoCapsule1.States = ...
    [linspace(0,100,numSteps)' ... % x
    3*sin(linspace(0,2*pi,numSteps))' ... % y
    zeros(numSteps,1)]; % theta
```

```
updateEgoPose(obsList,1,egoCapsule1);

show(obsList,"TimeStep",[1:numSteps],"ShowCollisions",1);
ylim([-20 20])
```




## Input Arguments

**capsuleListObj — Dynamic capsule list**
dynamicCapsuleList object | dynamicCapsuleList3D object

Dynamic capsule list, specified as a `dynamicCapsuleList` or `dynamicCapsuleList3D` object.

**obstacleIDs — IDs of obstacles to update**
vector of positive integers

IDs of obstacles to update, specified as a vector of positive integers.

**geomStruct — Geometry parameters for ego bodies**
structure | structure array

Geometry parameters for ego bodies, specified as a structure or structure array, where each structure contains the fields of the structure in the `Geometry` field of the obstacle to be updated.. The fields of this structure depend on whether you are using a `dynamicCapsuleList` or `dynamicCapsuleList3D` object.

Data Types: `struct`

## Output Arguments

**`status` — Result of updating obstacles**
*N*-element column vector

Result of updating obstacles, specified as *N*-element column vector of ones, zeros, and negative ones. *N* is the number of obstacles specified in the `obstacleIDs` argument. Each value indicates whether the obstacle is removed (`1`), not found (`0`), or a duplicate (`-1`). If you specify the same obstacle ID multiple times in the `obstacleIDs` input argument, then all entries besides the last are marked as a duplicate.

# Version History

**Introduced in R2020b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
`dynamicCapsuleList` | `dynamicCapsuleList3D`

**Functions**
`addEgo` | `addObstacle` | `checkCollision` | `egoGeometry` | `egoPose` | `obstacleGeometry` | `obstaclePose` | `removeEgo` | `removeObstacle` | `show` | `updateEgoGeometry` | `updateEgoPose` | `updateObstaclePose`

**Topics**
"Highway Trajectory Planning Using Frenet Reference Path"

# updateObstaclePose

Update states of obstacles

## Syntax

```
updateObstaclePose(capsuleListObj,obstacleIDs,poseStruct)
status = updateObstaclePose(capsuleListObj,obstacleIDs,poseStruct)
```

## Description

`updateObstaclePose(capsuleListObj,obstacleIDs,poseStruct)` updates the states of the specified obstacles in the capsule list. If a specified obstacle ID does not already exist, the function adds a new ego body with that ID to the list.

`status = updateObstaclePose(capsuleListObj,obstacleIDs,poseStruct)` returns an indicator of whether an obstacle is added, updated, or a duplicate.

## Examples

### Build Ego Body Paths and Check for Collisions with Obstacles

Build an ego body path and maintain obstacle states using the `dynamicCapsuleList` object. Visualize the states of all objects in the environment at different timestamps. Validate the path of the ego body by checking for collisions with obstacles in the environment.

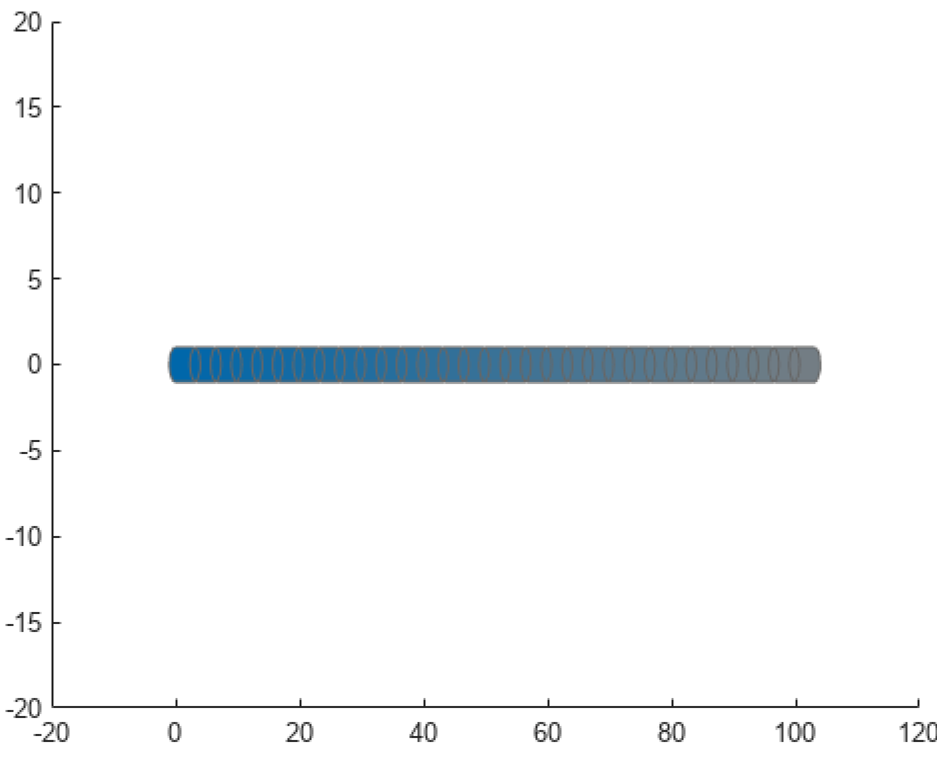
Create the `dynamicCapsuleList` object. Extract the maximum number of steps to use as the number of time stamps for your object paths.

```
obsList = dynamicCapsuleList;
numSteps = obsList.MaxNumSteps;
```

#### Add Ego Body

Define an ego body by specifying the ID, geometry, and state together in a structure. The capsule geometry has a length of 3 m and radius of 1 m. Specify the state as a linear path from $x$ = 0m to $x$ = 100m.

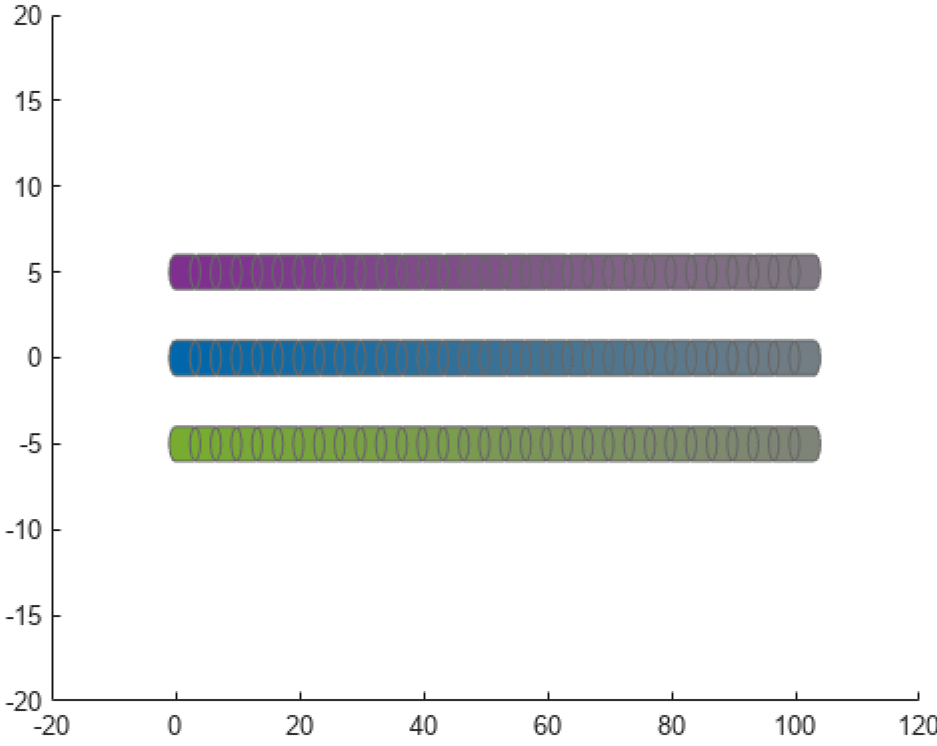
```
egoID1 = 1;
geom = struct("Length",3,"Radius",1,"FixedTransform",eye(3));
states = linspace(0,1,obsList.MaxNumSteps)'.*[100 0 0];

egoCapsule1 = struct('ID',egoID1,'States',states,'Geometry',geom);
addEgo(obsList,egoCapsule1);

show(obsList,"TimeStep",[1:numSteps]);
ylim([-20 20])
```




#### Add Obstacles

Specify states for two obstacles that are separated from the ego body by 5 m in opposite directions on the *y*-axis.. Assume the obstacles have the same geometry `geom` as the ego body.

```
obsState1 = states + [0 5 0];
obsState2 = states + [0 -5 0];

obsCapsule1 = struct('ID',1,'States',obsState1,'Geometry',geom);
obsCapsule2 = struct('ID',2,'States',obsState2,'Geometry',geom);

addObstacle(obsList,obsCapsule1);
addObstacle(obsList,obsCapsule2);

show(obsList,"TimeStep",[1:numSteps]);
ylim([-20 20])
```




### Update Obstacles

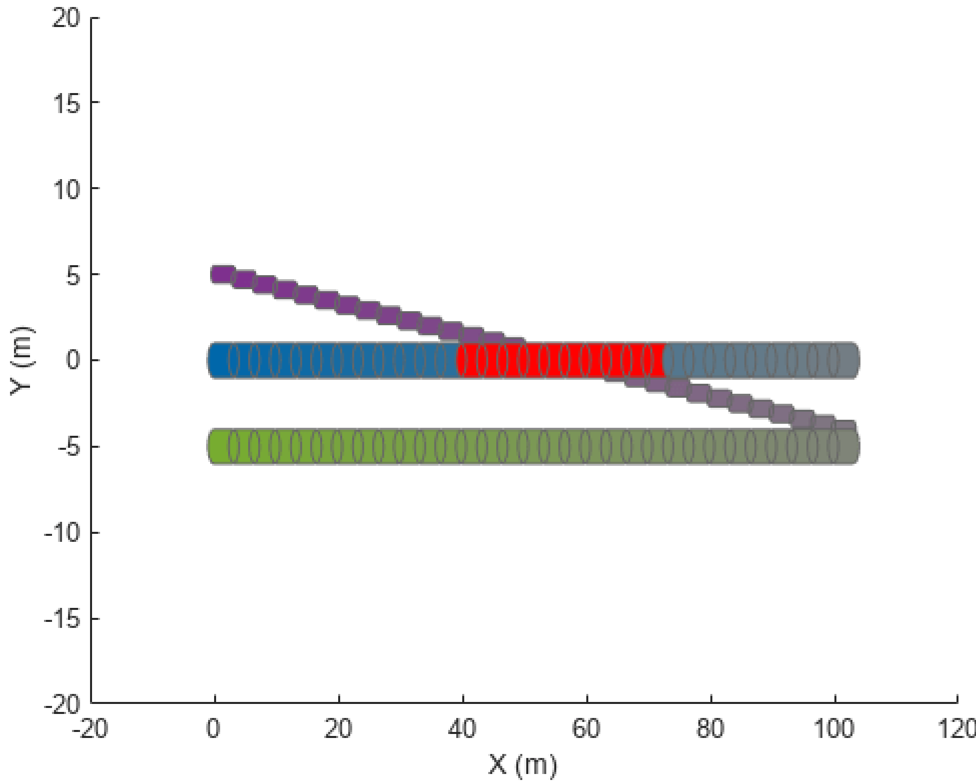
Alter your obstacle locations and geometry dimensions over time. Use the previously generated structure, modify the fields, and update the obstacles using the `updateObstacleGeometry` and `updateObstaclePose` object functions. Reduces the radius of the first obstacle to 0.5 m, and change the path to move it towards the ego body.

```
obsCapsule1.Geometry.Radius = 0.5;

obsCapsule1.States = ...
    [linspace(0,100,numSteps)' ... % x
     linspace(5,-4,numSteps)' ... % y
     zeros(numSteps,1)]; % theta

updateObstacleGeometry(obsList,1,obsCapsule1);
updateObstaclePose(obsList,1,obsCapsule1);
```

### Check for Collisions

Visualize the new paths. Show where collisions between the ego body and an obstacle, which the display highlights in red. Notice that collisions between the obstacles are not checked.

```
show(obsList,"TimeStep",[1:numSteps],"ShowCollisions",1);
ylim([-20 20])
xlabel("X (m)")
ylabel("Y (m)")
```




Programmatically check for collisions by using the `checkCollision` object function. The function returns a vector of logical values that indicates the status of each time step. The vector is transposed for display purposes.

```
collisions = checkCollision(obsList)'
```

```
collisions = 1x31 logical array

   0   0   0   0   0   0   0   0   0   0   0   0   1   1   1   1   1   1   1   1   1   1   0   0
```

To validate paths with a large number of steps, use the `any` function on the vector of collision values.

```
if any(collisions)
    disp("Collision detected.")
end
```

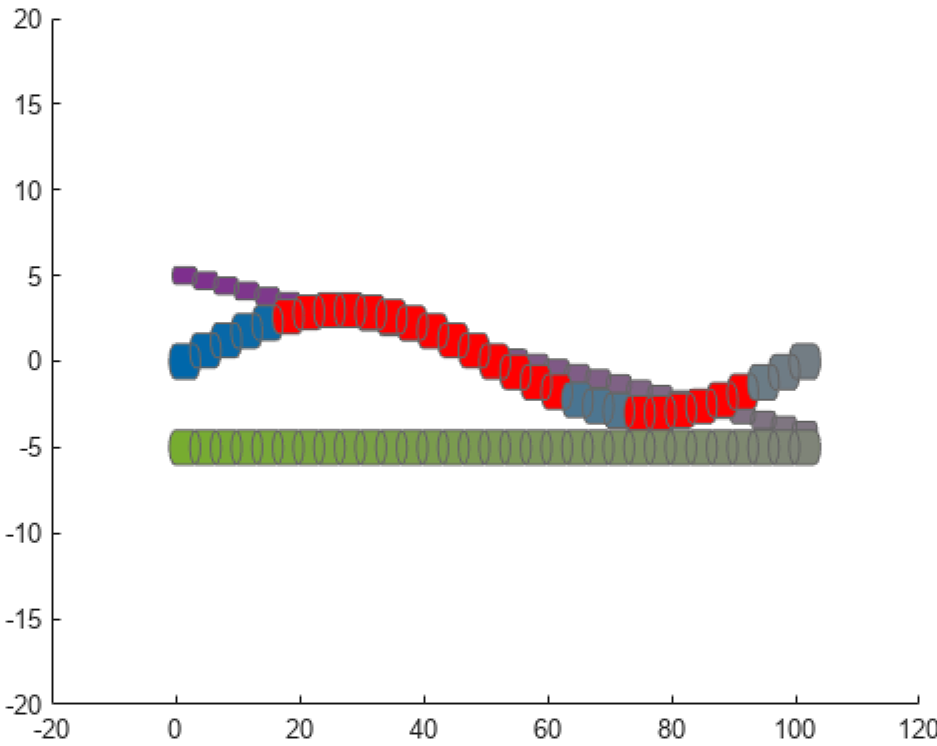
```
Collision detected.
```

#### Update Ego Path

Specify a new path for the ego body. Visualize the paths again, displaying collisions.

```
egoCapsule1.States = ...
    [linspace(0,100,numSteps)' ... % x
    3*sin(linspace(0,2*pi,numSteps))' ... % y
    zeros(numSteps,1)]; % theta
```

```
updateEgoPose(obsList,1,egoCapsule1);

show(obsList,"TimeStep",[1:numSteps],"ShowCollisions",1);
ylim([-20 20])
```




## Input Arguments

**capsuleListObj — Dynamic capsule list**
dynamicCapsuleList object | dynamicCapsuleList3D object

Dynamic capsule list, specified as a dynamicCapsuleList or dynamicCapsuleList3D object.

**obstacleIDs — IDs of obstacles to update**
vector of positive integers

IDs of obstacles to update, specified as a vector of positive integers.

**poseStruct — States for obstacles**
structure | structure array

States for ego bodies, specified as a structure or structure array, where each structure contains the fields of the structure in the Geometry field of the obstacle to be updated. Each element of the structure array contains a matrix of states for each ego body. The state matrix size depends on whether you are using a dynamicCapsuleList or dynamicCapsuleList3D object.

Data Types: struct

## Output Arguments

**`status` — Result of updating obstacles**
*N*-element column vector

Result of updating obstacles, specified as *N*-element column vector of ones, zeros, and negative ones. *N* is the number of obstacles specified in the `obstacleIDs` argument. Each value indicates whether the obstacle is removed (`1`), not found (`0`), or a duplicate (`-1`). If you specify the same obstacle ID multiple times in the `obstacleIDs` input argument, then all entries besides the last are marked as a duplicate.

# Version History

**Introduced in R2020b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
`dynamicCapsuleList` | `dynamicCapsuleList3D`

**Functions**
`addEgo` | `addObstacle` | `checkCollision` | `egoGeometry` | `egoPose` | `obstacleGeometry` | `obstaclePose` | `removeEgo` | `removeObstacle` | `show` | `updateEgoGeometry` | `updateEgoPose` | `updateObstacleGeometry`

**Topics**
"Highway Trajectory Planning Using Frenet Reference Path"

# dynamicCapsuleList3D

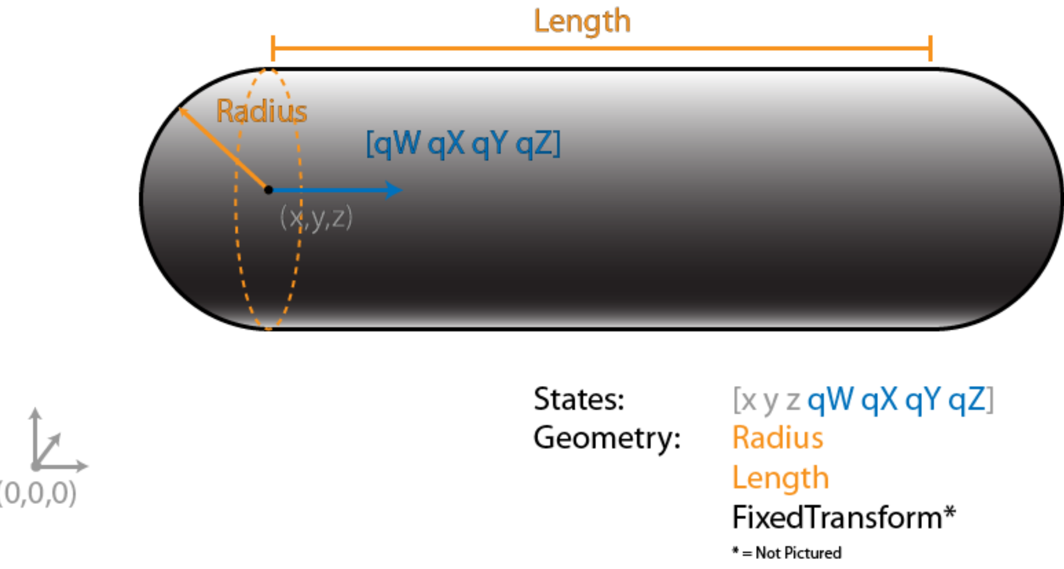
Dynamic capsule-based obstacle list

## Description

The `dynamicCapsuleList3D` object manages two lists of capsule-based collision objects in 3-D space. Collision objects are separated into two lists, ego bodies and obstacles. For ego bodies and obstacles in 2-D, see the `dynamicCapsuleList` object.

Each collision object in the two lists has three key elements:

- **ID** –– Integer that identifies each object, stored in the `EgoIDs` property for ego bodies and the `ObstacleIDs` property for obstacles.
- **States** –– Location and orientation of the object as an *M*-by-6 matrix, where each row is of form `[x y z qW qX qY qZ]`, and *M* is the number of states along the path of the object in the world frame. The list of states assumes each state is separated by a fixed time interval. *xyz*-positions are in meters, and the orientation is a four-element quaternion vector. The default local origin is located at the center of the left hemisphere of the capsule.
- **Geometry** –– Size of the capsule-based object based on the specified length and radius. The radius applies to the spherical ends, and the length applies to the cylinder length. To shift the capsule geometry and local origin relative to the default origin point, specify a 4-by-4 transform relative to the local frame of the capsule. To keep the default transform, specify `eye(4)`.




Use the object functions to dynamically add, remove, and update the geometries and states of the various objects in your environment. To add an ego body, see the `addEgo` object function. To add an obstacle, see the `addObstacle` object function.

After specifying all the object paths, validate the ego-body paths and check for collisions with obstacles at every step using the `checkCollision` object function. The function only checks if an ego body collides with an obstacle, ignoring collisions between only obstacles or only ego bodies.

# Creation

## Syntax

`obstacleList = dynamicCapsuleList3D`

### Description

`obstacleList = dynamicCapsuleList3D` creates a dynamic capsule-based obstacle list with no ego bodies or obstacles. To begin building an obstacle list, use the `addEgo` or `addObstacle` object functions.

## Properties

**`MaxNumSteps` — Maximum number of time steps in obstacle list**
`31` (default) | positive integer

Maximum number of time steps in the obstacle list, specified as a positive integer. The number of steps determines to the maximum length of the `States` field for a specific ego body or obstacle.

Data Types: `double`

**`EgoIDs` — List of IDs for ego bodies**
vector of positive integers

This property is read-only.

List of identifiers for ego bodies, returned as a vector of positive integers.

Data Types: `double`

**`ObstacleIDs` — IDs for obstacles**
vector of positive integers

This property is read-only.

List of identifiers for obstacles, returned as a vector of positive integers.

Data Types: `double`

**`NumObstacles` — Number of obstacles in list**
integer

This property is read-only.

Number of obstacles in list, returned as an integer.

Data Types: `double`

**`NumEgos` — Number of ego bodies in list**
integer

This property is read-only.

Number of ego bodies in list, returned as an integer.

Data Types: `double`

## Object Functions

| | |
|---|---|
| addEgo | Add ego bodies to 3D capsule list |
| addObstacle | Add obstacles to 3-D capsule list |
| checkCollision | Check for collisions between ego bodies and obstacles |
| egoGeometry | Geometric properties of ego bodies |
| egoPose | Poses of ego bodies |
| obstacleGeometry | Geometric properties of obstacles |
| obstaclePose | Poses of obstacles |
| removeEgo | Remove ego bodies from capsule list |
| removeObstacle | Remove obstacles from capsule list |
| show | Display ego bodies and obstacles in environment |
| updateEgoGeometry | Update geometric properties of ego bodies |
| updateEgoPose | Update states of ego bodies |
| updateObstacleGeometry | Update geometric properties of obstacles |
| updateObstaclePose | Update states of obstacles |

## Examples

### Build 3-D Ego Body Paths and Check for Collisions with 3-D Obstacles

Build an ego body path and maintain obstacle states using the `dynamicCapsuleList3D` object. Visualize the states of all objects in the environment at different timestamps. Validate the path of the ego body by checking for collisions with obstacles in the environment.

Create the `dynamicCapsuleList3D` object. Extract the maximum number of steps to use as the number of time stamps for your object paths.

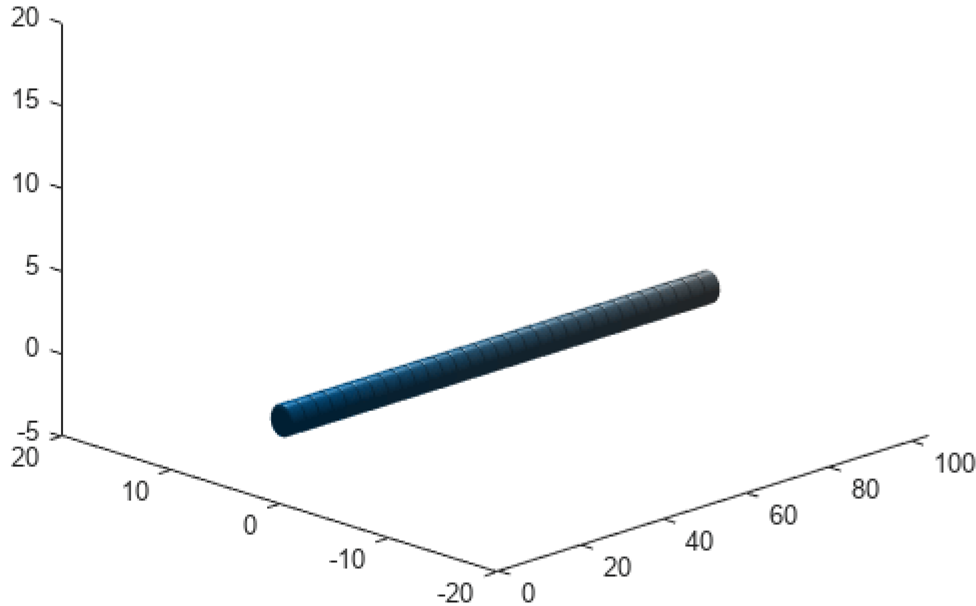
```
obsList = dynamicCapsuleList3D;
numSteps = obsList.MaxNumSteps;
```

#### Add Ego Body

Define an ego body by specifying the ID, geometry, and state together in a structure. The capsule geometry has a length of 3 m and radius of 1 m. Specify the state as a linear path from $x = 0$ m *to* $x =$ 100 m.

```
egoID1 = 1;
geom = struct("Length",3,"Radius",1,"FixedTransform",eye(4));
states = linspace(0,1,obsList.MaxNumSteps)'.*[100 0 0];
states = [states ones(numSteps,2) zeros(numSteps,2)];

egoCapsule1 = struct('ID',egoID1,'States',states,'Geometry',geom);
addEgo(obsList,egoCapsule1);

show(obsList,"TimeStep",1:numSteps);
ylim([-20 20])
zlim([-5 20])
```

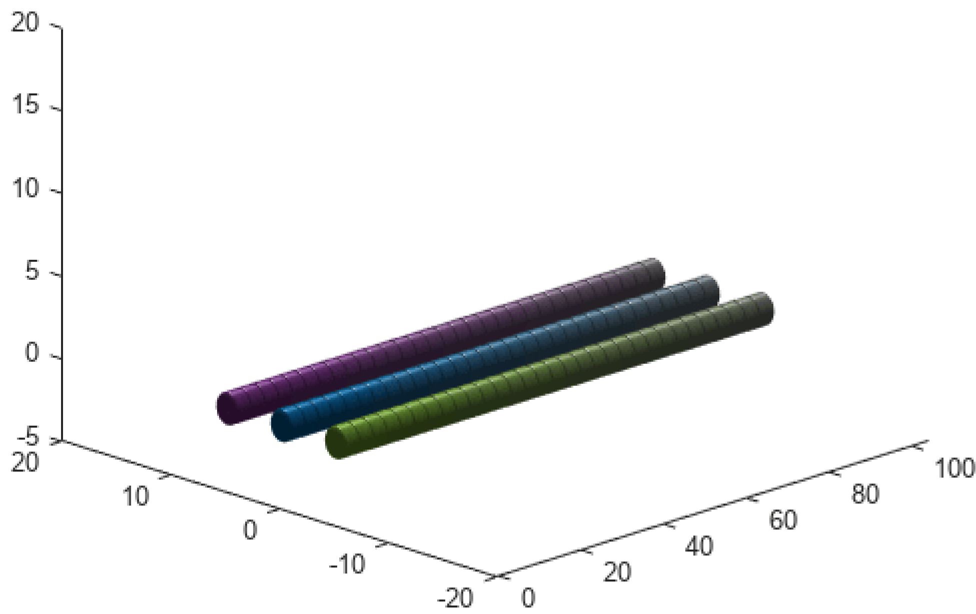
```
view(-45,25)
hold on
```




#### Add Obstacles

Specify states for two obstacles that are separated from the ego body by 5 m in opposite directions on the *y*-axis. Assume the obstacles have the same geometry `geom` as the ego body.

```
obsState1 = states + [0 5 0 0 0 0 0];
obsState2 = states + [0 -5 0 0 0 0 0];

obsCapsule1 = struct('ID',1,'States',obsState1,'Geometry',geom);
obsCapsule2 = struct('ID',2,'States',obsState2,'Geometry',geom);

addObstacle(obsList,obsCapsule1);
addObstacle(obsList,obsCapsule2);

cla
show(obsList,"TimeStep",1:numSteps);
```




#### Update Obstacles

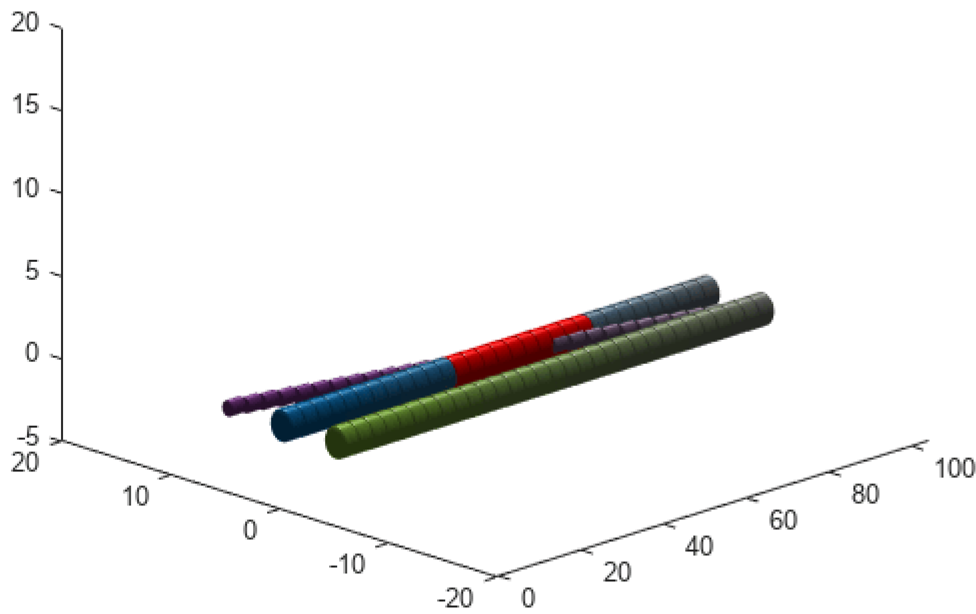
Alter your obstacle locations and geometry dimensions over time. Use the previously generated structure, modify the fields, and update the obstacles using the `updateObstacleGeometry` and `updateObstaclePose` object functions. Reduce the radius of the first obstacle to 0.5 m, and change the path to move it towards the ego body.

```
obsCapsule1.Geometry.Radius = 0.5;

obsCapsule1.States = ...
    [linspace(0,100,numSteps)' ... % x
     linspace(5,-4,numSteps)' ... % y
     zeros(numSteps,1) ... % z
     ones(numSteps,2) zeros(numSteps,2)]; % quaternion                              % quaternion

updateObstacleGeometry(obsList,1,obsCapsule1);
updateObstaclePose(obsList,1,obsCapsule1);
```

#### Check for Collisions

Visualize the new paths. Show where collisions between the ego body and an obstacle occur, which the display highlights in red. Notice that collisions between the obstacles are not checked.

```
cla
show(obsList,"TimeStep",1:numSteps,"ShowCollisions",1);
```




Programmatically check for collisions bu using the `checkCollision` object function. The function returns a vector of logical values that indicates the collision status at each time step. The vector is transposed for display purposes.

```
collisions = checkCollision(obsList)'
```

```
collisions = 1x31 logical array

   0   0   0   0   0   0   0   0   0   0   0   0   1   1   1   1   1   1   1   1   1   1   0   0
```

To validate paths with a large number of steps, use the `any` function on the vector of collision values.

```
if any(collisions)
    disp("Collision detected.")
end
```

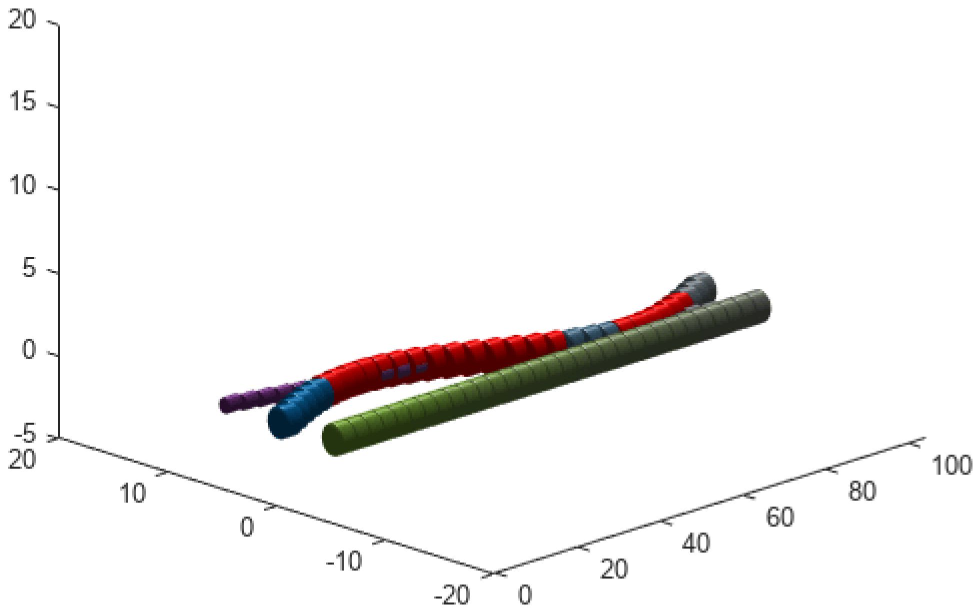
```
Collision detected.
```

#### Update Ego Path

Specify a new path for the ego body. Visualize the paths again, displaying collisions.

```
egoCapsule1.States = ...
    [linspace(0,100,numSteps)' ... % x
    3*sin(linspace(0,2*pi,numSteps))' ... % y
    zeros(numSteps,1)... % z
    ones(numSteps,2) zeros(numSteps,2)]; %quaternion                                    % quaternio
```

```
updateEgoPose(obsList,1,egoCapsule1);

cla
show(obsList,"TimeStep",1:numSteps,"ShowCollisions",1);
```




# Version History

**Introduced in R2020b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Objects

`dynamicCapsuleList`

### Functions

`addEgo` | `addObstacle` | `checkCollision` | `egoGeometry` | `egoPose` | `obstacleGeometry` | `obstaclePose` | `removeEgo` | `removeObstacle` | `show` | `updateEgoGeometry` | `updateEgoPose` | `updateObstacleGeometry` | `updateObstaclePose`

**Topics**

"Highway Trajectory Planning Using Frenet Reference Path"

# addEgo

Add ego bodies to 3D capsule list

## Syntax

```
addEgo(capsuleListObj,egoStruct)
status = addEgo(capsuleListObj,egoStruct)
```

## Description

`addEgo(capsuleListObj,egoStruct)` adds one or more ego bodies to the 3-D dynamic capsule list with the specified ID, state, and geometry values given in `egoStruct`.

`status = addEgo(capsuleListObj,egoStruct)` additionally returns an indicator of whether each specified ego body was added, updated, or a duplicate.

## Examples

### Build 3-D Ego Body Paths and Check for Collisions with 3-D Obstacles

Build an ego body path and maintain obstacle states using the `dynamicCapsuleList3D` object. Visualize the states of all objects in the environment at different timestamps. Validate the path of the ego body by checking for collisions with obstacles in the environment.

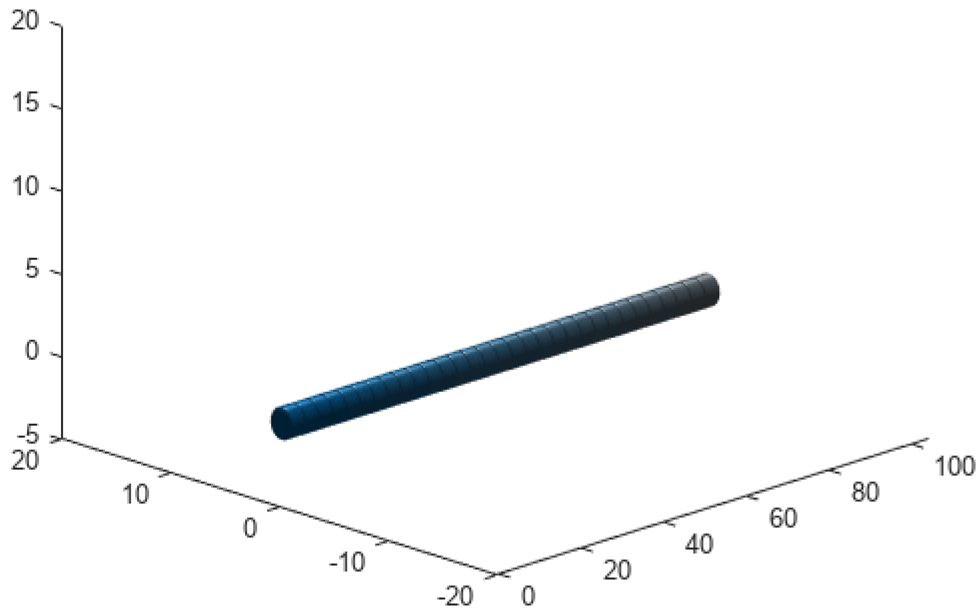
Create the `dynamicCapsuleList3D` object. Extract the maximum number of steps to use as the number of time stamps for your object paths.

```
obsList = dynamicCapsuleList3D;
numSteps = obsList.MaxNumSteps;
```

#### Add Ego Body

Define an ego body by specifying the ID, geometry, and state together in a structure. The capsule geometry has a length of 3 m and radius of 1 m. Specify the state as a linear path from $x = 0$ m *to* $x = 100$ m.

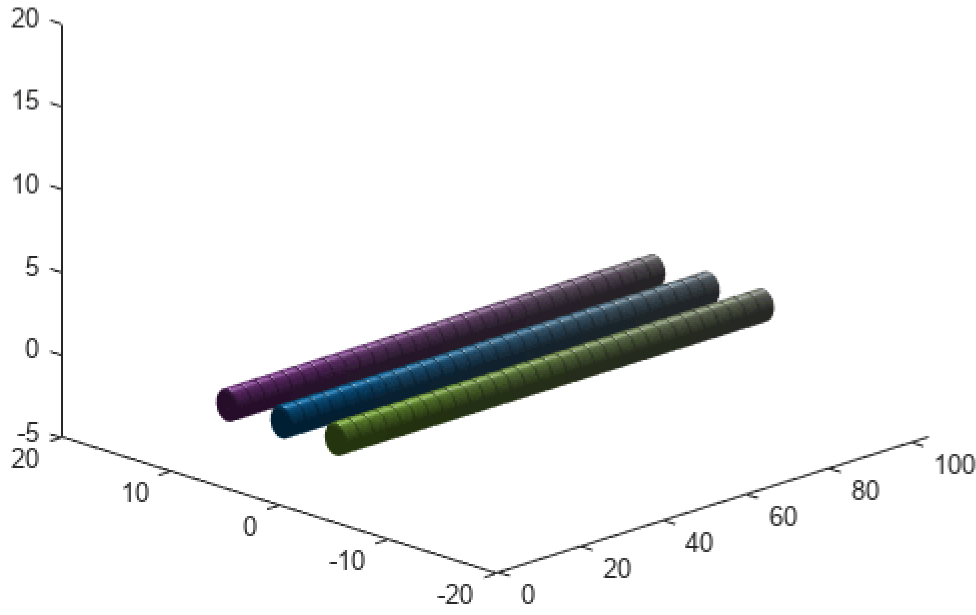
```
egoID1 = 1;
geom = struct("Length",3,"Radius",1,"FixedTransform",eye(4));
states = linspace(0,1,obsList.MaxNumSteps)'.*[100 0 0];
states = [states ones(numSteps,2) zeros(numSteps,2)];

egoCapsule1 = struct('ID',egoID1,'States',states,'Geometry',geom);
addEgo(obsList,egoCapsule1);

show(obsList,"TimeStep",1:numSteps);
ylim([-20 20])
zlim([-5 20])
view(-45,25)
hold on
```




#### Add Obstacles

Specify states for two obstacles that are separated from the ego body by 5 m in opposite directions on the *y*-axis. Assume the obstacles have the same geometry `geom` as the ego body.

```
obsState1 = states + [0 5 0 0 0 0 0];
obsState2 = states + [0 -5 0 0 0 0 0];

obsCapsule1 = struct('ID',1,'States',obsState1,'Geometry',geom);
obsCapsule2 = struct('ID',2,'States',obsState2,'Geometry',geom);

addObstacle(obsList,obsCapsule1);
addObstacle(obsList,obsCapsule2);

cla
show(obsList,"TimeStep",1:numSteps);
```




#### Update Obstacles

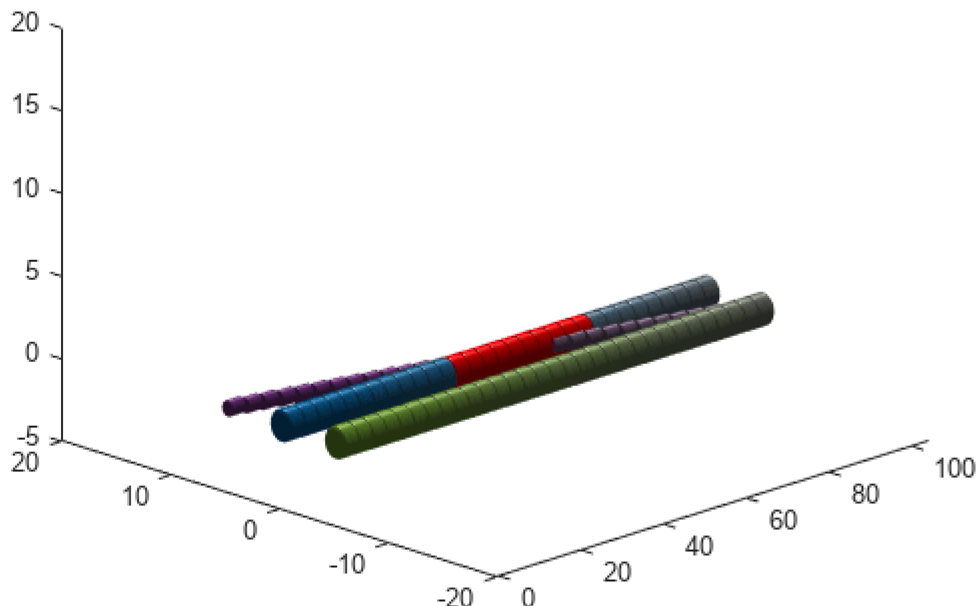
Alter your obstacle locations and geometry dimensions over time. Use the previously generated structure, modify the fields, and update the obstacles using the `updateObstacleGeometry` and `updateObstaclePose` object functions. Reduce the radius of the first obstacle to 0.5 m, and change the path to move it towards the ego body.

```
obsCapsule1.Geometry.Radius = 0.5;

obsCapsule1.States = ...
    [linspace(0,100,numSteps)' ... % x
     linspace(5,-4,numSteps)' ... % y
     zeros(numSteps,1) ... % z
     ones(numSteps,2) zeros(numSteps,2)]; % quaternion                              % quaternio

updateObstacleGeometry(obsList,1,obsCapsule1);
updateObstaclePose(obsList,1,obsCapsule1);
```

#### Check for Collisions

Visualize the new paths. Show where collisions between the ego body and an obstacle occur, which the display highlights in red. Notice that collisions between the obstacles are not checked.

```
cla
show(obsList,"TimeStep",1:numSteps,"ShowCollisions",1);
```




Programmatically check for collisions bu using the `checkCollision` object function. The function returns a vector of logical values that indicates the collision status at each time step. The vector is transposed for display purposes.

```
collisions = checkCollision(obsList)'
```

```
collisions = 1x31 logical array

   0   0   0   0   0   0   0   0   0   0   0   0   1   1   1   1   1   1   1   1   1   1   0   0
```

To validate paths with a large number of steps, use the `any` function on the vector of collision values.

```
if any(collisions)
    disp("Collision detected.")
end
```

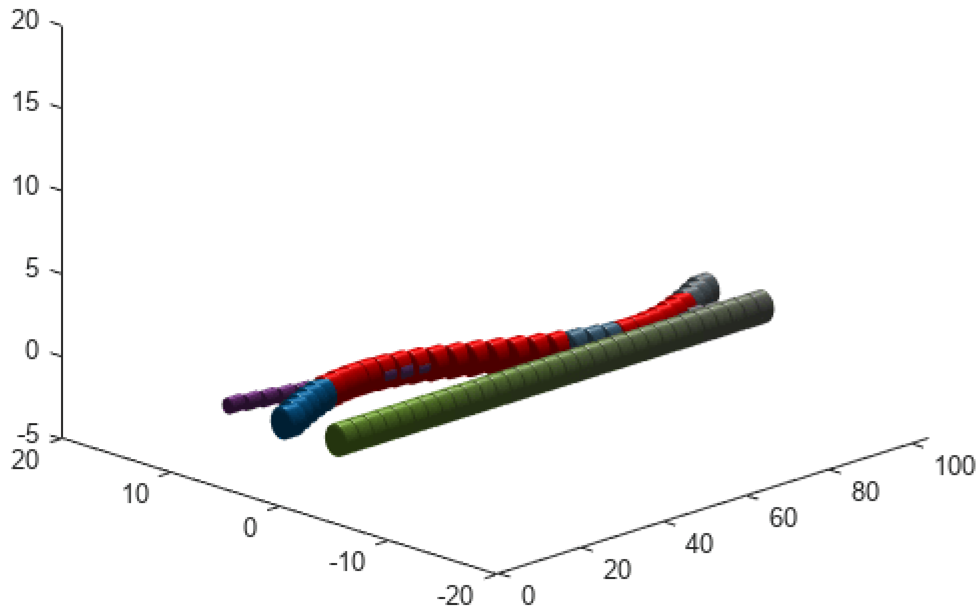
```
Collision detected.
```

### Update Ego Path

Specify a new path for the ego body. Visualize the paths again, displaying collisions.

```
egoCapsule1.States = ...
    [linspace(0,100,numSteps)' ... % x
    3*sin(linspace(0,2*pi,numSteps))' ... % y
    zeros(numSteps,1)... % z
    ones(numSteps,2) zeros(numSteps,2)]; %quaternion                                  % quaterni
```

```
updateEgoPose(obsList,1,egoCapsule1);

cla
show(obsList,"TimeStep",1:numSteps,"ShowCollisions",1);
```




## Input Arguments

**capsuleListObj — Dynamic capsule list**
dynamicCapsuleList3D object

Dynamic capsule list, specified as a dynamicCapsuleList3D object.

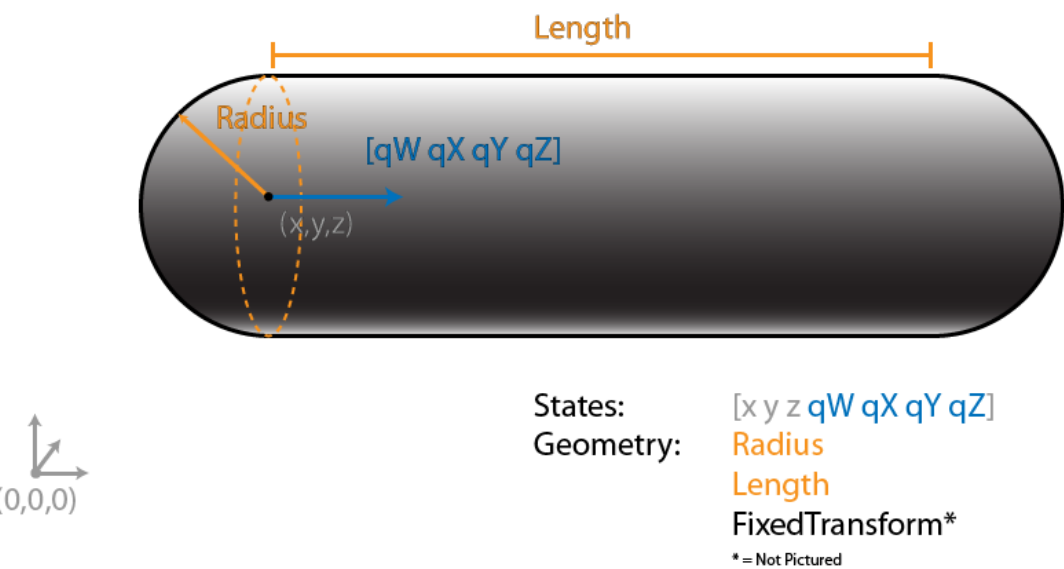
**egoStruct — Ego body parameters**
structure | structure array

Ego body parameters, specified as an *N*-element structure or a structure array, where *N* is the number of added ego bodies. The fields of each structure define the ID, geometry, and states of an ego body:

- ID -– Integer that identifies each object. Stored in the EgoIDs property of the dynamicCapsuleList3D object specified by the capsuleListObj argument.
- States -– Location and orientation of the object as an *M*-by-6 matrix, where each row is of form [x y z qW qX qY qZ], and *M* is the number of states along the path of the object in the world frame. The list of states assumes each state is separated by a fixed time interval. *xyz*-positions are

in meters, and the orientation is a four-element quaternion vector. The default local origin is located at the center of the left hemisphere of the capsule.

- `Geometry` –– Structure with fields `Length`, `Radius`, and `FixedTransform`. These fields define the size of the capsule-based object using the specified length for the cylinder and hemisphere radius for the end caps. To shift the capsule geometry from the default origin, specify the `FixedTransform` field as a fixed transform relative to the local frame of the capsule. To keep the default capsule origin, specify the transform as `eye(4)`.




## Output Arguments

**`status` — Result of adding ego bodies**
*N*-element column vector

Result of adding ego bodies, returned as a *N*-element column vector of ones, zeros, and negative ones. *N* is the number of ego bodies specified in the `egoStruct` argument. Each value indicates whether the associated body is added (`1`), updated (`0`), or a duplicate (`-1`). While adding ego bodies, if multiple structures with the same body ID are found in the structure array `egoStruct`, then the function marks the previous entry as duplicate and ignores it.

# Version History

**Introduced in R2020b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
`dynamicCapsuleList` | `dynamicCapsuleList3D`

**Functions**
`addObstacle` | `checkCollision` | `egoGeometry` | `egoPose` | `obstacleGeometry` | `obstaclePose` | `removeEgo` | `removeObstacle` | `show` | `updateEgoGeometry` | `updateEgoPose` | `updateObstacleGeometry` | `updateObstaclePose`

**Topics**
"Highway Trajectory Planning Using Frenet Reference Path"

# addObstacle

Add obstacles to 3-D capsule list

## Syntax

```
addObstacle(capsuleListObj,obstacleStruct)
status = addObstacle(capsuleListObj,obstacleStruct)
```

## Description

`addObstacle(capsuleListObj,obstacleStruct)` adds one or more obstacles to the 3-D dynamic capsule list with the specified ID, state, and geometry values given in `obstacleStruct`.

`status = addObstacle(capsuleListObj,obstacleStruct)` additionally returns an indicator of whether each specified obstacle was added, updated, or a duplicate.

## Examples

### Build 3-D Ego Body Paths and Check for Collisions with 3-D Obstacles

Build an ego body path and maintain obstacle states using the `dynamicCapsuleList3D` object. Visualize the states of all objects in the environment at different timestamps. Validate the path of the ego body by checking for collisions with obstacles in the environment.

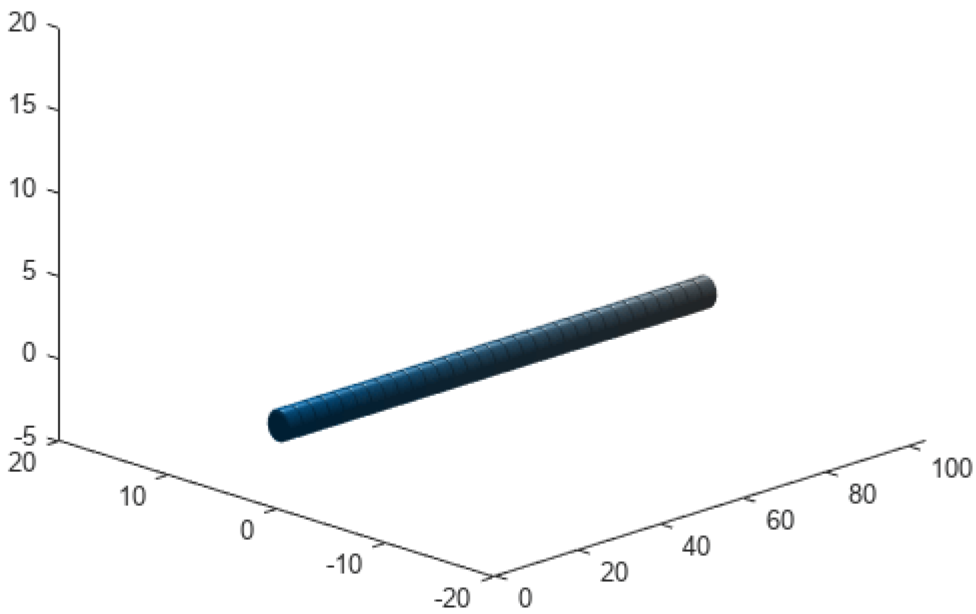
Create the `dynamicCapsuleList3D` object. Extract the maximum number of steps to use as the number of time stamps for your object paths.

```
obsList = dynamicCapsuleList3D;
numSteps = obsList.MaxNumSteps;
```

**Add Ego Body**

Define an ego body by specifying the ID, geometry, and state together in a structure. The capsule geometry has a length of 3 m and radius of 1 m. Specify the state as a linear path from $x$ = 0 m *to* $x$ = 100 m.

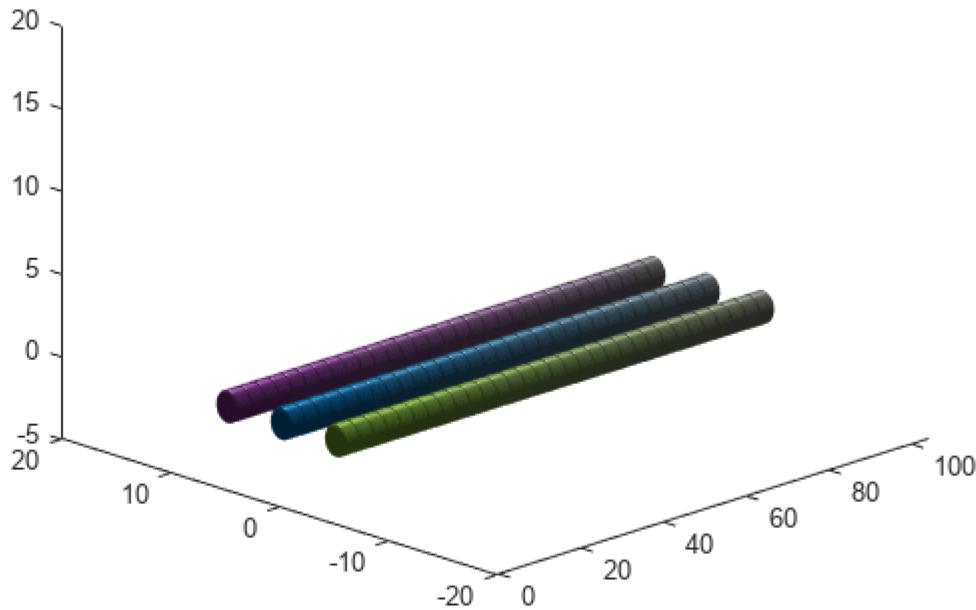
```
egoID1 = 1;
geom = struct("Length",3,"Radius",1,"FixedTransform",eye(4));
states = linspace(0,1,obsList.MaxNumSteps)'.*[100 0 0];
states = [states ones(numSteps,2) zeros(numSteps,2)];

egoCapsule1 = struct('ID',egoID1,'States',states,'Geometry',geom);
addEgo(obsList,egoCapsule1);

show(obsList,"TimeStep",1:numSteps);
ylim([-20 20])
zlim([-5 20])
view(-45,25)
hold on
```




#### Add Obstacles

Specify states for two obstacles that are separated from the ego body by 5 m in opposite directions on the *y*-axis. Assume the obstacles have the same geometry `geom` as the ego body.

```
obsState1 = states + [0 5 0 0 0 0 0];
obsState2 = states + [0 -5 0 0 0 0 0];

obsCapsule1 = struct('ID',1,'States',obsState1,'Geometry',geom);
obsCapsule2 = struct('ID',2,'States',obsState2,'Geometry',geom);

addObstacle(obsList,obsCapsule1);
addObstacle(obsList,obsCapsule2);

cla
show(obsList,"TimeStep",1:numSteps);
```




#### Update Obstacles

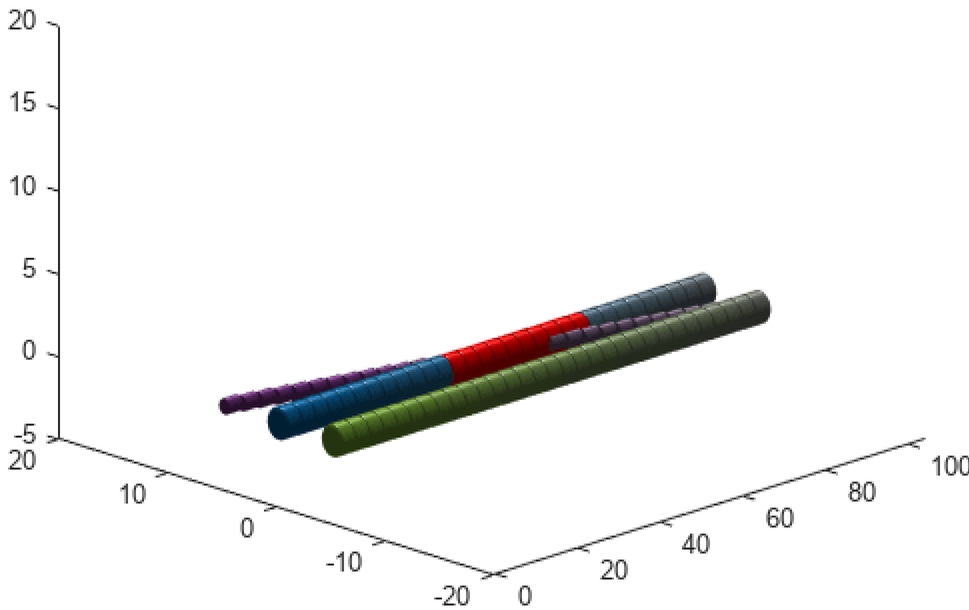
Alter your obstacle locations and geometry dimensions over time. Use the previously generated structure, modify the fields, and update the obstacles using the `updateObstacleGeometry` and `updateObstaclePose` object functions. Reduce the radius of the first obstacle to 0.5 m, and change the path to move it towards the ego body.

```
obsCapsule1.Geometry.Radius = 0.5;

obsCapsule1.States = ...
    [linspace(0,100,numSteps)' ... % x
     linspace(5,-4,numSteps)' ... % y
     zeros(numSteps,1) ... % z
     ones(numSteps,2) zeros(numSteps,2)]; % quaternion                              % quaternio

updateObstacleGeometry(obsList,1,obsCapsule1);
updateObstaclePose(obsList,1,obsCapsule1);
```

#### Check for Collisions

Visualize the new paths. Show where collisions between the ego body and an obstacle occur, which the display highlights in red. Notice that collisions between the obstacles are not checked.

```
cla
show(obsList,"TimeStep",1:numSteps,"ShowCollisions",1);
```




Programmatically check for collisions bu using the `checkCollision` object function. The function returns a vector of logical values that indicates the collision status at each time step. The vector is transposed for display purposes.

```
collisions = checkCollision(obsList)'
```

```
collisions = 1x31 logical array

   0   0   0   0   0   0   0   0   0   0   0   0   1   1   1   1   1   1   1   1   1   1   0   0
```

To validate paths with a large number of steps, use the `any` function on the vector of collision values.

```
if any(collisions)
    disp("Collision detected.")
end
```

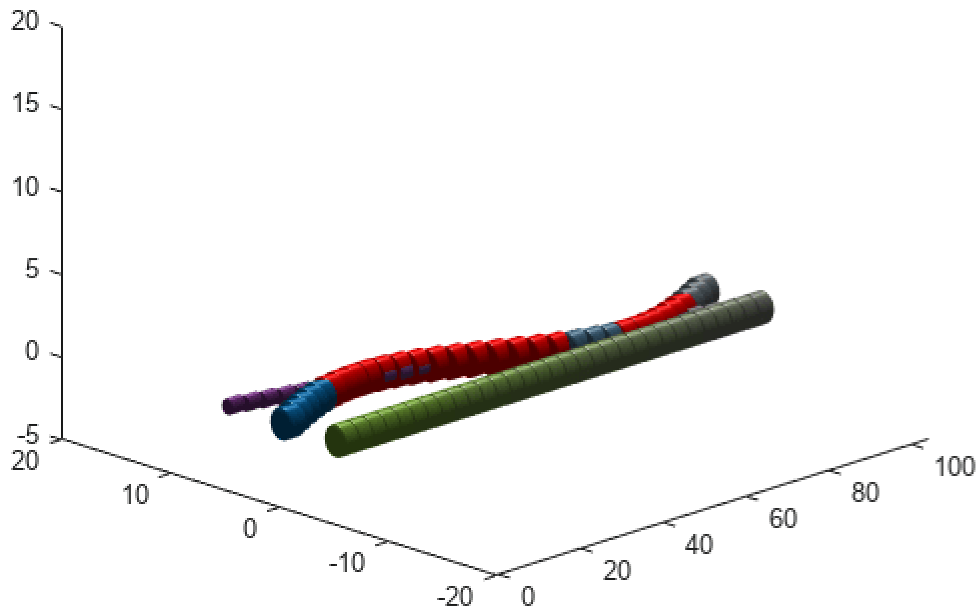
```
Collision detected.
```

### Update Ego Path

Specify a new path for the ego body. Visualize the paths again, displaying collisions.

```
egoCapsule1.States = ...
    [linspace(0,100,numSteps)' ... % x
    3*sin(linspace(0,2*pi,numSteps))' ... % y
    zeros(numSteps,1)... % z
    ones(numSteps,2) zeros(numSteps,2)]; %quaternion                                % quaterni
```

```
updateEgoPose(obsList,1,egoCapsule1);

cla
show(obsList,"TimeStep",1:numSteps,"ShowCollisions",1);
```




## Input Arguments

**capsuleListObj — Dynamic capsule-list**
dynamicCapsuleList3D object

Dynamic capsule-list, specified as a dynamicCapsuleList3D object.

## Output Arguments

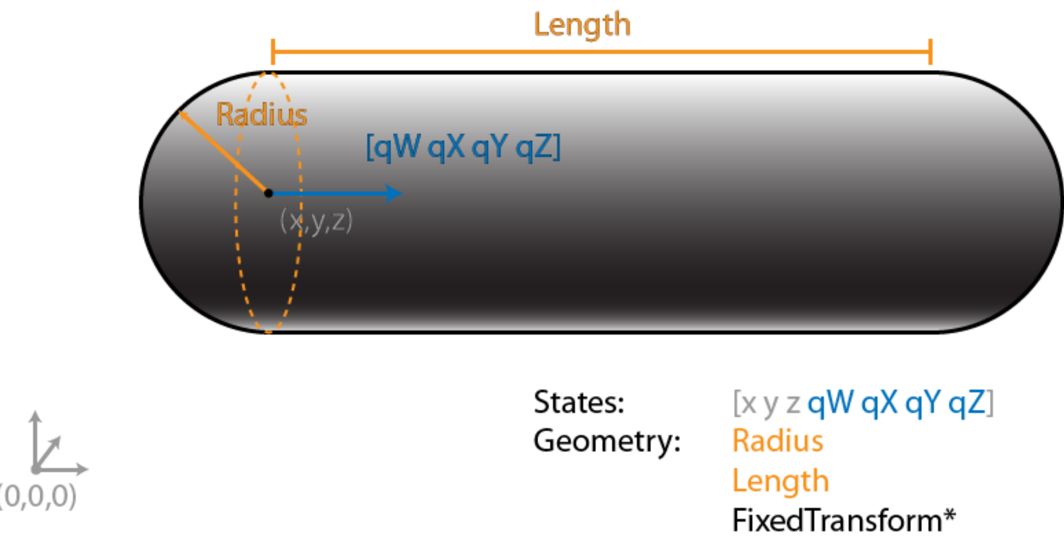
**obstacleStruct — Obstacle parameters**
structure | structure array

Obstacle parameters, specified as an *N*-element structure or a structure array, where *N* is the number of added ego bodies. The fields of each structure define the ID, geometry, and states of an obstacle:

- ID -- Integer that identifies each object. Stored in the ObstacleIDs property of the dynamicCapsuleList3D object specified by the capsuleListObj argument.
- States -- Location and orientation of the object as an *M*-by-6 matrix, where each row is of form [x y z qW qX qY qZ], and *M* is the number of states along the path of the object in the world

frame. The list of states assumes each state is separated by a fixed time interval. *xyz*-positions are in meters, and the orientation is a four-element quaternion vector. The default local origin is located at the center of the left hemisphere of the capsule.

- `Geometry` -- Structure with fields `Length`, `Radius`, and `FixedTransform`. These fields define the size of the capsule-based object using the specified length for the cylinder and hemisphere radius for the end caps. To shift the capsule geometry from the default origin, specify the `FixedTransform` field as a fixed transform relative to the local frame of the capsule. To keep the default capsule origin, specify the transform as `eye(4)`.




**`status` — Result of adding obstacles**
*N*-element column vector

Result of adding obstacles, returned as a *N*-element column vector of ones, zeros, and negative ones. *N* is the number of obstacles specified in the `obstacleStruct` argument. Each value indicates whether the associated body is added (`1`), updated (`0`), or a duplicate (`-1`). While adding obstacles, if multiple structures with the same body ID are found in the structure array `obstaclesStruct`, then the function marks the previous entry as duplicate and ignores it.

# Version History

**Introduced in R2020b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
dynamicCapsuleList | dynamicCapsuleList3D

**Functions**
addEgo | checkCollision | egoGeometry | egoPose | obstacleGeometry | obstaclePose | removeEgo | removeObstacle | show | updateEgoGeometry | updateEgoPose | updateObstacleGeometry | updateObstaclePose

**Topics**
"Highway Trajectory Planning Using Frenet Reference Path"

# ekfSLAM

Perform simultaneous localization and mapping using extended Kalman filter

## Description

The `ekfSLAM` object performs simultaneous localization and mapping (SLAM) using an extended Kalman filter (EKF). It takes in observed landmarks from the environment and compares them with known landmarks to find associations and new landmarks. Use the associations to correct the state and state covariance. The new landmarks are augmented in the state vector.

## Creation

### Syntax

```
slamObj = ekfSLAM
slamObj = ekfSLAM(Name,Value)
slamObj = ekfSLAM('MaxNumLandmark',N,Name,Value)
slamObj = ekfSLAM('MaxNumLandmark',N,‘MaxNumPoseStored’,M,Name,Value)
```

#### Description

`slamObj = ekfSLAM` creates an EKF SLAM object with default properties.

`slamObj = ekfSLAM(Name,Value)` sets properties using one or more name-value pair arguments in addition to any combination of input arguments from previous syntaxes. Any unspecified properties have default values.

`slamObj = ekfSLAM('MaxNumLandmark',N,Name,Value)` specifies an upper bound on the number of landmarks `N` allowed in the state vector when generating code. This limit on the number of landmarks applies only when generating code.

`slamObj = ekfSLAM('MaxNumLandmark',N,‘MaxNumPoseStored’,M,Name,Value)` specifies the maximum size of the pose history `M` along with the maximum number of landmarks `N` in the state vector while generating code. These limits apply only when generating code.

## Properties

You cannot change the value of the properties State, StateCovariance, StateTransitionFcn, and MaxNumLandmark after the object is created. Set the value of these properties as a default or while creating the object.

**`State` — State vector**
`[0; 0; 0]` (default) | *M*-element column vector

State vector, specified as an *M*-element column vector.

Data Types: `single` | `double`

**`StateCovariance` — State estimation error covariance**
`eye(3)` (default) | *M*-by-*M* matrix

State estimation error covariance, specified as an *M*-by-*M* matrix. *M* is the number of states in the state vector.

Data Types: `single` | `double`

**`StateTransitionFcn` — State transition function**
`nav.algs.velocityMotionModel` (default) | function handle

State transition function, specified as a function handle. This function calculates the state vector at time step `k` from the state vector at time step `k-1`. The function can take additional input parameters, such as control inputs or time step size.

The function also calculates the Jacobians with respect to the current pose and controller input. If not specified, the Jacobians are computed using numerical differencing at each call to the `predict` function. This computation can increase processing time and numerical inaccuracy.

The function considers nonadditive process noise, and should have this signature:

```
[pose(k),jacPose,jacControl] =
StateTransitionFcn(pose(k-1),controlInput,parameters)
```

- `pose(k)` is the estimated pose at time `k`.
- `jacPose` is the Jacobian of `StateTransitionFcn` with respect to `pose(k-1)`.
- `jacControl` is the Jacobian of `StateTransitionFcn` with respect to `controlInput`.
- `controlInput` is the input for propagating the state.
- `parameters` are any additional arguments required by the state transition function.

Data Types: `function_handle`

**`MeasurementFcn` — Measurement function**
`nav.algs.rangeBearingMeasurement` (default) | function handle

Measurement function, specified as a function handle. This function calculates an *N*-element measurement vector for an *M*-element state vector.

The function also calculates the Jacobians with respect to the current pose and landmark position. If not specified, the Jacobians are computed using numerical differencing at each call to the `correct` function. This computation can increase processing time and numerical inaccuracy.

The function considers additive measurement noise, and should have this signature:

```
[measurements(k),jacPose,jacLandmarks] = MeasurementFcn(pose(k),landmarks)
```

- `pose(k)` is the estimated pose at time `k`.
- `measurements(k)` is the estimated measurement at time `k`.
- `landmarks` are the positions of the landmarks.
- `jacPose` is the Jacobian of `MeasurementFcn` with respect to `pose(k)`.
- `jacLandmarks` is the Jacobian of `MeasurementFcn` with respect to `landmarks`.

Data Types: `function_handle`

**InverseMeasurementFcn — Inverse measurement function**
nav.algs.rangeBearingInverseMeasurement (default) | function handle

Inverse measurement function, specified as a function handle. This function calculates the landmark position as an *M*-element state vector for an *N*-element measurement vector.

The function also calculates the Jacobians with respect to the current pose and measurement. If not specified, the Jacobians are computed using numerical differencing at each call to the `correct` function. This computation can increase processing time and numerical inaccuracy.

The function should have this signature:

```
[landmarks(k),jacPose,jacMeasurements] =
InverseMeasurementFcn(pose(k),measurements)
```

- `pose(k)` is the estimated pose at time `k`.
- `landmarks(k)` is the landmark position at time `k`.
- `measurements` are the observed landmarks at time `k`.
- `jacPose` is the Jacobian of `InverseMeasurementFcn` with respect to `pose(k)`.
- `jacMeasurements` is the Jacobian of `InverseMeasurementFcn` with respect to `measurements`.

Data Types: `function_handle`

**DataAssociationFcn — Data association function**
nav.algs.associateMaxLikelihood (default) | function handle

Data association function, specified as a function handle. This function associates the measurements with the landmarks already available in the state vector. The function may take additional input parameters.

The function should have this signature:

```
[associations,newLandmarks] =
DataAssociationFcn(knownLandmarks,knownLandmarksCovariance,observedLandmarks,
observedLandmarksCovariance,parameters)
```

- `knownLandmarks` are known landmarks in the map.
- `knownLandmarksCovariance` is the covariance of `knownLandmarks`.
- `observedLandmarks` are the observed landmarks in the environment.
- `observedLandmarksCovariance` is the covariance of `observedLandmarks`.
- `parameters` are any additional arguments required.
- `associations` is a list of associations from `knownLandmarks` to `observedLandmarks`.
- `newLandmarks` are the indices of `observedLandmarks` that qualify as new landmarks.

Data Types: `function_handle`

**ProcessNoise — Process noise covariance**
eye(2) (default) | *W*-by-*W* matrix

Process noise covariance, specified as a *W*-by-*W* matrix. *W* is the number of process noise terms.

Data Types: `single` | `double`

**MaxAssociationRange — Maximum range for landmarks to be checked for association**
inf (default) | positive integer

Maximum range for the landmarks to be checked for association, specified as a positive integer.

Data Types: single | double

**MaxNumLandmark — Maximum number of landmarks in state vector**
inf (default) | positive integer

Maximum number of landmarks in the state vector, specified as a positive integer.

Data Types: single | double

**MaxNumPoseStored — Maximum size of pose history**
inf (default) | positive integer

Maximum size of pose history, specified as a positive integer.

Data Types: single | double

## Object Functions

| | |
|---|---|
| copy | Create deep copy of EKF SLAM object |
| correct | Correct state and state error covariance |
| landmarkInfo | Retrieve landmark information |
| poseHistory | Retrieve corrected and predicted pose history |
| predict | Predict state and state error covariance |
| removeLandmark | Remove landmark from state vector |
| reset | Reset state and state estimation error covariance |

## Examples

### Perform Landmark SLAM Using Extended Kalman Filter

Load a race track data set that contains the initial vehicle state, initial vehicle state covariance, process noise covariance, control input, time step size, measurement, measurement covariance, and validation gate values.

```
load("racetrackDataset.mat","initialState","initialStateCovariance", ...
     "processNoise","controllerInputs","timeStep", ...
     "measurements","measCovar","validationGate");
```

Create an ekfSLAM object with initial state, initial state covariance, and process noise.

```
ekfSlamObj = ekfSLAM("State",initialState, ...
                     "StateCovariance",initialStateCovariance, ...
                     "ProcessNoise",processNoise);
```

Initialize a variable to store the pose.

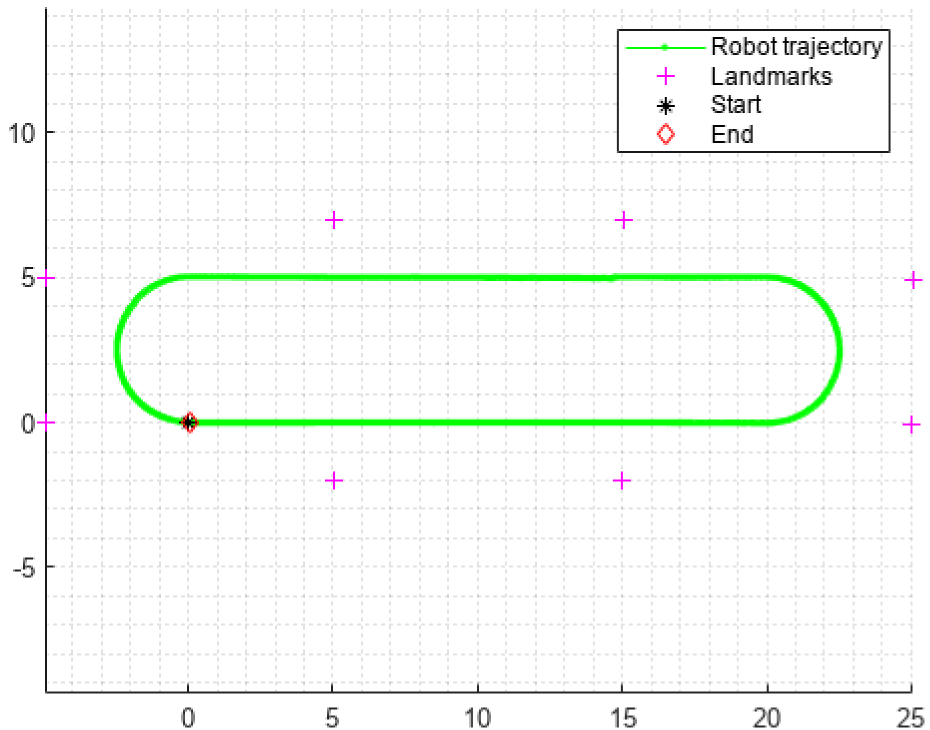
```
storedPose = nan(size(controllerInputs,1)+1,3);
storedPose(1,:) = ekfSlamObj.State(1:3);
```

Predict the state using the control input and time step size for the state transition function. Then, correct the state using the data of the observed landmarks, measurement covariance, and validation gate for the data association function.

```
for count = 1:size(controllerInputs,1)
    % Predict the state
    predict(ekfSlamObj,controllerInputs(count,:),timeStep);

    % Get the landmarks in the environment
    observedLandmarks = measurements{count};

    % Correct the state
    if ~isempty(observedLandmarks)
        correct(ekfSlamObj,observedLandmarks, ...
                measCovar,validationGate);
    end

    % Log the estimated pose
    storedPose(count+1,:) = ekfSlamObj.State(1:3);
end
```

Visualize the created map.

```
fig = figure;
figAx = axes(fig);
axis equal
grid minor
hold on
plot(figAx,storedPose(:,1),storedPose(:,2),"g.-")
landmarks = reshape(ekfSlamObj.State(4:end),2,[])';
plot(figAx,landmarks(:,1),landmarks(:,2),"m+")
plot(figAx,storedPose(1,1),storedPose(1,2),"k*")
plot(figAx,storedPose(end,1),storedPose(end,2),"rd")
legend("Robot trajectory","Landmarks","Start","End")
```




# Version History

**Introduced in R2021b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Objects

`lidarSLAM`

### Functions

`copy` | `correct` | `landmarkInfo` | `poseHistory` | `predict` | `removeLandmark` | `reset`

### Topics

"EKF-Based Landmark SLAM"

# copy

Create deep copy of EKF SLAM object

## Syntax

```
newSlamObj = copy(slamObj)
```

## Description

`newSlamObj = copy(slamObj)` creates a deep copy of `slamObj` with the same properties. Any changes made to `newSlamObj` are not reflected in `slamObj`.

## Examples

### Remove Landmark from `ekfSLAM` Object

Specify the initial vehicle state.

```
initialState = [1; -2; 0.1];
```

Specify the initial landmark positions.

```
landmarkPosition = [15.8495; -12.9496;
                    25.2455; -15.4705;
                    37.5880;   3.1023;
                    16.5690;   2.7466];
```

Specify the initial vehicle state covariance.

```
initialStateCovar = diag([0.1*ones(1,3) 1.1*ones(1,8)]);
```

Create an `ekfSLAM` object with initial state and initial state covariance.

```
ekfSlamObj = ekfSLAM('State',[initialState; landmarkPosition], ...
                     'StateCovariance',initialStateCovar);
landmarkInfo(ekfSlamObj)
```

```
ans=4×3 table
    landmark number    landmark state index    landmark position
    _______________    ____________________    _________________

           1                  4      5          15.85    -12.95
           2                  6      7         25.245    -15.47
           3                  8      9         37.588    3.1023
           4                 10     11         16.569    2.7466
```

Create a deep copy of the `ekfSLAM` object.

```
newEkfSlamObj = copy(ekfSlamObj);
```

Specify the landmark number to be removed.

```
removeLandmark(newEkfSlamObj,3);
landmarkInfo(newEkfSlamObj)
```

```
ans=3×3 table
    landmark number    landmark state index    landmark position
    _______________    ____________________    _________________

           1                  4    5            15.85    -12.95
           2                  6    7           25.245    -15.47
           3                  8    9           16.569    2.7466
```

## Input Arguments

**slamObj — EKF SLAM object**
ekfSLAM object

EKF SLAM object, specified as an ekfSLAM object.

## Output Arguments

**newSlamObj — Copy of EKF SLAM object**
ekfSLAM object

Copy of the EKF SLAM object, returned as an ekfSLAM object.

# Version History

**Introduced in R2021b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
ekfSLAM | lidarSLAM

**Functions**
correct | landmarkInfo | poseHistory | predict | removeLandmark | reset

# correct

Correct state and state error covariance

## Syntax

`[associations,newLandmark] = correct(slamObj,measurement,`
`measurementCovariance)`
`[associations,newLandmark] = correct(slamObj,measurement,`
`measurementCovariance,varargin)`

## Description

`[associations,newLandmark] = correct(slamObj,measurement,`
`measurementCovariance)` corrects the state and its associated state covariance based on the `measurement` and `measurementCovariance` at the current time step. `correct` uses the data association function specified in the DataAssociationFcn property of the `ekfSLAM` object, `slamObj`, to associate the measurement to landmarks and extract new landmarks from the measurement.

The `correct` function uses these associations to correct the state and associated state covariance, then augments the state with new landmarks.

`[associations,newLandmark] = correct(slamObj,measurement,`
`measurementCovariance,varargin)` passes all additional arguments specified in `varargin` to the underlying DataAssociationFcn property of `slamObj`.

The first four inputs to the `DataAssociationFcn` property are the landmark position, landmark position covariance, measurement, and measurement covariance, followed by all arguments in `varargin`.

## Examples

### Perform Landmark SLAM Using Extended Kalman Filter

Load a race track data set that contains the initial vehicle state, initial vehicle state covariance, process noise covariance, control input, time step size, measurement, measurement covariance, and validation gate values.

```
load("racetrackDataset.mat","initialState","initialStateCovariance", ...
     "processNoise","controllerInputs","timeStep", ...
     "measurements","measCovar","validationGate");
```

Create an `ekfSLAM` object with initial state, initial state covariance, and process noise.

```
ekfSlamObj = ekfSLAM("State",initialState, ...
                     "StateCovariance",initialStateCovariance, ...
                     "ProcessNoise",processNoise);
```

Initialize a variable to store the pose.

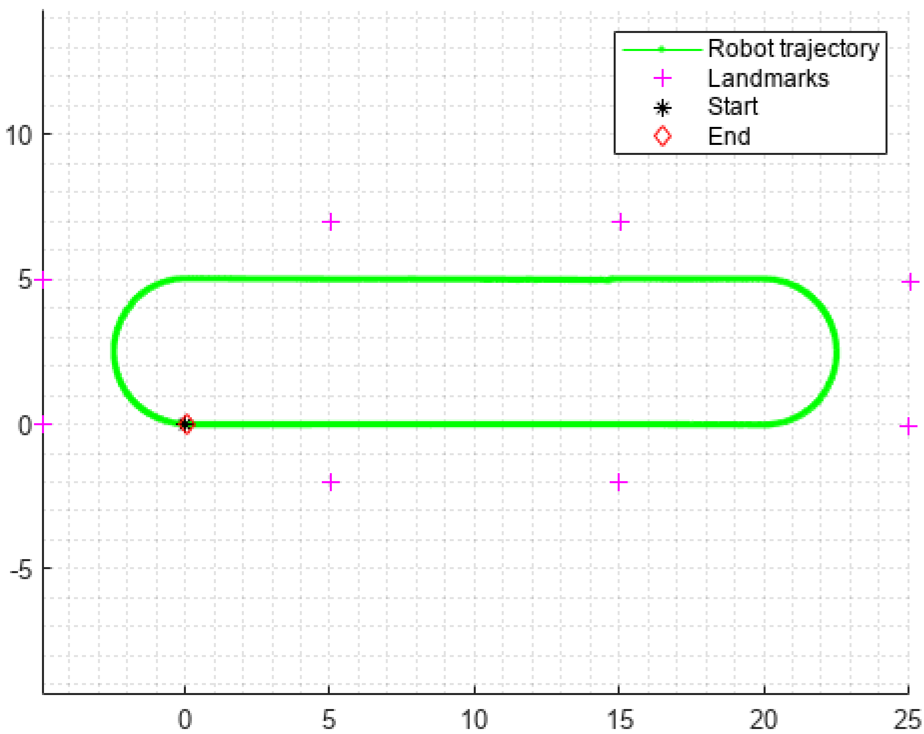
```
storedPose = nan(size(controllerInputs,1)+1,3);
storedPose(1,:) = ekfSlamObj.State(1:3);
```

Predict the state using the control input and time step size for the state transition function. Then, correct the state using the data of the observed landmarks, measurement covariance, and validation gate for the data association function.

```
for count = 1:size(controllerInputs,1)
    % Predict the state
    predict(ekfSlamObj,controllerInputs(count,:),timeStep);

    % Get the landmarks in the environment
    observedLandmarks = measurements{count};

    % Correct the state
    if ~isempty(observedLandmarks)
        correct(ekfSlamObj,observedLandmarks, ...
                measCovar,validationGate);
    end

    % Log the estimated pose
    storedPose(count+1,:) = ekfSlamObj.State(1:3);
end
```

Visualize the created map.

```
fig = figure;
figAx = axes(fig);
axis equal
grid minor
hold on
plot(figAx,storedPose(:,1),storedPose(:,2),"g.-")
landmarks = reshape(ekfSlamObj.State(4:end),2,[])';
plot(figAx,landmarks(:,1),landmarks(:,2),"m+")
plot(figAx,storedPose(1,1),storedPose(1,2),"k*")
plot(figAx,storedPose(end,1),storedPose(end,2),"rd")
legend("Robot trajectory","Landmarks","Start","End")
```




## Input Arguments

**`slamObj` — EKF SLAM object**
`ekfSLAM` object

EKF SLAM object, specified as an `ekfSLAM` object.

**`measurement` — Measurements of landmarks in environment**
*N*-by-*K* matrix

Measurements of the landmarks in the environment, specified as an *N*-by-*K* matrix. *K* is the dimension of the measurement. *N* is the number of measurements.

Data Types: `single` | `double`

**`measurementCovariance` — Covariance of measurements**
*K*-element vector | *N***K*-by-*N***K* matrix

Covariance of the measurements, specified as a *K*-element vector or *N***K*-by-*N***K* matrix. *K* is the dimension of the measurement. *N* is the number of measurements. When specified as a vector, the same covariance value is used for all measurements.

Data Types: `single` | `double`

**`varargin` — Variable-length input argument list**
comma-separated list

Variable-length input argument list, specified as a comma-separated list. This input is passed directly into the DataAssociationFcn property of `slamObj`. When you call:

```
correct(slamObj,measurement,measurementCovariance,arg1,arg2)
```

MATLAB essentially calls the `dataAssociationFcn` as:

```
dataAssociationFcn(knownLandmarks,knownLandmarksCovariance, ...
measurement,measurementCovariance,arg1,arg2)
```

## Output Arguments

**`associations` — List of associations of landmarks to measurements**
*P*-by-2 matrix

List of associations of landmarks to measurements, returned as a *P*-by-2 matrix. *P* is the number of associations. The first column of the matrix contains the indices of the associated landmarks, and the second column contains the associated measurement indices.

**`newLandmark` — List of indices of measurements that qualify as new landmarks**
*Q*-element vector

List of indices of the measurements that qualify as new landmarks, returned as a *Q*-element vector. *Q* is the number of measurements that qualify as new landmarks.

# Version History

**Introduced in R2021b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
`ekfSLAM`

**Functions**
`landmarkInfo` | `poseHistory` | `predict` | `removeLandmark` | `reset`

# landmarkInfo

Retrieve landmark information

## Syntax

```
Info = landmarkInfo(slamObj)
Info = landmarkInfo(slamObj,landmarkIndex)
```

## Description

`Info = landmarkInfo(slamObj)`retrieves landmark information from the `ekfSLAM` object as a table that contains each landmark number along with its position and state index.

`Info = landmarkInfo(slamObj,landmarkIndex)` retrieves landmark information for only those landmarks specified by `landmarkIndex`.

## Examples

### Retrieve All Landmark Information from `ekfSLAM` Object

Specify the initial vehicle state.

```
initialState = [1; -2; 0.1];
```

Specify the initial landmark positions.

```
landmarkPosition = [15.8495; -12.9496;
                    25.2455; -15.4705;
                    37.5880;   3.1023;
                    16.5690;   2.7466];
```

Specify the initial vehicle state covariance.

```
initialStateCovar = diag([0.1*ones(1,3) 1.1*ones(1,8)]);
```

Create an `ekfSLAM` object with initial state and initial state covariance.

```
ekfSlamObj = ekfSLAM('State',[initialState; landmarkPosition], ...
                     'StateCovariance',initialStateCovar)
```

```
ekfSlamObj = 
  ekfSLAM with properties:

                 State: [11x1 double]
       StateCovariance: [11x11 double]
        MaxNumLandmark: Inf
    StateTransitionFcn: @nav.algs.velocityMotionModel
          ProcessNoise: [2x2 double]

           MeasurementFcn: @nav.algs.rangeBearingMeasurement
    InverseMeasurementFcn: @nav.algs.rangeBearingInverseMeasurement
```

```
     DataAssociationFcn: @nav.algs.associateMaxLikelihood
    MaxAssociationRange: Inf
```

Get the information for all the landmarks.

```
info = landmarkInfo(ekfSlamObj)
```

```
info=4×3 table
    landmark number    landmark state index    landmark position
    _______________    ____________________    _________________

           1                   4     5            15.85    -12.95
           2                   6     7           25.245    -15.47
           3                   8     9           37.588    3.1023
           4                  10    11           16.569    2.7466
```

## Input Arguments

**`slamObj` — EKF SLAM object**
`ekfSLAM` object

EKF SLAM object, specified as an `ekfSLAM` object.

**`landmarkIndex` — Indices of landmarks for which to retrieve information**
*N*-element column vector | *N*-by-2 matrix

Indices of landmarks for which to retrieve information, specified as an *N*-element column vector of landmark numbers in the state vector or an *N*-by-2 matrix of exact positions of landmarks in the state vector. *N* is the number of landmarks.

Data Types: `single` | `double`

## Output Arguments

**`Info` — Landmark information**
table

Landmark information, returned as a table.

# Version History

**Introduced in R2021b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
`ekfSLAM`

**Functions**
`correct` | `poseHistory` | `predict` | `removeLandmark` | `reset`

# poseHistory

Retrieve corrected and predicted pose history

## Syntax

```
[correctedPose,predictedPose] = poseHistory(slamObj)
```

## Description

`[correctedPose,predictedPose] = poseHistory(slamObj)` retrieves the corrected and predicted pose history up to the current pose.

---

**Note** To use this function during code generation, you must specify the `MaxNumPoseStored` property of the `ekfSLAM` object. Otherwise, this function returns an error.

---

## Examples

### Retrieve Pose History from `ekfSLAM` Object

Specify the initial vehicle state.

```
initialState = [1; -2; 0.1];
```

Specify the initial landmark positions.

```
landmarkPosition = [15.8495; -12.9496;
                    25.2455; -15.4705;
                    37.5880;   3.1023;
                    16.5690;   2.7466];
```

Specify the initial vehicle state covariance.

```
initialStateCovar = diag([0.1*ones(1,3) 1.1*ones(1,8)]);
```

Create an `ekfSLAM` object with initial state and initial state covariance.

```
ekfSlamObj = ekfSLAM('State',[initialState; landmarkPosition], ...
                     'StateCovariance',initialStateCovar);
```

Specify the control input and time step size for the state transition function.

```
velocity = [1 0];
timeStep = 0.25;
```

Call the `predict` function.

```
predict(ekfSlamObj,velocity,timeStep);
```

Specify the measurement and measurement covariance for the data association function.

```
measurement = [18.4500 -0.7354;
               27.7362 -0.6071;
               36.9421  0.0386;
               16.2765  0.1959];
measureCovar = [0.1^2 (1.0*pi/180)^2];
```

Call the `correct` function.

```
validationGate = 5.991;
associations = correct(ekfSlamObj,measurement, ...
                       measureCovar,validationGate);
```

Get the pose history.

```
[corrPose,predPose] = poseHistory(ekfSlamObj)
```

```
corrPose = 1×3

    1.1609   -1.9736    0.0981


predPose = 1×3

    1.2488   -1.9750    0.1000
```

## Input Arguments

**`slamObj` — EKF SLAM object**
`ekfSLAM` object

EKF SLAM object, specified as an `ekfSLAM` object.

## Output Arguments

**`correctedPose` — Corrected poses**
*M*-by-3 matrix

Corrected poses, returned as an *M*-by-3 matrix with rows of the form [*X Y Yaw*]. *X* and *Y* specify the position in meters. *Yaw* specifies the orientation in radians.

**`predictedPose` — Predicted poses**
*M*-by-3 matrix

Predicted poses, returned as an *M*-by-3 matrix with rows of the form [*X Y Yaw*]. *X* and *Y* specify the position in meters. *Yaw* specifies the orientation in radians.

# Version History

**Introduced in R2021b**

## Extended Capabilities

### C/C++ Code Generation
Generate C and C++ code using MATLAB® Coder™.

## See Also

### Objects
ekfSLAM

### Functions
correct | landmarkInfo | predict | removeLandmark | reset

# predict

Predict state and state error covariance

## Syntax

```
predict(slamObj,controlInput)
predict(slamObj,controlInput,varargin)
```

## Description

`predict(slamObj,controlInput)` predicts the state and state error covariance. `predict` uses the StateTransitionFcn property of the `ekfSLAM` object, `slamObj`, and the controller input `controlInput` to predict the state.

`predict(slamObj,controlInput,varargin)` passes all additional arguments specified in `varargin` to the underlying StateTransitionFcn property of `slamObj`.

The first input to `StateTransitionFcn` is the pose from the previous time step, followed by all user-defined arguments in `varargin`.

## Examples

### Perform Landmark SLAM Using Extended Kalman Filter

Load a race track data set that contains the initial vehicle state, initial vehicle state covariance, process noise covariance, control input, time step size, measurement, measurement covariance, and validation gate values.

```
load("racetrackDataset.mat","initialState","initialStateCovariance", ...
     "processNoise","controllerInputs","timeStep", ...
     "measurements","measCovar","validationGate");
```

Create an `ekfSLAM` object with initial state, initial state covariance, and process noise.

```
ekfSlamObj = ekfSLAM("State",initialState, ...
                     "StateCovariance",initialStateCovariance, ...
                     "ProcessNoise",processNoise);
```

Initialize a variable to store the pose.

```
storedPose = nan(size(controllerInputs,1)+1,3);
storedPose(1,:) = ekfSlamObj.State(1:3);
```

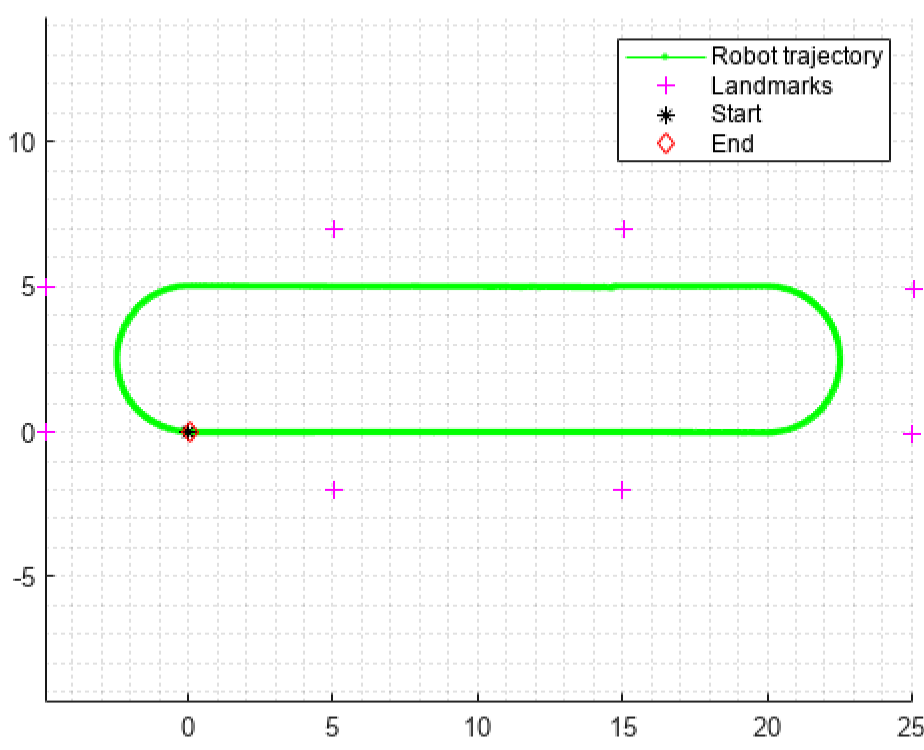
Predict the state using the control input and time step size for the state transition function. Then, correct the state using the data of the observed landmarks, measurement covariance, and validation gate for the data association function.

```
for count = 1:size(controllerInputs,1)
    % Predict the state
    predict(ekfSlamObj,controllerInputs(count,:),timeStep);
```

```
    % Get the landmarks in the environment
    observedLandmarks = measurements{count};

    % Correct the state
    if ~isempty(observedLandmarks)
        correct(ekfSlamObj,observedLandmarks, ...
                measCovar,validationGate);
    end

    % Log the estimated pose
    storedPose(count+1,:) = ekfSlamObj.State(1:3);
end
```

Visualize the created map.

```
fig = figure;
figAx = axes(fig);
axis equal
grid minor
hold on
plot(figAx,storedPose(:,1),storedPose(:,2),"g.-")
landmarks = reshape(ekfSlamObj.State(4:end),2,[])';
plot(figAx,landmarks(:,1),landmarks(:,2),"m+")
plot(figAx,storedPose(1,1),storedPose(1,2),"k*")
plot(figAx,storedPose(end,1),storedPose(end,2),"rd")
legend("Robot trajectory","Landmarks","Start","End")
```



## Input Arguments

**`slamObj` — EKF SLAM object**
`ekfSLAM` object

EKF SLAM object, specified as a `ekfSLAM` object.

**`controlInput` — Controller input required to propagate state**
*N*-element vector

Controller input required to propagate the state from initial value to final value, specified as an *N*-element vector.

---

**Note** The dimension of the process noise must be equal to the number of elements in `controlInput`.

---

Data Types: `single` | `double`

**`varargin` — Variable-length input argument list**
comma-separated list

Variable-length input argument list, specified as a comma-separated list. This input is passed directly into the StateTransitionFcn property of `slamObj` to evolve the state. When you call:

```
predict(slamObj,controlInput,arg1,arg2)
```

MATLAB essentially calls the `stateTransitionFcn` as:

```
stateTransitionFcn(pose(k-1),controlInput,arg1,arg2)
```

# Version History

**Introduced in R2021b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
`ekfSLAM`

**Functions**
`correct` | `landmarkInfo` | `poseHistory` | `removeLandmark` | `reset`

# removeLandmark

Remove landmark from state vector

## Syntax

```
removeLandmark(slamObj,landmarkIndex)
```

## Description

`removeLandmark(slamObj,landmarkIndex)` removes the landmarks at the specified indices `landmarkIndex` from the state vector, along with associated covariances from the state covariance matrix.

## Examples

### Remove Landmark from ekfSLAM Object

Specify the initial vehicle state.

```
initialState = [1; -2; 0.1];
```

Specify the initial landmark positions.

```
landmarkPosition = [15.8495; -12.9496;
                    25.2455; -15.4705;
                    37.5880;   3.1023;
                    16.5690;   2.7466];
```

Specify the initial vehicle state covariance.

```
initialStateCovar = diag([0.1*ones(1,3) 1.1*ones(1,8)]);
```

Create an `ekfSLAM` object with initial state and initial state covariance.

```
ekfSlamObj = ekfSLAM('State',[initialState; landmarkPosition], ...
                     'StateCovariance',initialStateCovar);
landmarkInfo(ekfSlamObj)
```

```
ans=4×3 table
    landmark number    landmark state index    landmark position
    _______________    ____________________    _________________

           1                  4      5           15.85    -12.95
           2                  6      7          25.245    -15.47
           3                  8      9          37.588    3.1023
           4                 10     11          16.569    2.7466
```

Create a deep copy of the `ekfSLAM` object.

```
newEkfSlamObj = copy(ekfSlamObj);
```

Specify the landmark number to be removed.

```
removeLandmark(newEkfSlamObj,3);
landmarkInfo(newEkfSlamObj)
```

```
ans=3×3 table
    landmark number    landmark state index    landmark position
    _______________    ____________________    _________________

           1                  4    5            15.85    -12.95
           2                  6    7           25.245    -15.47
           3                  8    9           16.569    2.7466
```

## Input Arguments

**`slamObj` — EKF SLAM object**
`ekfSLAM` object

EKF SLAM object, specified as an `ekfSLAM` object.

**`landmarkIndex` — Indices of landmarks to remove**
*N*-element column vector | *N*-by-2 matrix

Indices of the landmarks to remove, specified as an *N*-element column vector of landmark numbers in the state vector or an *N*-by-2 matrix of the exact positions of landmarks in the state vector. *N* is the number of landmarks to remove.

Data Types: `single` | `double`

# Version History

**Introduced in R2021b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
`ekfSLAM`

**Functions**
`correct` | `landmarkInfo` | `poseHistory` | `predict` | `reset`

# reset

Reset state and state estimation error covariance

## Syntax

`reset(slamObj)`

## Description

`reset(slamObj)` resets the state and state estimation error covariance to their default values, and resets the internal states.

## Examples

### Reset State and State Estimation Error Covariance in ekfSLAM Object

Specify the initial vehicle state.

```
initialState = [1; -2; 0.1];
```

Specify the initial vehicle state covariance.

```
initialStateCovar = 0.1*eye(3);
```

Create an `ekfSLAM` object with initial state and initial state covariance.

```
ekfSlamObj = ekfSLAM('State',initialState, ...
                     'StateCovariance',initialStateCovar);
```

Get the state and the state covariance from the `ekfSLAM` object.

```
ekfSlamObj.State
```

```
ans = 3×1

    1.0000
   -2.0000
    0.1000
```

```
ekfSlamObj.StateCovariance
```

```
ans = 3×3

    0.1000         0         0
         0    0.1000         0
         0         0    0.1000
```

Reset the state and state estimation error covariance to the default value.

```
reset(ekfSlamObj)
```

Get the state and the state covariance from the ekfSLAM object.

```
ekfSlamObj.State
```

```
ans = 3×1

     0
     0
     0
```

```
ekfSlamObj.StateCovariance
```

```
ans = 3×3

     1     0     0
     0     1     0
     0     0     1
```

## Input Arguments

**slamObj — EKF SLAM object**
ekfSLAM object

EKF SLAM object, specified as an ekfSLAM object.

# Version History

**Introduced in R2021b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
ekfSLAM

**Functions**
correct | landmarkInfo | poseHistory | predict | removeLandmark

# factorIMU

Convert IMU readings to factor

## Description

The `factorIMU` object converts raw IMU readings into constraints between poses, velocities, and IMU biases for a `factorGraph` object.

## Creation

### Syntax

```
F = factorIMU(nodeID,GyroscopeReadings,AccelerometerReadings)
F = factorIMU(nodeID,GyroscopeReadings,AccelerometerReadings,imuparams)
F = factorIMU(nodeID,SampleRate,GyroscopeBiasNoise,AccelerometerBiasNoise,
GyroscopeNoise,AccelerometerNoise,GyroscopeReadings,AccelerometerReadings)
F = factorIMU( ___ ,Name=Value)
```

#### Description

`F = factorIMU(nodeID,GyroscopeReadings,AccelerometerReadings)` creates a `factorIMU` object, `F`, with the specified node identification numbers property `NodeID` set to `nodeID`, and with the gyroscope readings and accelerometer readings properties set to the values of their corresponding arguments.

`F = factorIMU(nodeID,GyroscopeReadings,AccelerometerReadings,imuparams)` specifies IMU parameters, such as sampling rate, gyroscope bias noise, and accelerometer bias noise, as a `factorIMUParameters` object.

`F = factorIMU(nodeID,SampleRate,GyroscopeBiasNoise,AccelerometerBiasNoise, GyroscopeNoise,AccelerometerNoise,GyroscopeReadings,AccelerometerReadings)` creates a `factorIMU` object, `F`, with the specified node identification numbers property `NodeID` set to `nodeID`, and with a sample rate, gyroscope bias noise, accelerometer bias noise, gyroscope noise, accelerometer noise, gyroscope readings, and accelerometer readings set to their corresponding values, respectively.

`F = factorIMU( ___ ,Name=Value)` specifies properties using one or more name-value arguments in addition to all input arguments from the previous syntax.

#### Input Arguments

**`imuparams` — Factor IMU parameters**
`factorIMUParameters` object

Factor IMU parameters, specified as a `factorIMUParameters` object.

## Properties

**`NodeID` — Node ID numbers**
six-element row vector of integers

This property is read-only.

Node ID numbers, specified as a six-element row vector. The `factorIMU` object factor connects to these nodes in the factor graph.

If there are no nodes in the factor graph with the specified ID, nodes with the specified IDs are automatically created and added to the factor graph when this factor is added to the factor graph.

You must specify this property at object creation.

**`SampleRate` — IMU sampling rate**
numeric scalar greater than `100`

This property is read-only.

IMU sampling rate, in Hz, specified as a numeric scalar greater than `100`.

You must specify this property at object creation.

**`GyroscopeBiasNoise` — Gyroscope bias noise covariance**
3-by-3 matrix

This property is read-only.

Gyroscope bias noise covariance, specified as a 3-by-3 matrix.

You must specify this property at object creation.

**`AccelerometerBiasNoise` — Accelerometer bias noise covariance**
3-by-3 matrix

This property is read-only.

Accelerometer bias noise covariance, specified as a 3-by-3 matrix.

You must specify this property at object creation.

**`GyroscopeNoise` — Gyroscope measurement noise covariance**
3-by-3 matrix

This property is read-only.

Gyroscope measurement noise covariance, specified as a 3-by-3 matrix.

You must specify this property at object creation.

**`AccelerometerNoise` — Accelerometer measurement noise covariance**
3-by-3 matrix

This property is read-only.

Accelerometer measurement noise covariance, specified as a 3-by-3 matrix.

You must specify this property at object creation.

**`GyroscopeReadings` — Gyroscope readings**
*N*-by-3 matrix

This property is read-only.

Gyroscope readings, specified as an *N*-by-3 matrix, where *N* is the number of readings. The specified gyroscope readings are preintegrated into the factor. `GyroscopeReadings` and `AccelerometerReadings` must have the same size.

You must specify this property at object creation.

**`AccelerometerReadings` — Accelerometer readings**
*N*-by-3 matrix

This property is read-only.

Accelerometer readings, specified as an *N*-by-3 matrix, where N is the number of readings. The specified accelerometer readings are preintegrated into the factor. `GyroscopeReadings` and `AccelerometerReadings` must have the same size.

You must specify this property at object creation.

**`ReferenceFrame` — Reference frame for local coordinate system**
`"ENU"` (default) | `"NED"`

Reference frame for the local coordinate system, specified as `"ENU"` (east-north-up) or `"NED"` (north-east-down).

Data Types: `string` | `char`

**`SensorTransform` — Transformation consisting of 3-D translation and rotation to transform connecting pose nodes to initial IMU frame**
`se3()` (default) | `se3` object

Transformation consisting of 3-D translation and rotation to transform connecting pose nodes to the initial IMU sensor reference frame, specified as an `se3` object.

For example, if the connected pose nodes store camera poses in the initial camera sensor reference frame, the sensor transform rotates and translates a pose in the initial camera sensor reference frame to the initial IMU sensor reference frame. The initial sensor reference frame has the very first sensor pose at its origin.

A sensor transform is unnecessary if the connecting pose nodes contain poses in the initial IMU sensor reference frame. Otherwise, you must specify the sensor transform.

## Object Functions

| | |
|---|---|
| nodeType | Get node type of node in factor graph |
| predict | Predict pose and velocity of factor |

## Examples

### Add factorIMU Object to Factor Graph

Set up parameters such as the connected node IDs, sample rate, noise, and readings. Then create an IMU factor with these parameters as arguments.

```
nodeID = [1,2,3,4,5,6];
sampleRate = 400; % Hz
gyroBiasNoise = 1.5e-9 * eye(3);
accelBiasNoise = diag([9.62e-9, 9.62e-9, 2.17e-8]);
gyroNoise = 6.93e-5 * eye(3);
accelNoise = 2.9e-6 * eye(3);
gyroReadings = [ -0.0151    0.0299    0.0027
                -0.0079    0.0370   -0.0014
                -0.0320    0.0306    0.0035
                -0.0043    0.0340   -0.0066
                -0.0033    0.0331   -0.0011];
accelReadings = [   1.0666    0.0802    9.9586
                   1.1002    0.0199    9.6650
                   1.0287    0.3071   10.1864
                   0.9077   -0.2239   10.2989
                   1.2322    0.0174    9.8411];

f = factorIMU(nodeID, sampleRate, gyroBiasNoise, accelBiasNoise, ...
             gyroNoise, accelNoise, gyroReadings, accelReadings, ReferenceFrame="NED");
```

Create a default factor graph and add the factor to the graph using the `addFactor` function.

```
g = factorGraph;
addFactor(g,f);
```

# Version History

**Introduced in R2022a**

## References

[1] Forster, Christian, Luca Carlone, Frank Dellaert, and Davide Scaramuzza. “On-Manifold Preintegration for Real-Time Visual-Inertial Odometry.” *IEEE Transactions* on Robotics 33, no. 1 (February 2017): 1–21. https://doi.org/10.1109/TRO.2016.2597321.

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Objects

`factorGraph` | `factorIMUParameters` | `factorPoseSE2AndPointXY` | `factorPoseSE3AndPointXYZ` | `factorGPS` | `factorTwoPoseSE2` | `factorTwoPoseSE3` | `factorIMUBiasPrior` | `factorVelocity3Prior` | `factorPoseSE3Prior` | `factorCameraSE3AndPointXYZ`

**Functions**
estimateGravityRotation | estimateGravityRotationAndPoseScale

**Topics**
“Factor Graph-Based Pedestrian Localization with IMU and GPS Sensors”

# factorIMUParameters

Factor IMU parameters

## Description

Use a `factorIMUParameters` object to specify factor IMU parameters to a `factorIMU` object.

## Creation

### Syntax

```
params = factorIMUParameters
params = factorIMUParameters(Name=Value)
```

#### Description

`params = factorIMUParameters` returns a default factor IMU parameters object, `params`.

`params = factorIMUParameters(Name=Value)` specifies properties using one or more name-value arguments.

### Properties

**`SampleRate` — IMU sampling rate**
`100` (default) | numeric scalar greater than or equal to `100`

IMU sampling rate, in Hz, specified as a numeric scalar greater than or equal to `100`.

Example: `SampleRate=400`

Data Types: `single` | `double`

**`GyroscopeBiasNoise` — Gyroscope bias process noise covariance**
`eye(3)` (default) | 3-by-3 matrix | three-element row vector | numeric scalar

Gyroscope bias process noise covariance, specified as a 3-by-3 matrix, three-element row vector, or numeric scalar in $(rad/s)^2$.

Example: `GyroscopeBiasNoise=1.5e-9*eye(3)`

Data Types: `single` | `double`

**`AccelerometerBiasNoise` — Accelerometer bias process noise covariance**
`eye(3)` (default) | 3-by-3 matrix | three-element row vector | numeric scalar

Accelerometer bias process noise covariance, specified as a 3-by-3 matrix, three-element row vector, or numeric scalar in $(m/s^2)^2$.

Example: `AccelerometerBiasNoise=diag([9.62e-9,9.62e-9,2.17e-8])`

Data Types: `single` | `double`

**GyroscopeNoise — Gyroscope measurement noise covariance**
eye(3) (default) | 3-by-3 matrix | three-element row vector | numeric scalar

Gyroscope measurement noise covariance, specified as a 3-by-3 matrix, three-element row vector, or numeric scalar in $(rad/s)^2$.

Example: GyroscopeNoise=6.93e-5*eye(3)

Data Types: single | double

**AccelerometerNoise — Accelerometer measurement noise covariance**
eye(3) (default) | 3-by-3 matrix | three-element row vector | numeric scalar

Accelerometer measurement noise covariance, specified as a 3-by-3 matrix, three-element row vector, or numeric scalar in $(m/s^2)^2$.

Example: AccelerometerNoise=2.9e-6*eye(3)

Data Types: single | double

**ReferenceFrame — Reference frame for local coordinate system**
"ENU" (default) | "NED"

Reference frame for the local coordinate system, specified as "ENU" (east-north-up) or "NED" (north-east-down).

Data Types: string | char

## Examples

### Specify IMU Parameters of factorIMU Object Using factorIMUParameters Object

Specify IMU parameters for sample rate and the gyroscope and accelerometer measurement bias and noises.

```
sampleRate = 400; % Hz
gyroBiasNoise = 1.5e-9*eye(3);
accelBiasNoise = diag([9.62e-9 9.62e-9 2.17e-8]);
gyroNoise = 6.93e-5*eye(3);
accelNoise = 2.9e-6*eye(3);
```

Create a factorIMUParameters object using the specified IMU parameters.

```
imuparams = factorIMUParameters(SampleRate=sampleRate, ...
                                GyroscopeBiasNoise=gyroBiasNoise, ...
                                AccelerometerBiasNoise=accelBiasNoise, ...
                                GyroscopeNoise=gyroNoise, ...
                                AccelerometerNoise=accelNoise, ...
                                ReferenceFrame="NED");
```

Specify the gyroscope and accelerometer readings.

```
gyroReadings = [-0.0151    0.0299    0.0027
                -0.0079    0.0370   -0.0014
                -0.0320    0.0306    0.0035
                -0.0043    0.0340   -0.0066
                -0.0033    0.0331   -0.0011];
```

```
accelReadings = [1.0666    0.0802    9.9586
                 1.1002    0.0199    9.6650
                 1.0287    0.3071   10.1864
                 0.9077   -0.2239   10.2989
                 1.2322    0.0174    9.8411];
```

Create a `factorIMU` object using the `factorIMUParameters` object and the readings.

```
nodeID = 1:6;
f = factorIMU(nodeID,gyroReadings,accelReadings,imuparams);
```

Create a default factor graph and add the factor to the graph using the `addFactor` function.

```
g = factorGraph;
addFactor(g,f);
```

# Version History

**Introduced in R2023a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Objects

`factorGraph` | `factorIMU`

### Functions

`estimateGravityRotation` | `estimateGravityRotationAndPoseScale`

# predict

Predict pose and velocity of factor

## Syntax

`[predictedpose,predictedvel] = predict(factor,prevpose,prevvel,prevbias)`

## Description

`[predictedpose,predictedvel] = predict(factor,prevpose,prevvel,prevbias)` predicts the pose `predictpose` and velocity `predictedvel` of the factor `factor` based on IMU readings and the initial pose, `prevpose`, velocity `prevvel`, and bias`prevbias`.

## Examples

### Predict Pose and Velocity of IMU Factor

Predict the next pose and velocity of an IMU factor based on the previous pose, velocity, and biases.

Set up parameters such as the connected node IDs, sample rate, noise, and readings. Then create an IMU factor with these parameters as arguments.

```
nodeID = [1,2,3, 4,5,6];
sampleRate = 400; % Hz
gyroBiasNoise = 1.5e-9 * eye(3);
accelBiasNoise = diag([9.62e-9, 9.62e-9, 2.17e-8]);
gyroNoise = 6.93e-5 * eye(3);
accelNoise = 2.9e-6 * eye(3);

gyroReadings = [ -0.0151    0.0299    0.0027
                -0.0079    0.0370   -0.0014
                -0.0320    0.0306    0.0035
                -0.0043    0.0340   -0.0066
                -0.0033    0.0331   -0.0011];
accelReadings = [   1.0666    0.0802    9.9586
                   1.1002    0.0199    9.6650
                   1.0287    0.3071   10.1864
                   0.9077   -0.2239   10.2989
                   1.2322    0.0174    9.8411];

f = factorIMU(nodeID, sampleRate, gyroBiasNoise, accelBiasNoise, ...
             gyroNoise, accelNoise, gyroReadings, accelReadings, ReferenceFrame="NED");
```

### Predict Pose and Velocity

Set up previous pose, velocity and biases measurements to use to predict the next pose and velocity.

```
prevpose = rand(1,7);
prevvel = rand(1,3);
prevaccelbias = rand(1,3);
```

```
prevgyrobias = rand(1,3);
prevbiases = [prevgyrobias,prevaccelbias]
```

```
prevbiases = 1×6

    0.4854    0.8003    0.1419    0.1576    0.9706    0.9572
```

Use the `predict` function and the previous measurements to predict the next pose and velocity.

```
[predictedpose,predictedvel] = predict(f,prevpose,prevvel,prevbiases)
```

```
predictedpose = 1×7

    0.8220    0.9170    0.1383    0.6307    0.7048    0.1055    0.3071

predictedvel = 1×3

    0.6202    0.8395    0.8509
```

## Input Arguments

### `factor` — IMU factor

`factorIMU` object

IMU factor, specified as a `factorIMU` object.

### `prevpose` — Previous pose of factor

seven-element vector

Previous pose of the factor, specified as a seven-element vector. The pose consists of the 3-D position and orientation quaternion of the factor of the form [*x y z w qx qy qz*].

### `prevvel` — Previous 3-D velocity

three-element vector

Previous 3-D velocity, specified as a three-element vector of the form [*vx vy vz*].

### `prevbias` — Previous 3-D biases of gyroscope and accelerometer

six-element vector

Previous 3-D biases of the gyroscope and accelerometer, specified as a six-element vector of the form [*gx gy gz ax ay az*].

## Output Arguments

### `predictedpose` — Predicted pose

seven-element vector

Predicted 3-D position and orientation quaternion, returned as a seven-element vector of the form [*x y z w qx qy qz*]..

### `predictedvel` — Predicted velocity

three-element vector

predicted 3-D velocity, returned as a three-element vector of the form [*vx vy vz*].

# Version History

**Introduced in R2022a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`factorIMU` | `factorGraph`

### Topics

"Factor Graph-Based Pedestrian Localization with IMU and GPS Sensors"

# factorCameraSE3AndPointXYZ

Factor relating SE(3) camera pose and 3-D point

## Description

The `factorCameraSE3AndPointXYZ` object describes the visual projection factor relating the poses of a pinhole camera in the SE(3) state space and 3-D landmark points. You can add this object as a factor to a `factorGraph` object.

## Creation

### Syntax

```
F = factorCameraSE3AndPointXYZ(nodeID,cameraIntrinsicMatrix)
F = factorCameraSE3AndPointXYZ( ___ ,Name=Value)
```

#### Description

`F = factorCameraSE3AndPointXYZ(nodeID,cameraIntrinsicMatrix)` creates a `factorCameraSE3AndPointXYZ` object, `F`, with the specified node ID pairs property NodeID set to `nodeID`, and the property K set to `cameraIntrinsicMatrix`. The factor object supports the construction of multiple factors with different node ID pairs at the same time.

`F = factorCameraSE3AndPointXYZ( ___ ,Name=Value)` specifies properties using one or more name-value arguments in addition to the arguments from the previous syntax.

### Properties

**`NodeID` — Node ID pairs**
*N*-by-2 matrix of nonnegative integers

This property is read-only.

Node ID pairs, specified as an *N*-by-2 matrix of nonnegative integers. *N* is the number of factors. Each row represents a factor that connects to nodes of types `POSE_SE3` and `POINT_XYZ` at the specified node IDs in the factor graph. The rows are of the form [*cameraPoseID landmarkID*], where *cameraPoseID* is the camera pose node ID, and *landmarkID* is the landmark node ID.

If a factor in this `factorCameraSE3AndPointXYZ` object specifies a node that does not exist in the factor graph with the specified ID, a node of the required type with that ID is automatically created and adds it to the factor graph when you add the factor to the factor graph.

You must specify this property at object creation.

Data Types: `double`

**K — Camera intrinsic matrix**
3-by-3 matrix | 3-by-3-by-*N* array

This property is read-only.

Camera intrinsic matrix, specified as a 3-by-3 matrix or 3-by-3-by-*N* array. *N* is the number of factors. When specified as a 3-by-3 matrix, the same camera intrinsic matrix applies to all the factors. The 3-by-3 matrix has the format

$$\begin{bmatrix} f_x & 0 & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{bmatrix}.$$

The coordinates [$c_x$, $c_y$] represent the principal point of the camera, in pixels. The coordinates [$f_x$ ,$f_y$] represent the focal length of the camera, in pixels.

---

**Note** This property is equivalent to the property K of the `cameraIntrinsics` object from Computer Vision Toolbox.

---

You must specify this property at object creation.

Data Types: `double`

**`Measurement` — Measured image point position**
`[0 0]` (default) | two-element row vector | *N*-by-2 matrix

Measured image point position, specified as a two-element row vector or *N*-by-2 matrix. *N* is the number of factors. Each row represents a 2-D image point observation [*x y*] of a specified 3-D point in a specified camera frame.

Data Types: `single` | `double`

**`Information` — Information matrix associated with measurement**
`eye(2)` (default) | 2-by-2 matrix | 2-by-2-by-*N* array

Information matrix associated with the uncertainty of the measurement, specified as a 2-by-2 matrix or 2-by-2-by-*N* array. *N* is the number of factors. When specified as a 2-by-2 matrix, the same information matrix applies to all the factors.

Data Types: `single` | `double`

**`SensorTransform` — Transformation consisting of 3-D translation and rotation to transform connecting pose nodes to the initial camera frame**
`se3()` (default) | `se3` object

Transformation consisting of 3-D translation and rotation to transform connecting pose nodes to the initial camera sensor reference frame, specified as an `se3` object.

For example, if the connected pose nodes store IMU poses in the initial IMU sensor reference frame, the sensor transform rotates and translates a pose in the initial IMU sensor reference frame to the initial camera sensor reference frame. The initial sensor reference frame has the very first sensor pose at its origin.

A sensor transform is unnecessary if the connecting pose nodes contain poses in the initial camera sensor reference frame. Otherwise, you must specify the sensor transform.

## Object Functions

nodeType    Get node type of node in factor graph

## Examples

### Create `factorCameraSE3AndPointXYZ` Object and Add It to `factorGraph` Object

Create a `factorGraph` object.

```
G = factorGraph;
```

Generate a new unique node ID to represent a camera pose node.

```
camId = generateNodeID(G,1);
```

Generate two new unique IDs to represent 3-D points.

```
pointIds = generateNodeID(G,2);
```

Specify a camera intrinsic matrix.

```
focalLength    = [800 800]; % specified in units of pixels
principalPoint = [320 240]; % in pixels [x, y]
cameraIntrinsicMatrix = [focalLength(1) 0 principalPoint(1); ...
                         0 focalLength(2) principalPoint(2); ...
                         0 0 1];

camMeasurements = [240 115; ... % first factor measurement
                   100 315];    % second factor measurement
```

Create a `factorCameraSE3AndPointXYZ` object that specifies two factors. The first factor connects the camera pose node and the first point node. The second factor connects the camera pose node and the second point node.

```
fCam = factorCameraSE3AndPointXYZ([camId pointIds(1); camId pointIds(2)], ...
                                  cameraIntrinsicMatrix, ...
                                  Measurement=camMeasurements);
```

Adding the factor object to the factor graph adds the nodes with IDs `camId` and `pointIds` to the factor graph, connecting them as specified by the factors.

```
addFactor(G,fCam);
```

Node `camId` is of type `"POSE_SE3"`. Nodes `pointIds` are of type `"POINT_XYZ"`, and both connect to the camera node.

```
nodeType(G,camId)
```

```
ans = 
"POSE_SE3"
```

```
nodeType(G,pointIds(1))
```

```
ans = 
"POINT_XYZ"
```

```
nodeType(G,pointIds(2))
```

```
ans = 
"POINT_XYZ"
```

# Version History

**Introduced in R2023a**

## See Also

**Objects**

factorGraph | factorIMU | factorGPS | factorTwoPoseSE2 | factorTwoPoseSE3 | factorPoseSE2AndPointXY | factorPoseSE3AndPointXYZ | factorIMUBiasPrior | factorPoseSE3Prior | factorVelocity3Prior

**Functions**

estimateGravityRotation | estimateGravityRotationAndPoseScale

# factorGPS

Factor for GPS measurement

## Description

The `factorGPS` object adds a constraint to a node in a `factorGraph` by using a GPS position measurement.

## Creation

### Syntax

```
F = factorGPS(NodeID)
F = factorGPS(NodeID,Name=Value)
```

#### Description

`F = factorGPS(NodeID)` returns a `factorGPS` object, `F`, with the node identification number set to `NodeID`. The GPS factor adds a constraint to the corresponding factor graph node by using a GPS position measurement.

`F = factorGPS(NodeID,Name=Value)` specifies properties using one or more name-value arguments. For example, `factorGPS(1,VDOP=1)` sets the `VDOP` property of the `factorGPS` object to `1`.

### Properties

**`NodeID` — Node ID number**
nonnegative integer

This property is read-only.

Node ID number, specified as a nonnegative integer. The `factorGPS` object factor connects to this node in the factor graph.

If there is no node in the factor graph with the specified ID, a node with that ID is automatically created and added to the factor graph when this factor is added to the factor graph.

You must specify this property at object creation.

**`Location` — Geodetic position measurement**
`[0 0 0]` (default) | three-element row vector

Geodetic position measurement, specified as a three-element row vector of geodetic coordinates in the form (`latitude longitude altitude`). Latitude and longitude are in degrees and altitude is in meters.

**HDOP — Horizontal dilution of precision**
1 (default) | positive scalar

Horizontal dilution of precision, specified as a positive scalar.

**VDOP — Vertical dilution of precision**
2 (default) | positive scalar

Vertical dilution of precision, specified as a positive scalar.

**ReferenceLocation — Origin of local coordinate system**
[0 0 0] (default) | 3-element row vector

Origin of the local coordinate system, specified as a three-element row vector of geodetic coordinates in the form (latitude longitude altitude). Latitude and longitude are in degrees and altitude is in meters.

Altitude is the height above the reference ellipsoid mode, WGS84.

**ReferenceFrame — Reference frame for local coordinate system**
"ENU" (default) | "NED"

Reference frame for the local coordinate system, specified as "ENU" (east-north-up) or "NED" (north-east-down).

Data Types: string | char

## Object Functions

nodeType    Get node type of node in factor graph

## Examples

### Add factorGPS Object to Factor Graph

Set up parameters such as the connected node ID, and reference location. Then create a GPS factor with these parameters as arguments, and set the reference frame to "NED".

```
id = 1;
loc = [5 5 1000];
hdop = 1.5;
vdop = 2.4;
refloc = [0 0 100];
f = factorGPS(id,Location=loc,HDOP=hdop,VDOP=vdop,ReferenceLocation=refloc,ReferenceFrame="NED")
```

Create a default factor graph and add the factor to the graph using the addFactor function.

```
g = factorGraph;
addFactor(g,f);
```

# Version History

**Introduced in R2022a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Objects

`factorGraph` | `factorPoseSE2AndPointXY` | `factorPoseSE3AndPointXYZ` | `factorIMU` | `factorTwoPoseSE2` | `factorTwoPoseSE3` | `factorIMUBiasPrior` | `factorVelocity3Prior` | `factorPoseSE3Prior` | `factorCameraSE3AndPointXYZ`

### Functions

`importFactorGraph`

### Topics

"Factor Graph-Based Pedestrian Localization with IMU and GPS Sensors"

# factorPoseSE2AndPointXY

Factor relating SE(2) position and 2-D point

## Description

The `factorPoseSE2AndPointXY` object contains factors that each describe the relationship between a position in the SE(2) state space and a 2-D landmark point. You can use this object to add one or more factors to a `factorGraph` object.

## Creation

### Syntax

```
F = factorPoseSE2AndPointXY(nodeID)
F = factorPoseSE2AndPointXY( ___ ,Name=Value)
```

#### Description

`F = factorPoseSE2AndPointXY(nodeID)` creates a `factorPoseSE2AndPointXY` object, `F`, with the node identification numbers property `NodeID` set to `nodeID`.

`F = factorPoseSE2AndPointXY( ___ ,Name=Value)` specifies properties using one or more name-value arguments in addition to the argument from the previous syntax. For example, `factorPoseSE2AndPointXY([1 2],Measurement=[1 5])` sets the `Measurement` property of the `factorPoseSE2AndPointXY` object to `[1 5]`.

## Properties

**`NodeID` — Node ID numbers**
*N*-by-2 matrix of nonnegative integers

This property is read-only.

Node ID numbers, specified as an *N*-by-2 matrix of nonnegative integers, where *N* is the total number of desired factors. Each row represents a factor connecting a node of type, `POSE_SE2` to a node of type `POINT_XY` in the form [*PoseID PointID*], where *PoseID* is the ID of the `POSE_SE2` node and *PointID* is the ID of the `POINT_XY` node in the factor graph.

If a factor in the `factorPoseSE2AndPointXY` object specifies an ID that does not correspond to a node in the factor graph, the factor graph automatically creates a node of the required type with that ID and adds it to the factor graph when adding the factor to the factor graph.

You must specify this property at object creation.

**`Measurement` — Measured relative position**
`zeros(N,2)` (default) | *N*-by-2 matrix

Measured relative position between the current position and landmark point, specified as an *N*-by-2 matrix where each row is of the form [*dx* *dy*], in meters. *N* is the total number of factors, and *dx* and *dy* are the change in position in *x* and *y*, respectively.

**`Information` — Information matrix associated with uncertainty of measurements**
`eye(2)` (default) | 2-by-2 matrix | 2-by-2-by-*N* array

Information matrix associated with the uncertainty of the measurements, specified as a 2-by-2 matrix or a 2-by-2-by-*N* array. *N* is the total number of factors specified by the `factorPoseSE2AndPointXY` object. Each information matrix corresponds to the measurements of the corresponding node in `NodeID`.

If you specify this property as a 2-by-2 matrix when `NodeID` contains more than one row, the information matrix corresponds to all measurements in `Measurement`.

This information matrix is the inverse of the covariance matrix, where the covariance matrix is of the form:

$$\begin{bmatrix} \sigma(x,x) & \sigma(x,y) \\ \sigma(y,x) & \sigma(y,y) \end{bmatrix}$$

Each element indicates the covariance between two variables. For example, *σ(x,y)* is the covariance between *x* and *y*.

## Object Functions

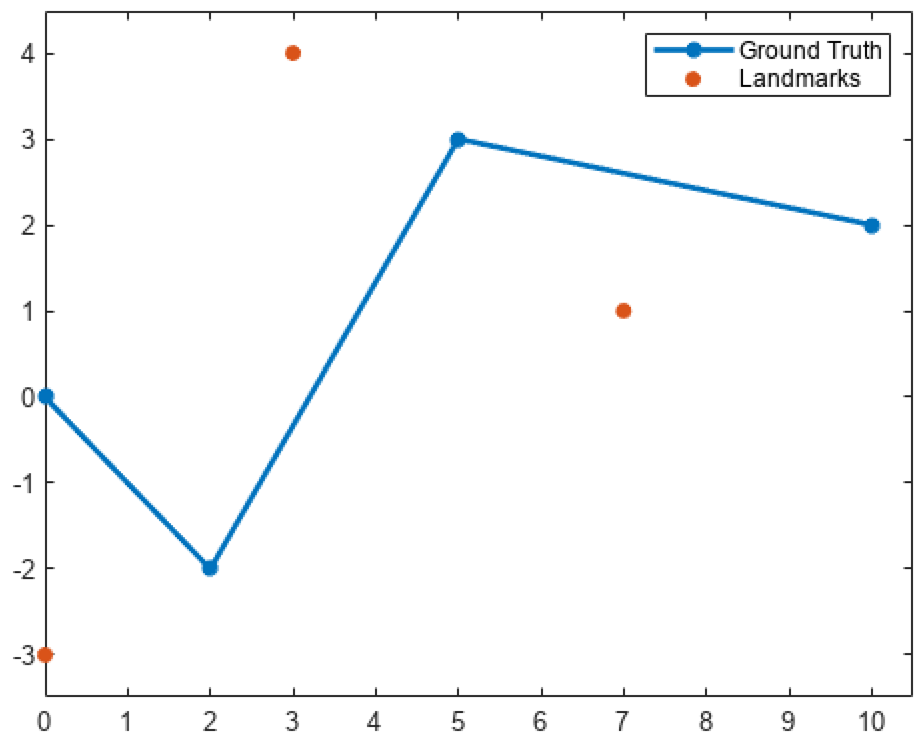
nodeType    Get node type of node in factor graph

## Examples

### Estimate Position Using Landmark Factors

Create a matrix of positions of the landmarks to use for localization, and the real positions of the robot to compare your factor graph estimate against. Use the `exampleHelperPlotPositionsAndLandmarks` helper function to visualize the landmark points and the real path of the robot..

```
landmarks = [0 -3  0;
             3  4  0;
             7  1  0];
realpos = [0  0  0;
           2 -2  0;
           5  3  0;
           10 2  0];
exampleHelperPlotPositionsAndLandmarks(realpos,landmarks)
```




### Create Robot Pose Nodes

Create a factor graph, and add a prior factor to loosely fix the start pose of the robot by providing an estimate pose.

```
fg = factorGraph;
rng(1)
pf = factorPoseSE3Prior(0);
```

Generate node IDs to use to create three `factorTwoPoseSE3` relative pose factors that relate four robot poses. To simulate sensor readings for the measurements of each factor, take the difference between a consecutive pair of ground truth positions, add noise, and append a quaternion of zero to provide a rotation of zero. Then add the prior factor and the pose factors to the factor graph.

```
zeroQuat = [1 0 0 0];
rpfIDs = generateNodeID(fg,3,"factorTwoPoseSE3")
```

```
rpfIDs = 3×2

     0     1
     1     2
     2     3
```

```
rpfmeasure = [(diff(realpos) + 0.1*rand(3)) repmat(zeroQuat,3,1)];
rpf = factorTwoPoseSE3(rpfIDs,Measurement=rpfmeasure);
addFactor(fg,pf);
addFactor(fg,rpf);
```

#### Create Landmark Factors

Generate node IDs to create three `factorPoseSE3AndXYZ` landmark factor objects that relate to the pose nodes. The first and second pose nodes observe the first landmark point so they should connect to that landmark with a factor. The second and third pose nodes observe the second landmark. The third and fourth pose nodes observe the third landmark.

```
landmarkIDs = generateNodeID(fg,3)'
```

```
landmarkIDs = 3×1

     4
     5
     6
```

The landmark factors used here are for 3-D state space but the process is identical for landmark factors for 2-D state space. Add some random number to the relative position between the landmark and the ground truth position to simulate real sensor measurements. Then create the landmark factors and add them to the factor graph.

```
lmf1measure = [landmarks(1,:) - realpos(1:2,:)] + 0.5*rand(1,3);
lmf2measure = [landmarks(2,:) - realpos(2:3,:)] + 0.5*rand(1,3);
lmf3measure = [landmarks(3,:) - realpos(3:4,:)] + 0.5*rand(1,3);
lmf1 = factorPoseSE3AndPointXYZ([[0 1]' repmat(landmarkIDs(1),2,1)],Measurement=lmf1measure);
lmf2 = factorPoseSE3AndPointXYZ([[1 2]' repmat(landmarkIDs(2),2,1)],Measurement=lmf2measure);
lmf3 = factorPoseSE3AndPointXYZ([[2 3]' repmat(landmarkIDs(3),2,1)],Measurement=lmf3measure);
addFactor(fg,lmf1);
addFactor(fg,lmf2);
addFactor(fg,lmf3);
```

#### Optimize Factor Graph

Optimize the factor graph with the default solver options. The optimization updates the states of all nodes in the factor graph, so the positions of vehicle and the landmarks update.

```
fgso = factorGraphSolverOptions;
optimize(fg,fgso)
```

```
ans = struct with fields:
             InitialCost: 72.6129
               FinalCost: 0.0011
      NumSuccessfulSteps: 4
    NumUnsuccessfulSteps: 0
               TotalTime: 0.0026
         TerminationType: 0
        IsSolutionUsable: 1
```

#### Visualize and Compare Results

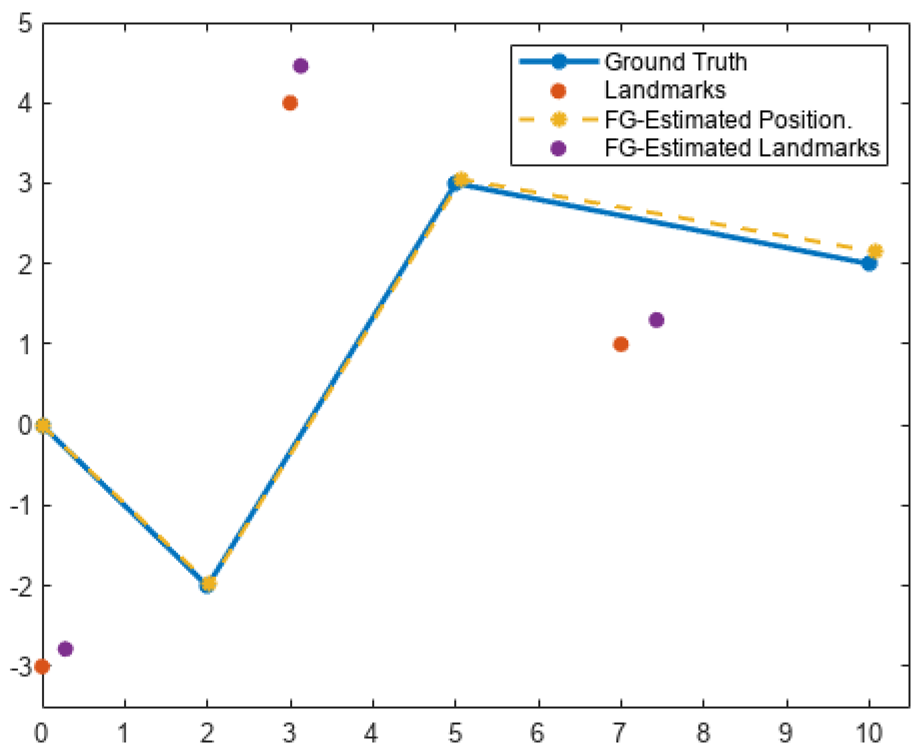
Get and store the updated node states for the vehicle and landmarks and plot the results, comparing the factor graph estimate of the robot path to the known ground truth of the robot.

```
poseIDs = nodeIDs(fg,NodeType="POSE_SE3");
fgposopt = nodeState(fg,poseIDs)
```

```
fgposopt = 4×7
```

```
     0.0000     0.0000     0.0000     1.0000     0.0000    -0.0000     0.0000
     2.0278    -1.9778     0.0173     1.0000     0.0018    -0.0034     0.0014
     5.0684     3.0500     0.0871     0.9999    -0.0010    -0.0072     0.0089
    10.0844     2.1475     0.1972     0.9999     0.0006    -0.0121     0.0100
```

```
fglmopt = nodeState(fg,landmarkIDs);
exampleHelperPlotPositionsAndLandmarks(realpos,landmarks,fgposopt,fglmopt)
```




## Version History

**Introduced in R2022b**

### R2023a: Specify multiple factors

The `NodeID`, `Measurement`, and `Information` properties now accept additional rows to specify multiple factors.

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
`factorGraph` | `factorPoseSE3AndPointXYZ` | `factorGPS` | `factorIMU` | `factorTwoPoseSE2` | `factorTwoPoseSE3` | `factorIMUBiasPrior` | `factorVelocity3Prior` | `factorPoseSE3Prior` | `factorCameraSE3AndPointXYZ`

# factorPoseSE3AndPointXYZ

Factor relating SE(3) position and 3-D point

## Description

The `factorPoseSE3AndPointXYZ` object contains factors that each describe the relationship between a position in the SE(3) state space and a 3-D landmark point. You can use this object to add one or more factors to a `factorGraph` object.

## Creation

### Syntax

```
F = factorPoseSE3AndPointXYZ(nodeID)
F = factorPoseSE3AndPointXYZ( ___ ,Name=Value)
```

#### Description

`F = factorPoseSE3AndPointXYZ(nodeID)` creates a `factorPoseSE3AndPointXYZ` object, `F`, with the node identification numbers property, `NodeID`, set to `nodeID`.

`F = factorPoseSE3AndPointXYZ( ___ ,Name=Value)` specifies properties using one or more name-value arguments in addition to the argument from the previous syntax. For example, `factorPoseSE3AndPointXYZ([1 2],Measurement=[1 2 3])` sets the `Measurement` property of the `factorPoseSE3AndPointXYZ` object to `[1 2 3]`.

## Properties

**`NodeID` — Node ID numbers**
*N*-by-2 matrix of nonnegative integers

This property is read-only.

Node ID numbers, specified as an *N*-by-2 matrix of nonnegative integers, where *N* is the total number of desired factors. Each row represents a factor connecting a node of type, `POSE_SE3` to a node of type `POINT_XYZ` in the form [*PoseID PointID*], where *PoseID* is the ID of the `POSE_SE3` node and *PointID* is the ID of the `POINT_XYZ` node in the factor graph.

If a factor in the `factorPoseSE3AndPointXYZ` object specifies an ID that does not correspond to a node in the factor graph, the factor graph automatically creates a node of the required type with that ID and adds it to the factor graph when adding the factor to the factor graph.

You must specify this property at object creation.

**`Measurement` — Measured relative position**
`zeros(N,3)` (default) | *N*-by-3 matrix

Measured relative position between current position and landmark point, specified as an *N*-by-3 matrix where each row is of the form [*dx dy dz*], in meters. *N* is the total number of factors, and *dx*, *dy*, and *dz* are the change in position in *x*, *y*, and *z*, respectively.

**`Information` — Information matrix associated with uncertainty of measurements**
`eye(3)` (default) | 3-by-3 matrix | 3-by-3-by-*N* array

Information matrix associated with the uncertainty of the measurements, specified as a 3-by-3 matrix or a 3-by-3-by-*N* array. *N* is the total number of factors specified by the `factorPoseSE3AndPointXYZ` object. Each information matrix corresponds to the measurements of the corresponding node in `NodeID`.

If you specify this property as a 3-by-3 matrix when `NodeID` contains more than one row, the information matrix corresponds to all measurements in `Measurement`.

This information matrix is the inverse of the covariance matrix, where the covariance matrix is of the form:

$$\begin{bmatrix} \sigma(x,x) & \sigma(x,y) & \sigma(x,z) \\ \sigma(y,x) & \sigma(y,y) & \sigma(y,z) \\ \sigma(z,x) & \sigma(y,x) & \sigma(z,z) \end{bmatrix}$$

Each element indicates the covariance between two variables. For example, *σ(x,y)* is the covariance between *x* and *y*.

## Object Functions

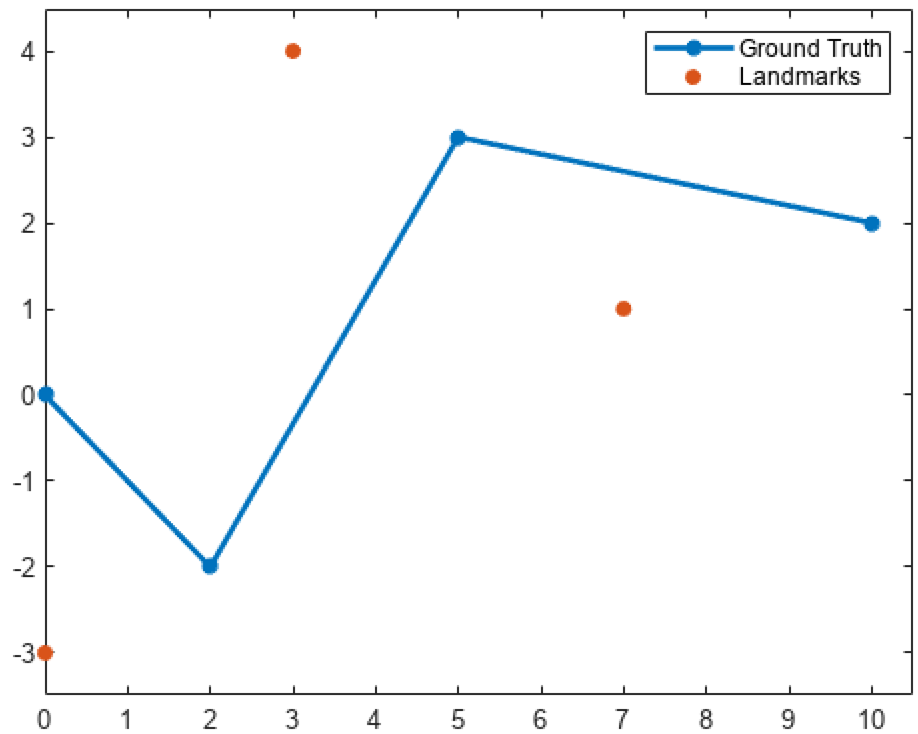
nodeType    Get node type of node in factor graph

## Examples

### Estimate Position Using Landmark Factors

Create a matrix of positions of the landmarks to use for localization, and the real positions of the robot to compare your factor graph estimate against. Use the `exampleHelperPlotPositionsAndLandmarks` helper function to visualize the landmark points and the real path of the robot..

```
landmarks = [0 -3  0;
             3  4  0;
             7  1  0];
realpos = [0  0  0;
           2 -2  0;
           5  3  0;
           10 2  0];
exampleHelperPlotPositionsAndLandmarks(realpos,landmarks)
```




**Create Robot Pose Nodes**

Create a factor graph, and add a prior factor to loosely fix the start pose of the robot by providing an estimate pose.

```
fg = factorGraph;
rng(1)
pf = factorPoseSE3Prior(0);
```

Generate node IDs to use to create three `factorTwoPoseSE3` relative pose factors that relate four robot poses. To simulate sensor readings for the measurements of each factor, take the difference between a consecutive pair of ground truth positions, add noise, and append a quaternion of zero to provide a rotation of zero. Then add the prior factor and the pose factors to the factor graph.

```
zeroQuat = [1 0 0 0];
rpfIDs = generateNodeID(fg,3,"factorTwoPoseSE3")
```

```
rpfIDs = 3×2

     0     1
     1     2
     2     3
```

```
rpfmeasure = [(diff(realpos) + 0.1*rand(3)) repmat(zeroQuat,3,1)];
rpf = factorTwoPoseSE3(rpfIDs,Measurement=rpfmeasure);
addFactor(fg,pf);
addFactor(fg,rpf);
```

### Create Landmark Factors

Generate node IDs to create three `factorPoseSE3AndXYZ` landmark factor objects that relate to the pose nodes. The first and second pose nodes observe the first landmark point so they should connect to that landmark with a factor. The second and third pose nodes observe the second landmark. The third and fourth pose nodes observe the third landmark.

```
landmarkIDs = generateNodeID(fg,3)'
```

```
landmarkIDs = 3×1

     4
     5
     6
```

The landmark factors used here are for 3-D state space but the process is identical for landmark factors for 2-D state space. Add some random number to the relative position between the landmark and the ground truth position to simulate real sensor measurements. Then create the landmark factors and add them to the factor graph.

```
lmf1measure = [landmarks(1,:) - realpos(1:2,:)] + 0.5*rand(1,3);
lmf2measure = [landmarks(2,:) - realpos(2:3,:)] + 0.5*rand(1,3);
lmf3measure = [landmarks(3,:) - realpos(3:4,:)] + 0.5*rand(1,3);
lmf1 = factorPoseSE3AndPointXYZ([[0 1]' repmat(landmarkIDs(1),2,1)],Measurement=lmf1measure);
lmf2 = factorPoseSE3AndPointXYZ([[1 2]' repmat(landmarkIDs(2),2,1)],Measurement=lmf2measure);
lmf3 = factorPoseSE3AndPointXYZ([[2 3]' repmat(landmarkIDs(3),2,1)],Measurement=lmf3measure);
addFactor(fg,lmf1);
addFactor(fg,lmf2);
addFactor(fg,lmf3);
```

### Optimize Factor Graph

Optimize the factor graph with the default solver options. The optimization updates the states of all nodes in the factor graph, so the positions of vehicle and the landmarks update.

```
fgso = factorGraphSolverOptions;
optimize(fg,fgso)
```

```
ans = struct with fields:
             InitialCost: 72.6129
               FinalCost: 0.0011
      NumSuccessfulSteps: 4
    NumUnsuccessfulSteps: 0
               TotalTime: 0.0026
         TerminationType: 0
        IsSolutionUsable: 1
```

### Visualize and Compare Results

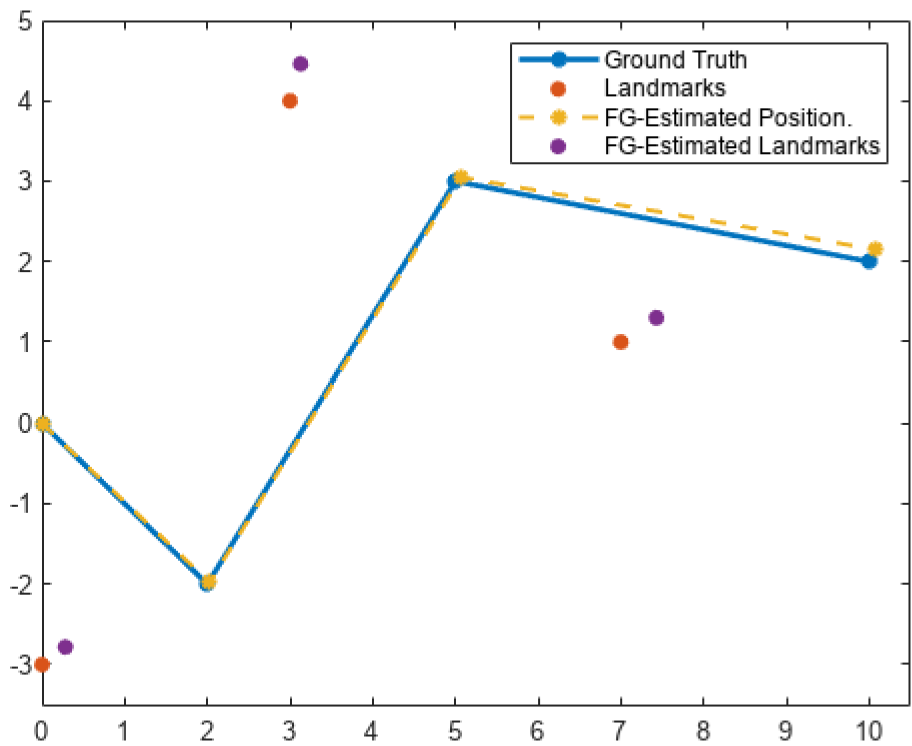
Get and store the updated node states for the vehicle and landmarks and plot the results, comparing the factor graph estimate of the robot path to the known ground truth of the robot.

```
poseIDs = nodeIDs(fg,NodeType="POSE_SE3");
fgposopt = nodeState(fg,poseIDs)
```

```
fgposopt = 4×7
```

```
     0.0000    0.0000    0.0000    1.0000    0.0000   -0.0000    0.0000
     2.0278   -1.9778    0.0173    1.0000    0.0018   -0.0034    0.0014
     5.0684    3.0500    0.0871    0.9999   -0.0010   -0.0072    0.0089
    10.0844    2.1475    0.1972    0.9999    0.0006   -0.0121    0.0100
```

```
fglmopt = nodeState(fg,landmarkIDs);
exampleHelperPlotPositionsAndLandmarks(realpos,landmarks,fgposopt,fglmopt)
```




## Version History

**Introduced in R2022b**

#### R2023a: Specify multiple factors

The `NodeID`, `Measurement`, and `Information` properties now accept additional rows to specify multiple factors.

## Extended Capabilities

#### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**

factorGraph | factorPoseSE2AndPointXY | factorGPS | factorIMU | factorTwoPoseSE2 | factorTwoPoseSE3 | factorIMUBiasPrior | factorVelocity3Prior | factorPoseSE3Prior | factorCameraSE3AndPointXYZ

**Topics**

"Landmark SLAM Using AprilTag Markers"

# factorTwoPoseSE2

Factor relating two SE(2) poses

## Description

The `factorTwoPoseSE2` object contains factors that relate pairs of poses in the SE(2) state space for a `factorGraph` object.

## Creation

### Syntax

```
F = factorTwoPoseSE2(nodeID)
F = factorTwoPoseSE2(nodeID,Name=Value)
```

#### Description

`F = factorTwoPoseSE2(nodeID)` creates a `factorTwoPoseSE2` object, `F`, with the node identification numbers property `NodeID` set to `nodeID`.

`F = factorTwoPoseSE2(nodeID,Name=Value)` specifies properties using one or more name-value arguments. For example, `factorTwoPoseSE2([1 2],Measurement=[1 5 7])` sets the `Measurement` property of the `factorTwoPoseSE2` object to `[1 5 7]`.

### Properties

**`NodeID` — Node ID numbers**
*N*-by-2 matrix of nonnegative integers

This property is read-only.

Node ID numbers, specified as an *N*-by-2 matrix of nonnegative integers, where *N* is the total number of desired factors. Each row represents a factor that connects to two nodes of type `POSE_SE2` at the specified node IDs in the factor graph. The rows are of the form [*PoseID PoseID*].

If a factor in the `factorTwoPoseSE2` object specifies an ID that does not correspond to a node in the factor graph, the factor graph automatically creates a node of the required type with that ID and adds it to the factor graph when adding the factor to the factor graph.

You must specify this property at object creation.

**`Measurement` — Measured relative pose**
`zeros(N,3)` (default) | *N*-by-3 matrix

Measured relative pose, specified as a *N*-by-3 matrix, where each row is of the form [*dx dy dtheta*]. *N* is the total number of factors. *dx* and *dy* are the change in position in *x* and *y*, respectively, and *dtheta* is the angle between the two positions.

**`Information` — Information matrix associated with measurements**
`eye(3)` (default) | 3-by-3 matrix | 3-by-3-*N* array

Information matrix associated with the measurement, specified as a 3-by-3 matrix or a 3-by-3-*N* matrix. *N* is the total number of factors specified by this `factorTwoPoseSE2` object. Each information matrix corresponds to the measurements of the specified nodes in `NodeIDs`.

If you specify this property as a 3-by-3 matrix when `NodeID` contains more than one row, the information matrix corresponds to all measurements in `Measurement`.

## Object Functions

nodeType    Get node type of node in factor graph

## Examples

### Add `FactorTwoPoseSE2` Object to Factor Graph

Create measurement vector, information matrix, and a node ID number vector. Create a `factorTwoPoseSE2` object, specifying the node IDs, measurement, and information as arguments.

```
nodeID = [1 2];
measure = [5 5 pi/2];
info = rand(3,3);
f = factorTwoPoseSE2(nodeID,Measurement=measure,Information=info);
```

Create a default factor graph and add the factor to the graph using the `addFactor` function.

```
g = factorGraph;
addFactor(g,f);
```

# Version History

**Introduced in R2022a**

### R2023a: Specify multiple factors

The `NodeID`, `Measurement`, and `Information` properties now accept additional rows to specify multiple factors.

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
factorGraph | factorPoseSE2AndPointXY | factorPoseSE3AndPointXYZ | factorGPS | factorIMU | factorTwoPoseSE3 | factorIMUBiasPrior | factorVelocity3Prior | factorPoseSE3Prior | factorCameraSE3AndPointXYZ

# factorTwoPoseSE3

Factor relating two SE(3) poses

## Description

The `factorTwoPoseSE3` object contains factors that relate pairs of poses in the SE(3) state space for a `factorGraph` object.

## Creation

### Syntax

```
F = factorTwoPoseSE3(nodeID)
F = factorTwoPoseSE3(nodeID,Name=Value)
```

#### Description

`F = factorTwoPoseSE3(nodeID)` creates a `factorTwoPoseSE3` object, `F`, with the node identification numbers property `NodeID` set to `nodeID`.

`F = factorTwoPoseSE3(nodeID,Name=Value)` specifies properties using one or more name-value arguments. For example, `factorTwoPoseSE3([1 2],Measurement=[1 2 3 4 5 6 7])` sets the `Measurement` property of the `factorTwoPoseSE3` object to `[1 2 3 4 5 6 7]`.

### Properties

**`NodeID` — Node ID numbers**
*N*-by-2 matrix of nonnegative integers

This property is read-only.

Node ID numbers, specified as an *N*-by-2 matrix of nonnegative integers, where *N* is the total number of desired factors. Each row represents a factor that connects to two nodes of type, `POSE_SE3`, at the specified node IDs in the factor graph. The rows are of the form [*PoseID PoseID*].

If a factor in the `factorTwoPoseSE3` object specifies an ID that does not correspond to a node in the factor graph, the factor graph automatically creates a node of the required type with that ID and adds it to the factor graph when adding the factor to the factor graph.

You must specify this property at object creation.

**`Measurement` — Measured relative pose**
`[zeros(N,3) ones(N,1) zeros(N,3)]` (default) | *N*-by-7 matrix

Measured relative pose, specified as a *N*-by-7 matrix, where each row is of the form [*dx dy dz dqw dqx dqy dqz*]. *N* is the total number of factors. *dx*, *dy*, and *dz* are the change in position in *x*, *y*, and *z* respectively. *dqw*, *dqx*, *dqy*, and *dqz* are the change in quaternion rotation in *w*, *x*, *y*, and *z*, respectively.

When you optimize the factor graph that this factor belongs to, the `optimize` function normalizes the quaternion measurement of the factor before the optimization.

**`Information` — Information matrices associated with measurements**
`eye(6)` (default) | 6-by-6 matrix | 6-by-6-by-*N* array

Information matrices associated with the measurements, specified as a 6-by-6 matrix or a 6-by-6-by-*N* array. *N* is the total number of factors specified by the `factorTwoPoseSE3` object. Each information matrix corresponds to the measurements of the corresponding node in `NodeID`.

If you specify this property as a 6-by-6 matrix when `NodeID` contains more than one row, the information matrix corresponds to all measurements in `Measurement`.

## Object Functions

nodeType    Get node type of node in factor graph

## Examples

### Add `factorTwoPoseSE3` Object to Factor Graph

Create a two pose SE(3) state space factor with the connected node IDs set to `1` and `2`.

```
f = factorTwoPoseSE3([1 2]);
```

Create a default factor graph and add the factor to the graph using the `addFactor` function.

```
g = factorGraph;
addFactor(g,f);
```

# Version History

**Introduced in R2022a**

### R2023a: Specify multiple factors

The `NodeID`, `Measurement`, and `Information` properties now accept additional rows to specify multiple factors.

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Objects

`factorGraph` | `factorPoseSE2AndPointXY` | `factorPoseSE3AndPointXYZ` | `factorTwoPoseSE2` | `factorIMU` | `factorGPS` | `factorIMUBiasPrior` | `factorVelocity3Prior` | `factorPoseSE3Prior` | `factorCameraSE3AndPointXYZ`

**Topics**
"Landmark SLAM Using AprilTag Markers"

# factorIMUBiasPrior

Prior factor for IMU bias

## Description

The `factorIMUBiasPrior` object is a factor that has prior information for an IMU bias for a `factorGraph` object.

## Creation

### Syntax

```
F = factorIMUBiasPrior(nodeID)
F = factorIMUBiasPrior(nodeID,Name=Value)
```

#### Description

`F = factorIMUBiasPrior(nodeID)` creates a `factorIMUBiasPrior` object, `F`, with the node identification numbers property `NodeID` set to `nodeID`

`F = factorIMUBiasPrior(nodeID,Name=Value)` specifies properties using one or more name-value arguments. For example, `factorIMUBiasPrior(1,Measurement=[1 2 3 1 2 3])` sets the `Measurement` property of the `factorIMUBiasPrior` object to `[1 2 3 1 2 3]`.

### Properties

**`NodeID` — Node ID numbers**
*N*-element column vector of nonnegative integers

This property is read-only.

Node ID numbers, specified as an *N*-element vector of nonnegative integers, where *N* is the total number of desired factors. Each element represents a factor that connects to a node of type `IMU_BIAS` in the factor graph using the specified node ID.

If a factor in the `factorIMUBiasPrior` object specifies ID that does not correspond to a node in the factor graph, the factor graph automatically creates an `IMU_BIAS` type node with that ID and adds it to the factor graph when adding the factor to the factor graph.

You must specify this property at object creation.

**`Measurement` — Measured prior IMU bias**
`zeros(N,6)` (default) | *N*-by-6 matrix

Measured prior IMU bias, specified as an *N*-by-6 matrix where each row is in the form [*GyroBias*, *AccelBias*]. *N* is the total number of factors, and *GyroBias* and *AccelBias* are three-element row vectors of the gyroscope bias and acceleration bias in radians per second and meters per second, respectively.

**`Information` — Information matrices associated with measurements**
`eye(6)` (default) | 6-by-6 matrix | 6-by-6-by-*N* array

Information matrices associated with the measurements, specified as a 6-by-6 matrix or a 6-by-6-by-*N* array. *N* is the total number of factors specified by the `factorIMUBiasPrior` object. Each information matrix corresponds to the measurements of the corresponding node in `NodeID`.

If you specify this property as a 6-by-6 matrix when `NodeID` contains more than one element, the information matrix corresponds to all measurements in `Measurement`.

## Object Functions

nodeType    Get node type of node in factor graph

## Examples

### Add `factorIMUBiasPrior` Object to Factor Graph

Create an IMU bias prior factor with a node ID of `1`.

```
f = factorIMUBiasPrior(1);
```

Create a default factor graph and add the factor to the graph using the `addFactor` function.

```
g = factorGraph;
addFactor(g,f);
```

# Version History

**Introduced in R2022a**

### R2023a: Specify multiple factors

The `NodeID`, `Measurement`, and `Information` properties now accept additional rows to specify multiple factors.

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Objects

`factorGraph` | `factorPoseSE2AndPointXY` | `factorPoseSE3AndPointXYZ` | `factorIMU` | `factorGPS` | `factorTwoPoseSE2` | `factorTwoPoseSE3` | `factorVelocity3Prior` | `factorPoseSE3Prior` | `factorCameraSE3AndPointXYZ`

### Topics

"Factor Graph-Based Pedestrian Localization with IMU and GPS Sensors"

# factorVelocity3Prior

Prior factor for 3-D velocity

## Description

The `factorVelocity3Prior` object is a factor that has information for a prior velocity in 3-D for a `factorGraph` object.

## Creation

### Syntax

```
F = factorVelocity3Prior(nodeID)
F = factorVelocity3Prior(nodeID,Name=Value)
```

#### Description

`F = factorVelocity3Prior(nodeID)` creates a `factorVelocity3Prior` object, `F`, with the node identification numbers property `NodeID` set to `nodeID`.

`F = factorVelocity3Prior(nodeID,Name=Value)` specifies properties using one or more name-value arguments. For example, `factorVelocity3Prior(1,Measurement=[1 5 7])` sets the `Measurement` property of the `factorVelocity3Prior` object to `[1 5 7]`.

## Properties

**`NodeID` — Node ID numbers**
*N*-element column vector of nonnegative integers

This property is read-only.

Node ID numbers, specified as an *N*-element vector of nonnegative integers, where *N* is the total number of desired factors. Each element represents a factor that connects to a node of type `VEL3` in the factor graph using the specified node ID.

If a factor in the `factorVelocity3Prior` object specifies ID that does not correspond to a node in the factor graph, the factor graph automatically creates an `VEL3` type node with that ID and adds it to the factor graph when adding the factor to the factor graph.

You must specify this property at object creation.

**`Measurement` — Measured prior velocity**
`zeros(N,3)` (default) | *N*-by-3 matrix

Measured prior velocity, specified as an *N*-by-3 matrix, where each row is of the form [*xz yz vz*]. *N* is the total number of factors. *xz*, *yz*, and *vz* are the velocity of the *x*, *y*, and *z* positions, respectively.

**`Information` — Information matrix associated with measurements**
`eye(3)` (default) | 3-by-3 matrix | 3-by-3-*N* array

Information matrix associated with the measurement, specified as a 3-by-3 matrix or a 3-by-3-*N* matrix. *N* is the total number of factors specified by this `factorVelocity3Prior` object. Each information matrix corresponds to the measurements of the specified nodes in `NodeIDs`.

If you specify this property as a 3-by-3 matrix when `NodeID` contains more than one element, the information matrix corresponds to all measurements in `Measurement`.

## Object Functions

nodeType    Get node type of node in factor graph

## Examples

### Add `factorVelocity3Prior` Object to Factor Graph

Create a velocity prior factor with a node ID of 1.

```
f = factorVelocity3Prior(1);
```

Create a default factor graph and add the factor to the graph using the `addFactor` function.

```
g = factorGraph;
addFactor(g,f);
```

# Version History

**Introduced in R2022a**

### R2023a: Specify multiple factors

The `NodeID`, `Measurement`, and `Information` properties now accept additional rows to specify multiple factors.

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Objects

`factorGraph` | `factorPoseSE2AndPointXY` | `factorPoseSE3AndPointXYZ` | `factorTwoPoseSE2` | `factorTwoPoseSE3` | `factorIMU` | `factorGPS` | `factorIMUBiasPrior` | `factorPoseSE3Prior` | `factorCameraSE3AndPointXYZ`

### Topics

"Factor Graph-Based Pedestrian Localization with IMU and GPS Sensors"

# factorPoseSE3Prior

Full-state prior factor for SE(3) pose

## Description

The `factorPoseSE3Prior` object is a full-state prior factor for an SE(3) state space pose for a `factorGraph` object.

## Creation

### Syntax

```
F = factorPoseSE3Prior(nodeID)
F = factorPoseSE3Prior(nodeID,Name=Value)
```

#### Description

`F = factorPoseSE3Prior(nodeID)` creates a `factorPoseSE3Prior` object, `F`, with the node identification numbers property `NodeID` set to `nodeID`.

`F = factorPoseSE3Prior(nodeID,Name=Value)` specifies properties using one or more name-value arguments. For example, `factorPoseSE3Prior(1,Measurement=[1 2 3 4 5 6 7])` sets the `Measurement` property of the `factorPoseSE3Prior` object to `[1 2 3 4 5 6 7]`.

## Properties

**`NodeID` — Node ID numbers**
*N*-element column vector of nonnegative integers

This property is read-only.

Node ID numbers, specified as an *N*-element vector of nonnegative integers, where *N* is the total number of desired factors. Each element represents a factor that connects to a node of type `POSE_SE3` in the factor graph using the specified node ID.

If a factor in the `factorPoseSE3Prior` object specifies ID that does not correspond to a node in the factor graph, the factor graph automatically creates an `POSE_SE3` type node with that ID and adds it to the factor graph when adding the factor to the factor graph.

You must specify this property at object creation.

**`Measurement` — Measured absolute SE(3) prior pose in local coordinates**
`[zeros(N,3) ones(N,1) zeros(N,3)]` (default) | *N*-by-7 matrix

Measured absolute SE(3) prior pose in local coordinates, specified as an *N*-by-7 matrix, where each row is of the form [*x y z qw qx qy qz*]. *N* is the total number of factors. *x*, *y*, and *z* are the change in position in *x*, *y*, and *z* respectively. *qw*, *qx*, *qy*, and *qz* are the change in quaternion rotation in *w*, *x*, *y*, and *z*, respectively.

The specified quaternion is expected to be normalized.

**`Information` — Information matrices associated with measurements**
`eye(6)` (default) | 6-by-6 matrix | 6-by-6-by-*N* array

Information matrices associated with the measurements, specified as a 6-by-6 matrix or a 6-by-6-by-*N* array. *N* is the total number of factors specified by the `factorPoseSE3Prior` object. Each information matrix corresponds to the measurements of the corresponding node in `NodeID`.

If you specify this property as a 6-by-6 matrix when `NodeID` contains more than one element, the information matrix corresponds to all measurements in `Measurement`.

## Object Functions

nodeType    Get node type of node in factor graph

## Examples

### Add `factorPoseSE3Prior` Object to Factor Graph

Create a prior SE(3) pose factor with a node ID of `1`.

```
f = factorPoseSE3Prior(1);
```

Create a default factor graph and add the factor to the graph using the `addFactor` function.

```
g = factorGraph;
addFactor(g,f);
```

# Version History

**Introduced in R2022a**

### R2023a: Specify multiple factors

The `NodeID`, `Measurement`, and `Information` properties now accept additional rows to specify multiple factors.

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Objects

`factorGraph` | `factorPoseSE2AndPointXY` | `factorPoseSE3AndPointXYZ` | `factorTwoPoseSE2` | `factorTwoPoseSE3` | `factorIMU` | `factorGPS` | `factorIMUBiasPrior` | `factorVelocity3Prior` | `factorCameraSE3AndPointXYZ`

**Topics**

"Factor Graph-Based Pedestrian Localization with IMU and GPS Sensors"
"Landmark SLAM Using AprilTag Markers"

# factorGraph

Bipartite graph of factors and nodes

## Description

A `factorGraph` object stores a bipartite graph consisting of factors connected to variable nodes. The nodes represent the unknown random variables in an estimation problem such as robot poses, and the factors represent probabilistic constraints on those nodes, derived from measurements or prior knowledge. During optimization, the factor graph uses all the factors and current node states to update the node states.

To use the factor graph:

1. Create an empty `factorGraph` object.
2. For each desired factor type.
   a. Generate node IDs using the `generateNodeID` object function.
   b. Define factors with the desired node IDs, using any of the supported factor objects:
      - `factorGPS`
      - `factorIMU`
      - `factorCameraSE3AndPointXYZ`
      - `factorPoseSE2AndPointXY`
      - `factorPoseSE3AndPointXYZ`
      - `factorTwoPoseSE2`
      - `factorTwoPoseSE3`
      - `factorIMUBiasPrior`
      - `factorPoseSE3Prior`
      - `factorVelocity3Prior`
   c. Add factors to the factor graph using the `addFactor` object function. If there is no node in the factor graph with the specified ID, a node with that ID is automatically created and added to the factor graph when this factor is added to the factor graph. If there is a node in the factor graph with the specified ID, ensure that adding the new factor does not cause a node type mismatch. For more information, see “Tips” on page 2-411.
3. Check if all the nodes in the factor graph are connected to at least one other node using the `isConnected` object function.
4. Create a `factorGraphSolverOptions` object to specify factor graph solver options.
5. Optimize the factor graph using the `optimize` object function with the desired factor graph solver options.
6. Extract factor graph node data such as node IDs and node states using the `nodeIDs` and `nodeState` object functions.

# Creation

## Syntax

```
graph = factorGraph
```

### Description

`graph = factorGraph` creates an empty `factorGraph` object.

# Properties

**`NumNodes` — Number of nodes in factor graph**
nonnegative integer

This property is read-only.

Number of nodes in the factor graph, specified as a positive integer. `NumNodes` has a value of `0` when the factor graph is empty and `NumNodes` increases each time you add a factor that specifies new node IDs to the factor graph.

The nodes in the factor graph can be any of these types:

- `"POSE_SE2"` — Pose in SE(2) state space
- `"POSE_SE3"` — Pose in SE(3) state space
- `"VEL3"` — 3-D velocity
- `"POINT_XY"` — 2-D point
- `"POINT_XYZ"` — 3-D point
- `"IMU_BIAS"` — IMU gyroscope and accelerometer bias

To check the node type of a node in the graph, use the `nodeType` function.

**Note** The node type is set by the factor graph when the factor object that specifies the node is added to the factor graph. You can not change the node type of a node after it has been added to the graph.

**`NumFactors` — Number of factors in factor graph**
nonnegative integer

This property is read-only.

Number of factors in the factor graph, specified as a positive integer. `NumFactors` has a value of `0` when the factor graph is empty and `NumFactors` increases each time you add a factor to the factor graph.

You can use `addfactor` to add any of these factor objects to the factor graph:

| Purpose | Factor Objects |
|---|---|
| Relate poses to sensor measurements | • factorGPS — Connect SE(3) pose node ("POSE_SE3") to a GPS measurement.<br>• factorIMU — Connect two SE(3) pose nodes ("POSE_SE3"), two 3-D velocity nodes ("VEL3"), and two IMU bias nodes ("IMU_BIAS") using an IMU measurement. |
| Relate poses to landmark positions | • factorCameraSE3AndPointXYZ — Connect the SE(3) pose node of a pinhole camera ("POSE_SE3") to 3-D landmark nodes ("Point_XYZ") using relative pose measurements.<br>• factorPoseSE2AndPointXY — Connect a SE(2) pose node ("POSE_SE2") to 2-D landmark nodes ("Point_XY") using relative pose measurements.<br>• factorPoseSE3AndPointXYZ — Connect a SE(3) pose node ("POSE_SE3") to 3-D landmark nodes ("Point_XYZ") using relative pose measurements. |
| Relate two poses to each other | • factorTwoPoseSE2 — Connect pairs of SE(2) pose nodes ("POSE_SE2") with relative poses using relative pose measurements.<br>• factorTwoPoseSE3 — Connect pairs of SE(3) pose nodes ("POSE_SE3") with relative poses using relative pose measurements. |
| Relate poses or velocities to a prior-known measurements | • factorIMUBiasPrior — Connect SE(3) pose nodes ("POSE_SE3"), 3-D velocity nodes ("VEL3"), and IMU bias nodes ("IMU_BIAS") to prior-known IMU measurements.<br>• factorPoseSE3Prior — Connect SE(3) pose nodes ("POSE_SE3") to prior-known SE(3) pose measurements.<br>• factorVelocity3Prior — Connect 3-D velocity node ("VEL_3") to prior-known SE(3) velocity measurements. |

## Object Functions

| | |
|---|---|
| addFactor | Add factor to factor graph |
| fixNode | Fix or free nodes in factor graph |
| generateNodeID | Generate new node IDs |
| hasNode | Check if node ID exists in factor graph |
| isConnected | Check if factor graph is connected |
| isNodeFixed | Check if node is fixed |
| nodeIDs | Get node IDs in factor graph |
| nodeState | Get or set node state in factor graph |
| nodeType | Get node type of node in factor graph |

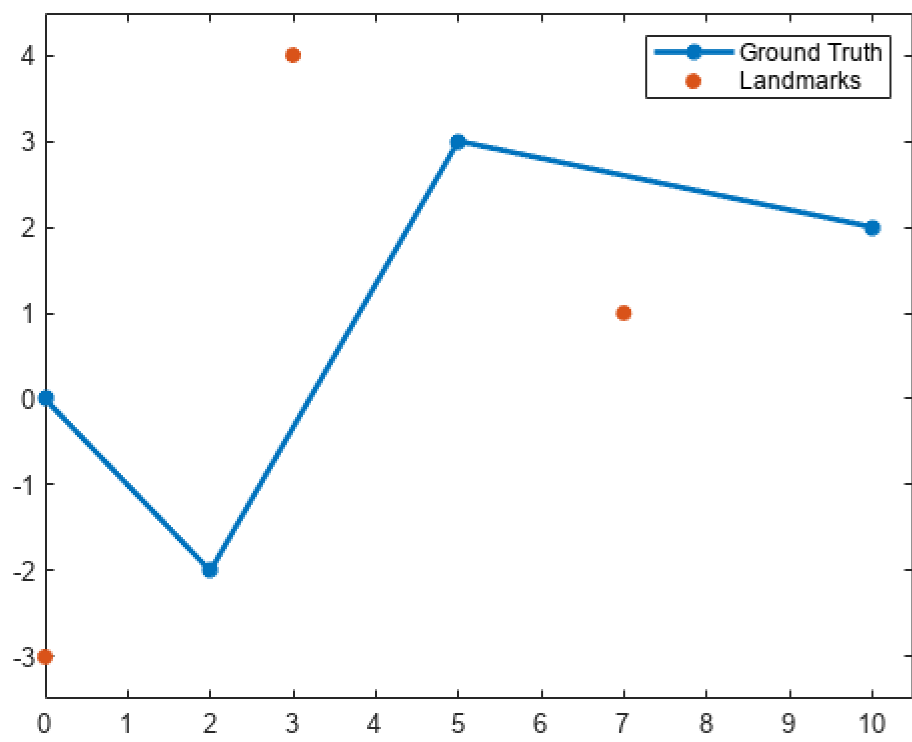
| | |
|---|---|
| optimize | Optimize factor graph |

## Examples

### Estimate Position Using Landmark Factors

Create a matrix of positions of the landmarks to use for localization, and the real positions of the robot to compare your factor graph estimate against. Use the `exampleHelperPlotPositionsAndLandmarks` helper function to visualize the landmark points and the real path of the robot..

```
landmarks = [0 -3  0;
             3  4  0;
             7  1  0];
realpos = [0  0  0;
           2 -2  0;
           5  3  0;
           10 2  0];
exampleHelperPlotPositionsAndLandmarks(realpos,landmarks)
```




### Create Robot Pose Nodes

Create a factor graph, and add a prior factor to loosely fix the start pose of the robot by providing an estimate pose.

```
fg = factorGraph;
rng(1)
pf = factorPoseSE3Prior(0);
```

Generate node IDs to use to create three `factorTwoPoseSE3` relative pose factors that relate four robot poses. To simulate sensor readings for the measurements of each factor, take the difference between a consecutive pair of ground truth positions, add noise, and append a quaternion of zero to provide a rotation of zero. Then add the prior factor and the pose factors to the factor graph.

```
zeroQuat = [1 0 0 0];
rpfIDs = generateNodeID(fg,3,"factorTwoPoseSE3")
```

```
rpfIDs = 3×2

     0     1
     1     2
     2     3
```

```
rpfmeasure = [(diff(realpos) + 0.1*rand(3)) repmat(zeroQuat,3,1)];
rpf = factorTwoPoseSE3(rpfIDs,Measurement=rpfmeasure);
addFactor(fg,pf);
addFactor(fg,rpf);
```

**Create Landmark Factors**

Generate node IDs to create three `factorPoseSE3AndXYZ` landmark factor objects that relate to the pose nodes. The first and second pose nodes observe the first landmark point so they should connect to that landmark with a factor. The second and third pose nodes observe the second landmark. The third and fourth pose nodes observe the third landmark.

```
landmarkIDs = generateNodeID(fg,3)'
```

```
landmarkIDs = 3×1

     4
     5
     6
```

The landmark factors used here are for 3-D state space but the process is identical for landmark factors for 2-D state space. Add some random number to the relative position between the landmark and the ground truth position to simulate real sensor measurements. Then create the landmark factors and add them to the factor graph.

```
lmf1measure = [landmarks(1,:) - realpos(1:2,:)] + 0.5*rand(1,3);
lmf2measure = [landmarks(2,:) - realpos(2:3,:)] + 0.5*rand(1,3);
lmf3measure = [landmarks(3,:) - realpos(3:4,:)] + 0.5*rand(1,3);
lmf1 = factorPoseSE3AndPointXYZ([[0 1]' repmat(landmarkIDs(1),2,1)],Measurement=lmf1measure);
lmf2 = factorPoseSE3AndPointXYZ([[1 2]' repmat(landmarkIDs(2),2,1)],Measurement=lmf2measure);
lmf3 = factorPoseSE3AndPointXYZ([[2 3]' repmat(landmarkIDs(3),2,1)],Measurement=lmf3measure);
addFactor(fg,lmf1);
addFactor(fg,lmf2);
addFactor(fg,lmf3);
```

### Optimize Factor Graph

Optimize the factor graph with the default solver options. The optimization updates the states of all nodes in the factor graph, so the positions of vehicle and the landmarks update.

```
fgso = factorGraphSolverOptions;
optimize(fg,fgso)
```

```
ans = struct with fields:
             InitialCost: 72.6129
               FinalCost: 0.0011
      NumSuccessfulSteps: 4
    NumUnsuccessfulSteps: 0
               TotalTime: 0.0026
         TerminationType: 0
        IsSolutionUsable: 1
```

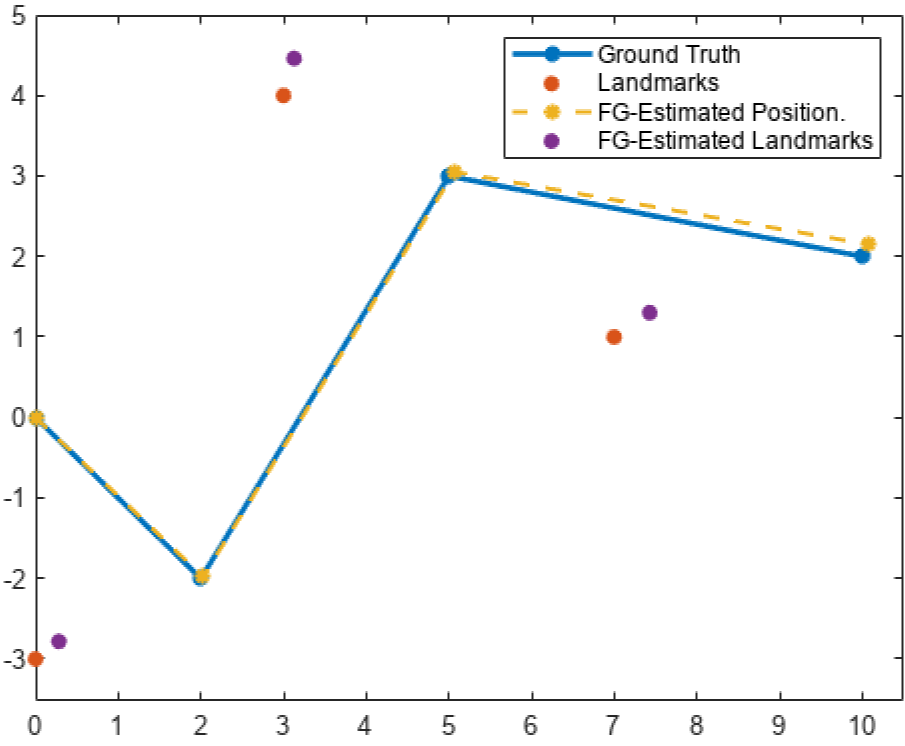
### Visualize and Compare Results

Get and store the updated node states for the vehicle and landmarks and plot the results, comparing the factor graph estimate of the robot path to the known ground truth of the robot.

```
poseIDs = nodeIDs(fg,NodeType="POSE_SE3");
fgposopt = nodeState(fg,poseIDs)
```

```
fgposopt = 4×7

    0.0000    0.0000    0.0000    1.0000    0.0000   -0.0000    0.0000
    2.0278   -1.9778    0.0173    1.0000    0.0018   -0.0034    0.0014
    5.0684    3.0500    0.0871    0.9999   -0.0010   -0.0072    0.0089
   10.0844    2.1475    0.1972    0.9999    0.0006   -0.0121    0.0100
```

```
fglmopt = nodeState(fg,landmarkIDs);
exampleHelperPlotPositionsAndLandmarks(realpos,landmarks,fgposopt,fglmopt)
```




## Tips

- To specify multiple factors and nodes at once for a specific factor type, use the `generateNodeID` function and specify the number of factors and the factor type. See the `generateNodeID` function for more details.

  ```
  poseIDPairs = generateNodeID(fg,3,"factorTwoPoseSE2");
  ftpse2 = factorTwoPoseSE2(poseIDPairs);
  ```

- If you constructed a factor graph containing SE(2) robot poses, you can get the states of all the pose nodes by first using the `nodeIDs` function and specifying the node type as `"POSE_SE2"`. Then use the `nodeState` function with those node IDs to get the node states of the robot pose nodes.

  ```
  poseIDs = nodeIDs(fg,NodeType="POSE_SE2");
  poseStates = nodeState(fg,poseIDs);
  ```

- Check the types of nodes that each factor creates or connects to before adding factors to the factor graph to avoid node type mismatch errors. These are the node types that the `NodeID` property of each factor object specifies and connects to:

| Factor Object | Expected Node Types of Specified Node IDs |
| --- | --- |
| factorGPS | ["POSE_SE3"] |

| Factor Object | Expected Node Types of Specified Node IDs |
| --- | --- |
| factorIMU | ["POSE_SE3","VEL3","IMU_BIAS","POSE_SE3","VEL3","IMU_BIAS"] |
| factorCameraSE3AndPointXYZ | ["POSE_SE3","POINT_XYZ"] |
| factorPoseSE2AndPointXY | ["POSE_SE2","POINT_XY"] |
| factorPoseSE3AndPointXYZ | ["POSE_SE3","POINT_XYZ"] |
| factorTwoPoseSE2 | ["POSE_SE2","POSE_SE2"] |
| factorTwoPoseSE3 | ["POSE_SE3","POSE_SE3"] |
| factorIMUBiasPrior | ["IMU_BIAS"] |
| factorPoseSE3Prior | ["POSE_SE3"] |
| factorVelocity3Prior | ["VEL_3"] |

For example, `factorPoseSE2AndPointXY([1 2])` creates a 2-D landmark factor connecting to node IDs 1 and 2. If you try to add that factor to a factor graph that already contains nodes 1 and 2, the factor expects nodes 1 and 2 to be of types `"POSE_SE2"` and `"POINT_XY"`, respectively.

# Version History

**Introduced in R2022a**

## References

[1] Dellaert, Frank. *Factor graphs and GTSAM: A Hands-On Introduction*. Georgia: Georgia Tech, September, 2012.

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
`factorGraphSolverOptions`

**Functions**
`importFactorGraph` | `estimateGravityDirection` | `estimateGravityDirectionAndPoseScale`

**Topics**
"Factor Graph-Based Pedestrian Localization with IMU and GPS Sensors"
"Landmark SLAM Using AprilTag Markers"

# addFactor

Add factor to factor graph

## Syntax

```
factorIDs = addFactor(graph,factor)
factorIDs = addFactor(graph,factor,groupID)
```

## Description

`factorIDs = addFactor(graph,factor)` adds one or more factors, `factor`, to the specified `factorGraph` object `graph` and returns the IDs `factorIDs` of the added factors.

If adding the factors results in an invalid node, then `addFactor` returns an error, and indicates the invalid nodes.

**Note** `addFactor` supports only single-factor addition for the `factorIMU` and `factorGPS` objects.

`factorIDs = addFactor(graph,factor,groupID)` adds a factor to the factor graph with group ID `groupID`. Node IDs of the same group can be retrieved by group ID using `nodeIDs` function.

## Input Arguments

**graph — Factor graph to add factor to**
`factorGraph` object

Factor graph to add factor to, specified as a `factorGraph` object.

**`factor` — Factors to add to factor graph**
valid factor object

Factors to add to the factor graph, specified as a valid factor object.

A valid factor object must be one of these objects, and the object must not create any invalid nodes when added to the factor graph:

- `factorGPS`
- `factorIMU`
- `factorCameraSE3AndPointXYZ`
- `factorPoseSE2AndPointXY`
- `factorPoseSE3AndPointXYZ`
- `factorTwoPoseSE2`
- `factorTwoPoseSE3`
- `factorIMUBiasPrior`
- `factorPoseSE3Prior`

- `factorVelocity3Prior`

With the exception of `factorGPS` and `factorIMU`, you can simultaneously add multiple factors to the factor graph using any one of the listed factor objects. `factorGPS` and `factorIMU` support only single-factor addition.

If the specified factor object creates any invalid nodes, then `addFactor` adds none of the factors from the factor object.

**`groupID` — Group IDs for nodes of added factor**
nonnegative integer | two-element row vector of nonnegative integers | *N*-element column vector of nonnegative integers | *N*-by-2 matrix of nonnegative integers

Group IDs for nodes of the added factor, specified as any of these options:

| `groupID` Size | Grouping Behavior |
| --- | --- |
| nonnegative integer | Assigns all nodes to one group.<br><br>For example, if you add a factor object that has a `NodeID` value of $\begin{bmatrix}1 & 2\\3 & 4\end{bmatrix}$ with a `groupID` value of `1`, `addFactor` adds nodes *1*, *2*, *3*, and *4* to group *1*. |
| two-element row vector of nonnegative integers | Specify groups for each column of nodes.<br><br>For example, if you add a factor object that has a `NodeID` value of $\begin{bmatrix}1 & 2\\3 & 4\end{bmatrix}$ with a `groupID` value of [1  2], `addFactor` adds nodes *1* and *3* to group *1* and adds nodes *2* and *4* to group *2*.<br><br>The behavior for IMU factors is different. If you add an IMU factor with a `NodeID` value of [1  2  3  4  5  6] and `groupID` set to [1  2], `addFactor` adds nodes *1*, *2*, and *3* to group *1* and nodes *4*, *5*, and *6* to group *2*. |
| *N*-element column vector of nonnegative integers | Group nodes by factor, where *N* is the total number of factors specified by the `NodeID` property of `factor`.<br><br>For example, if you add a factor object that has a `NodeID` value of $\begin{bmatrix}1 & 2\\3 & 4\end{bmatrix}$ with a `groupID` value of $\begin{bmatrix}1\\2\end{bmatrix}$, `addFactor` adds nodes *1* and *2* to group *1* and adds nodes *3* and *4* to group *2*. |

| groupID Size | Grouping Behavior |
|---|---|
| *N*-by-2 matrix of nonnegative integers | Add nodes in `NodeID` to the group specified at its corresponding index in `groupID`, where *N* is the total number of rows of the `NodeID` property of `factor`.<br><br>For example, if you add a factor object that has a `NodeID` value of $\begin{bmatrix}1 & 2\\3 & 4\end{bmatrix}$ with a `groupID` value of $\begin{bmatrix}1 & 2\\3 & 1\end{bmatrix}$, `addFactor` add nodes *1* and *4* into group *1*, adds node *2* to group *2*, and adds node *3* to group 3. |

**Note** When adding a `factorIMU` or `factorGPS` object to a factor graph, `groupID` accepts only these values:

- `factorIMU` — Nonnegative integer or a two-element row vector of nonnegative integers.
- `factorGPS` — Nonnegative integer

---

Adding nodes to groups enables you to query node IDs by group by specifying the `GroupID` name-value argument of the `nodeIDs` function.

## Output Arguments

### `factorIDs` — Factor IDs of added factors

*N*-element row vector of nonnegative integers

Factor IDs of the added factors, returned as an *N*-element row vector of nonnegative integers. *N* is the total number of factors added.

The function returns this argument only when it successfully adds the factors to the factor graph. If adding the factors results in an invalid node, then `addFactor` adds none of the factors from the factor object.

# Version History

**Introduced in R2022a**

### R2023a: Specify group IDs for added factors

`addFactor` now supports specifying groups to add nodes of added factors to by group ID.

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
factorGraph | factorTwoPoseSE2 | factorTwoPoseSE3 | factorPoseSE3Prior | factorVelocity3Prior | factorIMUBiasPrior | factorGPS | factorIMU

**Functions**
nodeIDs

**Topics**
"Factor Graph-Based Pedestrian Localization with IMU and GPS Sensors"
"Landmark SLAM Using AprilTag Markers"

# fixNode

Fix or free nodes in factor graph

## Syntax

```
fixNode(graph,nodeIDs)
fixNode(graph,nodeIDs,flag)
```

## Description

`fixNode(graph,nodeIDs)` fixes the nodes at the specified IDs, `nodeIDs` during optimization.

`fixNode(graph,nodeIDs,flag)` specifies whether to fix or free the node at the specified IDs, `nodeIDs`.

## Input Arguments

**graph — Factor graph containing nodes to fix**
`factorGraph` object

Factor graph containing nodes to fix, specified as a `factorGraph` object.

**nodeIDs — IDs of nodes to fix or free**
*N*-element row vector of nonnegative integers

IDs of the nodes to fix or free within the factor graph, specified as an *N*-element row vector of nonnegative integers. *N* is the total number of nodes to fix or free.

**flag — New fix status of node**
`true` or `1` (default) | `false` or `0`

New fix status of the node, specified as a logical `1` (`true`) or `0` (`false`). If specified as `true`, the function fixes the node. If specified as `false`, the function frees the node during optimization.

# Version History

**Introduced in R2022a**

**R2023a: Fix or free multiple nodes at a time**

`fixNode` now supports fixing or freeing more than one node at a time by specifying `nodeIDs` as a vector of node IDs.

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
`factorGraph`

# generateNodeID

Generate new node IDs

## Syntax

```
IDs = generateNodeID(graph,numNodes)
IDs = generateNodeID(graph,nodeMatrixSize)
IDs = generateNodeID(graph,numFactors,factorType)
```

## Description

`IDs = generateNodeID(graph,numNodes)` generates the specified number `numNodes` new node IDs `IDs` to use when creating new factors to add to the factor graph `graph`.

The first node ID in `IDs` is `0` if there are no nodes in `graph`, otherwise the first node ID in `IDs` is equal to `graph.NumNodes + 1`.

`IDs = generateNodeID(graph,nodeMatrixSize)` specifies the number of new node IDs to generate as the number of elements in a matrix with the specified dimensions `nodeMatrixSize`. The IDs increment in row-major order.

For example, `generateNodeID(graph,[3 2])` creates new node IDs as a matrix in this format.

$$\begin{bmatrix} ID_1 & ID_2 \\ ID_3 & ID_4 \\ ID_5 & ID_6 \end{bmatrix}$$

`IDs = generateNodeID(graph,numFactors,factorType)` generates new node IDs for the specified number of factors `numFactors`. The size of the generated node IDs and how the IDs increment depends on the number of factors and the factor type `factorType`

---

**Note** The `generateNodeID` can only generate node IDs for creating one factor using this syntax for the `factorIMU` and `factorGPS` objects. To use this syntax to generate node IDs for the `factorIMU` and `factorGPS` objects, `numFactors` must be `1`.

---

## Examples

### Generate Node IDs by Specifying Number of Nodes

Create a factor graph and generate ten node IDs.

```
fg = factorGraph;
nids = generateNodeID(fg,10)
```

```
nids = 1×10

     0     1     2     3     4     5     6     7     8     9
```

### Generate Node IDs by Specifying Node Matrix Size

Create a factor graph and generate a 4-by-2 node ID matrix.

```
fg = factorGraph;
nids = generateNodeID(fg,[4 2])
```

```
nids = 4×2

     0     1
     2     3
     4     5
     6     7
```

### Generate Node IDs by Specifying Factor Type

Create a factor graph and generate node IDs to specify four factors in a `factorPoseSE3AndPointXYZ` object.

```
fg = factorGraph;
poseAndLandmarkIDs = generateNodeID(fg,4,"factorPoseSE3AndPointXYZ")
```

```
poseAndLandmarkIDs = 4×2

     0     1
     0     2
     0     3
     0     4
```

Note that for landmark factors, the goal is to connect one pose to multiple landmarks. So for `"factorPoseSE3AndPointXYZ"` factor type, the first column is constant because it represents the single pose node, and the second column increments because it represents multiple landmarks nodes.

Create and add the factor object to the factor graph to create the factors.

```
poseAndLandmarkFactors = factorPoseSE3AndPointXYZ(poseAndLandmarkIDs);
addFactor(fg,poseAndLandmarkFactors);
```

Generate node IDs to create a `factorTwoPoseSE2` object with three factors. Because the last node ID of the factor graph is `4`, the new node IDs start at five.

```
poseIDs = generateNodeID(fg,3,"factorTwoPoseSE2")
```

```
poseIDs = 3×2

     5     6
     6     7
     7     8
```

Note that `"factorTwoPoseSE2"` factor type, the goal is create a chain of connected poses, meaning that each row should be connected to the row before and after it. So for every row after the first row,

the first element is the second node ID of the previous row. This ensures that each node connects to the nodes immediately before and after it in sequence.

Create and add the factorTwoPoseSE2 object to the factor graph.

```
twoPoseFactors = factorTwoPoseSE2(poseIDs);
addFactor(fg,twoPoseFactors);
```

## Input Arguments

**graph — Factor graph to generate nodes for**
factorGraph object

Factor graph to generate nodes for, specified as a factorGraph object.

The NumNodes property of graph determines what the first generated node ID of the IDs output is. The first node ID in IDs is 0 if there are no nodes in graph, otherwise the first node ID in IDs is equal to graph.NumNodes + 1.

**numNodes — Number of nodes**
nonnegative integer

Number of node IDs to generate, specified as a nonnegative integer.

Example: generateNodeID(fg,3) generates three node IDs as a row vector in the form [*NodeID1 NodeID2 NodeID3*]

**nodeMatrixSize — Generated node ID matrix size**
two-element vector of nonnegative integers

Generated node ID matrix size, specified as a two-element vector of nonnegative integers. The first element specifies the number of rows and the second element specifies the number of columns in the node ID matrix.

Example: generateNodeID(fg,[3 2]) generates two node IDs for three factors in the form [*NodeID1 NodeID2*; *NodeID3 NodeID4*; *NodeID5 NodeID6*]

**numFactors — Number of factors to generate IDs for**
nonnegative integer

Number of factors to generate node IDs for, specified as a nonnegative integer.

If factorType is either "factorGPS" or "factorIMU", then numFactors must be specified as 1.

Example: generateNodeID(fg,1,"factorPoseSE2AndPointXY") creates a set of two node IDs in the form [*SE2PoseNodeID LandmarkNodeID*] for one factor.

**factorType — Factor type for which to generate node IDs**
string scalar | character vector

Factor type for which to generate node IDs, specified as one of these options:

- "factorCameraSE3AndPointXYZ" — factorCameraSE3AndPointXYZ
- "factorIMUBiasPrior" — factorIMUBiasPrior

- "factorPoseSE2AndPointXY" — factorPoseSE2AndPointXY
- "factorPoseSE3AndPointXYZ" — factorPoseSE3AndPointXYZ
- "factorPoseSE3Prior" — factorPoseSE3Prior
- "factorTwoPoseSE2" — factorTwoPoseSE2
- "factorTwoPoseSE3" — factorTwoPoseSE3
- "factorVelocity3Prior" — factorVelocity3Prior

The generateNodeID function supports only generating node IDs to create a single factor for these options:

- "factorGPS" — factorGPS
- "factorIMU" — factorIMU

If factorType is either "factorGPS" or "factorIMU", then the numFactors argument must be specified as 1.

The format of the node IDs corresponds to the format of the NodeID property for that factor object. For example, if you specify "factorTwoPoseSE2", the function outputs node IDs of the form [*SE2Pose1NodeID SE2Pose2NodeID*].

Example: generateNodeID(fg,1,"factorPoseSE2AndPointXY") creates a set of two node IDs in the form [*SE2PoseNodeID LandmarkNodeID*]

Data Types: char | string

## Output Arguments

**IDs — Generated node IDs**
*N*-element row vector | *M*-by-*N* matrix

Generated node IDs, returned as one of these options depending on which input arguments you specify:

1. numNodes — *N*-element row vector, where *N* is equal to numNodes, and increments with each new node ID.
2. nodeMatrixSize — *M*-by-*N* matrix, where *M* and *N* are equal to the first and second elements of nodeMatrixSize, respectively. The node IDs increment in row-major order.

   For example, if you specify generateNodeID(fg,[3 2]) with no existing nodes in the factor graph fg, the function generates a node ID matrix in this format.

   $$\begin{bmatrix} ID_1 & ID_2 \\ ID_3 & ID_4 \\ ID_5 & ID_6 \end{bmatrix}$$
3. numFactors and factorType — *M*-by-*N* matrix, where *M* is equal to numFactors, and *N* is the number of node IDs generated per factor depending on the value of factorType:

| factorType | IDs Format |
|---|---|
| • "factorCameraAndPointXYZ"<br>• "factorPoseSE2AndPointXY"<br>• "factorPoseSE3AndPointXYZ" | *N*-by-2 matrix of node IDs, where *N* is equal to `numFactors`. The first column contains the first node ID for every row, and the second column contains unique node IDs that increment down the second column.<br>$\begin{bmatrix} ID_1 & ID_2 \\ ID_1 & ID_3 \\ \vdots & \vdots \\ ID_1 & ID_N \end{bmatrix}$ |
| • "factorTwoPoseSE2"<br>• "factorTwoPoseSE3" | *N*-by-2 matrix, where *N* is equal to `numFactors`. Each row represents a pair of consecutive nodes. For every row after the first row, the first element is the second node ID of the previous row. This ensures that each node connects to the nodes immediately before and after it in sequence.<br>$\begin{bmatrix} ID_1 & ID_2 \\ ID_2 & ID_3 \\ \vdots & \vdots \\ ID_N & ID_{N+1} \end{bmatrix}$ |
| • "factorIMUBiasPrior"<br>• "factorPoseSE3Prior"<br>• "factorVelocity3Prior" | *N*-element column vector, where *N* is equal to `numFactors`.<br>$\begin{bmatrix} ID_1 \\ ID_2 \\ \vdots \\ ID_N \end{bmatrix}$ |

The first node ID in `IDs` is `0` if there are no nodes in `graph`, otherwise the first node ID in `IDs` is equal to `graph.NumNodes + 1`.

# Version History

**Introduced in R2023a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`factorGraph` | `nodeIDs`

# hasNode

Check if node ID exists in factor graph

## Syntax

```
nodeExist = hasNode(graph,nodeID)
```

## Description

`nodeExist = hasNode(graph,nodeID)` checks if a node with the specified ID `nodeID` exists in the factor graph `graph`.

## Input Arguments

**graph — Factor graph**
`factorGraph` object

Factor graph, specified as a `factorGraph` object.

**nodeID — ID of node to check**
nonnegative integer

ID of node to check, specified as a nonnegative integer.

## Output Arguments

**nodeExist — Node exists in the factor graph**
`false` or `0` | `true` or `1`

Node exists in the factor graph, returned as a logical `0` (`false`) or `1` (`true`). The function returns `0` if the node does not exist, and `1` if it does exist.

# Version History

**Introduced in R2022a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
`factorGraph`

# isConnected

Check if factor graph is connected

## Syntax

```
connected = isConnected(graph)
```

## Description

`connected = isConnected(graph)` returns a logical flag indicating whether the specified `factorGraph` object `graph`, contains nodes that all have at least one connection.

## Input Arguments

**graph — Factor graph**
`factorGraph` object

Factor object, specified as a `factorGraph` object.

## Output Arguments

**connected — Graph is connected in factor graph**
`false` or `0` | `true` or `1`

Graph is connected in factor graph, returned as `1` (`true`) if the `factorGraph` has a single connected component and `0` or `false` if it does not have a single connected component.

# Version History

**Introduced in R2022a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
`factorGraph`

# isNodeFixed

Check if node is fixed

## Syntax

```
isFixed = isNodeFixed(graph,nodeID)
```

## Description

`isFixed = isNodeFixed(graph,nodeID)` returns a logical flag indicating whether the node with the specified `nodeID` in the factor graph, `graph` is fixed or not fixed during optimization.

## Input Arguments

**graph — Factor graph**
`factorGraph` object

Factor graph, specified as a `factorGraph` object.

**nodeID — Node ID of existing node**
nonnegative integer

Node ID of an existing node, specified as a nonnegative integer.

## Output Arguments

**isFixed — Fix status of node**
`true` or `1` | `false` or `0`

Fix status of the node, returned as a logical `1` (`true`) or `0` (`false`). The function returns `true` when the node is fixed, and returns `false` when the node is free.

# Version History

**Introduced in R2022a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
`factorGraph`

# nodeIDs

Get node IDs in factor graph

## Syntax

```
ids = nodeIDs(graph)
ids = nodeIDs(graph,Name=Value)
```

## Description

`ids = nodeIDs(graph)` gets all node IDs, `ids`, currently in the factor graph `graph`.

`ids = nodeIDs(graph,Name=Value)` specifies options using one or more name-value arguments.

## Input Arguments

**graph — Factor graph**
`factorGraph` object

Factor graph, specified as a `factorGraph` object.

### Name-Value Pair Arguments

Specify optional pairs of arguments as `Name1=Value1,...,NameN=ValueN`, where `Name` is the argument name and `Value` is the corresponding value. Name-value arguments must appear after other arguments, but the order of the pairs does not matter.

Example: `nodeIDs(fg,GroupID=1)` retrieves all of the node IDs of factor graph `fg` that are associated with group `1`.

**NodeType — Node type of desired nodes in factor graph**
string scalar | character vector

Node type of the desired nodes in the factor graph, specified as one of these options:

- `"POSE_SE2"` — Pose in SE(2) state space
- `"POSE_SE3"` — Pose in SE(3) state space
- `"VEL3"` — 3-D velocity
- `"POINT_XY"` — 2-D point
- `"POINT_XYZ"` — 3-D point
- `"IMU_BIAS"` — IMU gyroscope and accelerometer bias

Example: `nodeIDs(fg,NodeType="POSE_SE2")` retrieves all of the node IDs of nodes that are of node type `POSE_SE2`.

Data Types: `char` | `string`

**FactorType — Factor type that nodes relate to in factor graph**
string scalar | character vector

Factor type that the nodes relate to in the factor graph, specified as one of these options:

- `"factorIMU"` — `factorIMU`
- `"factorGPS"` — `factorGPS`
- `"factorCameraSE3AndPointXYZ"` — `factorCameraSE3AndPointXYZ`
- `"factorPoseSE2AndPointXY"` — `factorPoseSE2AndPointXY`
- `"factorPoseSE3AndPointXYZ"` — `factorPoseSE3AndPointXYZ`
- `"factorTwoPoseSE2"` — `factorTwoPoseSE2`
- `"factorTwoPoseSE3"` — `factorTwoPoseSE3`
- `"factorIMUBiasPrior"` — `factorIMUBiasPrior`
- `"factorPoseSE3Prior"` — `factorPoseSE3Prior`
- `"factorVelocity3Prior"` — `factorVelocity3Prior`

Example: `nodeIDs(fg,FactorType="factorTwoPoseSE2")` retrieves all of the node IDs of nodes that relate to factors of type `factorTwoPoseSE2`.

Data Types: `char` | `string`

**`GroupID` — Group ID of desired nodes**
nonnegative integer | *N*-element row vector of nonnegative integers

Group ID of desired nodes, specified as a nonnegative integer or *N*-element row vector of nonnegative integers. *N* is the number of groups.

If `GroupID` is an *N*-element row vector of nonnegative integers, there must be no duplicate group IDs in the vector.

To add nodes to a group, specify the group using the `groupID` argument of the `addFactor` function.

Example: `nodeIDs(fg,GroupID=4)` retrieves all of the node IDs of nodes that are in group `4`.

## Output Arguments

**`ids` — Node IDs**
*N*-element row vector

Node IDs of all nodes that fit the specified criteria within the specified `factorGraph` object, returned as an *N*-element row vector. *N* is the number of returned nodes. Note that the node IDs may not be continuous within the vector.

# Version History

**Introduced in R2022a**

**R2023a: Get node IDs that match node type, factor type, or group ID**

`nodeIDs` now supports getting node IDs that match node type, factor type, or group ID.

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`factorGraph` | `addFactor`

# nodeState

Get or set node state in factor graph

## Syntax

```
state = nodeState(graph,nodeIDs)
```

```
nodeState(graph,nodeIDs,newStates)
```

## Description

`state = nodeState(graph,nodeIDs)` gets the state of the nodes with the specified IDs `nodeIDs` in the specified `factorGraph` object `graph`.

`nodeState(graph,nodeIDs,newStates)` sets the state of the nodes with the specified IDs `nodeIDs` in the specified `factorGraph` object `graph` to the specified states `newStates`.

## Input Arguments

**`graph` — Factor graph**
`factorGraph` object

Factor graph, specified as a `factorGraph` object.

**`nodeIDs` — IDs of nodes to get or set**
*N*-element row vector of nonnegative integers

IDs of the nodes to get or set, specified as an *N*-element row vector of nonnegative integers. *N* is the total number of nodes to get or set.

All specified node IDs must specify nodes of the same type.

**`newStates` — New node states**
*M*-by-*N* matrix

New node states, specified as an *M*-by-*N* matrix. *M* is the number of specified IDs and *N* is the number of state elements for the specified nodes. Each row of the matrix specifies the state element values for the corresponding element of `nodeIDs`.

These are the supported node types and the form of their corresponding states:

- `POSE_SE2` — Pose in SE(2) state space in the form [*x y theta*]. *x* and *y* are the *x*- and *y*-positions, respectively, and *theta* is the orientation.
- `POSE_SE3` — Pose in SE(3) state space in the form [*x y z qw qx qy qz*]. *x*, *y*, and *z* are the *x*-, *y*-, and *z*-positions, respectively, and *qw*, *qx*, *qy*, and *qz* represent the orientation as a quaternion.
- `VEL3` — 3-D velocity in the form [*vx vy vz*]. *vx*, *vy*, and *vz* are the *x*-, *y*-, and *z*-velocities, respectively.
- `POINT_XY` — 2-D point in the form [*x y*]. *x* and *y* are the *x*- and *y*-positions, respectively.

- `POINT_XYZ` — 3-D point in the form [*x y z*]. *x*, *y*, and *z* are the *x*-, *y*-, and *z*-positions, respectively.
- `IMU_BIAS` — IMU gyroscope and accelerometer bias in the form [*bias_gyro_x bias_gyro_y bias_gyro_z bias_accel_x bias_accel_y bias_accel_z*], where:
  - *bias_gyro_x*, *bias_gyro_y*, and *bias_gyro_z* are the *x*, *y*, and *z* IMU gyroscope biases, respectively.
  - *bias_accel_x*, *bias_accel_y*, and *bias_accel_z* are the *x*, *y*, and *z* accelerometer biases, respectively.

## Output Arguments

### `state` — State of nodes

*M*-by-*N* matrix

State of the nodes, returned as an *M*-by-*N* matrix. *M* is the number of IDs and *N* is the number of state elements for the specified nodes.

These are the supported node types and the form of their corresponding states:

- `POSE_SE2` — Pose in SE(2) state space in the form [*x y theta*]. *x* and *y* are the *x*- and *y*-positions, respectively, and *theta* is the orientation.
- `POSE_SE3` — Pose in SE(3) state space in the form [*x y z qw qx qy qz*]. *x*, *y*, and *z* are the *x*-, *y*-, and *z*-positions, respectively, and *qw*, *qx*, *qy*, and *qz* represent the orientation as a quaternion.
- `VEL3` — 3-D velocity in the form [*vx vy vz*]. *vx*, *vy*, and *vz* are the *x*-, *y*-, and *z*-velocities, respectively.
- `POINT_XY` — 2-D point in the form [*x y*]. *x* and *y* are the *x*- and *y*-positions, respectively.
- `POINT_XYZ` — 3-D point in the form [*x y z*]. *x*, *y*, and *z* are the *x*-, *y*-, and *z*-positions, respectively.
- `IMU_BIAS` — IMU gyroscope and accelerometer bias in the form [*bias_gyro_x bias_gyro_y bias_gyro_z bias_accel_x bias_accel_y bias_accel_z*], where:
  - *bias_gyro_x*, *bias_gyro_y*, and *bias_gyro_z* are the *x*, *y*, and *z* IMU gyroscope biases, respectively.
  - *bias_accel_x*, *bias_accel_y*, and *bias_accel_z* are the *x*, *y*, and *z* accelerometer biases, respectively.

# Version History

**Introduced in R2022a**

### R2023a: Get or set multiple nodes at one time

`nodeState` now supports getting and setting more than one node at a time by specifying `nodeIDs` as a vector of node IDs. `newStates` also supports additional rows to specify states for multiple nodes at once.

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
`factorGraph`

# nodeType

Get node type of node in factor graph

## Syntax

```
type = nodeType(graph,nodeID)
```

## Description

`type = nodeType(graph,nodeID)` returns the type `type` of the specified node `nodeID`, in the factor graph `graph`.

## Input Arguments

**`graph` — Factor graph**
`factorGraph` object

Factor graph, specified as a `factorGraph` object.

**`nodeID` — ID of node to check**
nonnegative integer

ID of node to check, specified as a nonnegative integer.

## Output Arguments

**`type` — Type of node**
string scalar

Type of the node, returned as one of these node types:

- `"POSE_SE2"` — Pose in SE(2) state space
- `"POSE_SE3"` — Pose in SE(3) state space
- `"VEL3"` — 3-D velocity
- `"POINT_XY"` — 2-D point
- `"POINT_XYZ"` — 3-D point
- `"IMU_BIAS"` — IMU gyroscope and accelerometer bias

# Version History

**Introduced in R2022a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
`factorGraph`

# optimize

Optimize factor graph

## Syntax

```
solnInfo = optimize(graph,solverOptions)
```

## Description

`solnInfo = optimize(graph,solverOptions)` optimizes the `factorGraph` object `graph` using the specified factor graph solver options, `solverOptions`, and returns the resulting solution info `solnInfo`.

## Examples

### Create and Optimize Factor Graph with Custom Options

Create and optimize a factor graph with custom solver options.

#### Create Factor Graph and Solver Settings

Create a factor graph and solver options with custom settings. Set the maximum number of iterations to `1000` and set the verbosity of the `optimize` output to `2`.

```
G = factorGraph;
optns = factorGraphSolverOptions(MaxIterations=1000,VerbosityLevel=2)
```

```
optns =
  factorGraphSolverOptions with properties:

              MaxIterations: 1000
          FunctionTolerance: 1.0000e-06
          GradientTolerance: 1.0000e-10
              StepTolerance: 1.0000e-08
             VerbosityLevel: 2
    TrustRegionStrategyType: 1
```

#### Add GPS Factor

Create a GPS factor with node identification number of `1` with NED ReferenceFrame and add it to the factor graph.

```
fgps = factorGPS(1,ReferenceFrame="NED");
addFactor(G,fgps);
```

#### Optimize Factor Graph

Optimize the factor graph with the custom settings. The results of the optimization are displayed with the level of detail depending on the `VerbosityLevel.`

```
optimize(G,optns);
```

```
iter      cost      cost_change  |gradient|   |step|    tr_ratio  tr_radius  ls_iter  iter_time
   0  0.000000e+00    0.00e+00    0.00e+00   0.00e+00   0.00e+00  1.00e+04        0    6.39e-05
Terminating: Gradient tolerance reached. Gradient max norm: 0.000000e+00 <= 1.000000e-10

Solver Summary (v 2.0.0-eigen-(3.3.4)-no_lapack-eigensparse-no_openmp-no_custom_blas)

                                     Original                  Reduced
Parameter blocks                            1                        1
Parameters                                  7                        7
Effective parameters                        6                        6
Residual blocks                             1                        1
Residuals                                   3                        3

Minimizer                        TRUST_REGION

Sparse linear algebra library    EIGEN_SPARSE
Trust region strategy                  DOGLEG (TRADITIONAL)

                                        Given                     Used
Linear solver          SPARSE_NORMAL_CHOLESKY   SPARSE_NORMAL_CHOLESKY
Threads                                     1                        1
Linear solver ordering              AUTOMATIC                        1

Cost:
Initial                          0.000000e+00
Final                            0.000000e+00
Change                           0.000000e+00

Minimizer iterations                        1
Successful steps                            1
Unsuccessful steps                          0

Time (in seconds):
Preprocessor                         0.000103

  Residual only evaluation           0.000000 (0)
  Jacobian & residual evaluation     0.000041 (1)
  Linear solver                      0.000000 (0)
Minimizer                            0.006075

Postprocessor                        0.000012
Total                                0.006190

Termination:                      CONVERGENCE (Gradient tolerance reached. Gradient max norm: 0.0
```

## Input Arguments

**graph — Factor graph**
`factorGraph` object

Factor graph, specified as a `factorGraph` object.

**`solverOptions` — Solver options for factor graph**
`factorGraphSolverOptions` object

Solver options for the factor graph, specified as a `factorGraphSolverOptions` object.

## Output Arguments

**`solnInfo` — Results of optimization**
structure

Results of the optimization, returned as a structure containing:

- `InitialCost` — Initial cost of the non-linear least squares problem formulated by the factor graph before the optimization.
- `FinalCost` — Final cost of the non-linear least squares problem formulated by the factor graph after the optimization.

  **Note** Cost is the sum of error terms, known as residuals, where each residual is a function of a subset of factor measurements.

- `NumSuccessfulSteps` — Number of iterations in which the solver decreases the cost. This value includes the initialization iteration at 0 in addition to the minimizer iterations.
- `NumUnsuccessfulSteps` — Number of iterations in which the iteration is numerically invalid or the solver does not decrease the cost.
- `TotalTime` — Total solver optimization time in seconds.
- `TerminationType` — Termination type as an integer in the range [0, 2]:
  - `0` — Solver found a solution that meets convergence criterion and decreases in cost after optimization.
  - `1` — Solver could not find a solution that meets convergence criterion after running for the maximum number of iterations.
  - `2` — Solver terminated due to an error.
- `IsSolutionUsable` — Solution is usable if `1` (`true`), not usable if `0` (`false`).

# Version History

**Introduced in R2022a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
`factorGraph` | `factorGraphSolverOptions`

**Topics**
“Landmark SLAM Using AprilTag Markers”

# factorGraphSolverOptions

Solver options for factor graph

## Description

The `factorGraphSolverOptions` object contains solver options for optimizing a factor graph.

## Creation

### Syntax

```
Options = factorGraphSolverOptions
Options = factorGraphSolverOptions(Name=Value)
```

#### Description

`Options = factorGraphSolverOptions` returns a default factor graph solver options object, `Options`.

`Options = factorGraphSolverOptions(Name=Value)` specifies properties using one or more name-value arguments. For example, `factorGraphSolverOptions(MaxIterations=150)` sets the `MaxIterations` property of the `factorGraphSolverOptions` object to `150`.

### Properties

**`MaxIterations` — Maximum number of solver iterations**
`200` (default) | positive integer

Maximum number of solver iterations, specified as a positive integer.

**`FunctionTolerance` — Lower bound of change in cost function**
`1e-6` (default) | positive scalar

Lower bound of change in the cost function, specified as a positive scalar. The cost function is:

$|newCost - oldCost| < FunctionTolerance * oldCost$

All costs are greater than 0.

**`GradientTolerance` — Lower bound of norm of gradient**
`1e-10` (default) | positive scalar

Lower bound of the norm of the gradient, specified as positive scalar. The norm function is:

$max_norm\{x - [x * Oplus - g(x)]\} < \ = GradientTolerance$

*Oplus* is the manifold version of the plus operation and *g(x)* is the gradient at *x*.

### `StepTolerance` — Lower bound of step size

`1e-8` (default) | positive integer

Lower bound of step size of the linear solver, specified as a positive scalar. The relationship between the step size and the step tolerance is:

$|deltaX| <= (|x| + StepTolerance) * StepTolerance$

*deltaX* is the step size of the linear solver.

### `VerbosityLevel` — Command line verbosity flag

`0` (default) | `1` | `2`

Command line verbosity flag, specified as `1`, `2`, or `3`.

- `0` — Do not print to command line
- `1` — Print solver summary
- `2` — Print per-iteration updates and solver summary

### `TrustRegionStrategyType` — Trust region step computation algorithm

`1` (default) | `0`

Trust region step computation algorithm, specified as `0` or `1`.

- `0` — Levenberg Marquardt
- `1` — Dogleg

## Examples

### Create and Optimize Factor Graph with Custom Options

Create and optimize a factor graph with custom solver options.

#### Create Factor Graph and Solver Settings

Create a factor graph and solver options with custom settings. Set the maximum number of iterations to `1000` and set the verbosity of the `optimize` output to `2`.

```
G = factorGraph;
optns = factorGraphSolverOptions(MaxIterations=1000,VerbosityLevel=2)
```

```
optns = 
  factorGraphSolverOptions with properties:

              MaxIterations: 1000
          FunctionTolerance: 1.0000e-06
          GradientTolerance: 1.0000e-10
              StepTolerance: 1.0000e-08
             VerbosityLevel: 2
    TrustRegionStrategyType: 1
```

#### Add GPS Factor

Create a GPS factor with node identification number of 1 with NED ReferenceFrame and add it to the factor graph.

```
fgps = factorGPS(1,ReferenceFrame="NED");
addFactor(G,fgps);
```

#### Optimize Factor Graph

Optimize the factor graph with the custom settings. The results of the optimization are displayed with the level of detail depending on the VerbosityLevel.

```
optimize(G,optns);
```

```
iter      cost      cost_change  |gradient|   |step|    tr_ratio  tr_radius  ls_iter  iter_time
   0  0.000000e+00    0.00e+00    0.00e+00   0.00e+00   0.00e+00  1.00e+04        0    6.39e-05
Terminating: Gradient tolerance reached. Gradient max norm: 0.000000e+00 <= 1.000000e-10

Solver Summary (v 2.0.0-eigen-(3.3.4)-no_lapack-eigensparse-no_openmp-no_custom_blas)

                                     Original                  Reduced
Parameter blocks                            1                        1
Parameters                                  7                        7
Effective parameters                        6                        6
Residual blocks                             1                        1
Residuals                                   3                        3

Minimizer                        TRUST_REGION

Sparse linear algebra library    EIGEN_SPARSE
Trust region strategy                  DOGLEG (TRADITIONAL)

                                        Given                     Used
Linear solver          SPARSE_NORMAL_CHOLESKY   SPARSE_NORMAL_CHOLESKY
Threads                                     1                        1
Linear solver ordering              AUTOMATIC                        1

Cost:
Initial                          0.000000e+00
Final                            0.000000e+00
Change                           0.000000e+00

Minimizer iterations                        1
Successful steps                            1
Unsuccessful steps                          0

Time (in seconds):
Preprocessor                         0.000103

  Residual only evaluation           0.000000 (0)
  Jacobian & residual evaluation     0.000041 (1)
  Linear solver                      0.000000 (0)
Minimizer                            0.006075

Postprocessor                        0.000012
Total                                0.006190
```

```
Termination:                    CONVERGENCE (Gradient tolerance reached. Gradient max norm: 0.0
```

## Version History

**Introduced in R2022a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
`factorGraph`

**Functions**
`importFactorGraph`

**Topics**
"Factor Graph-Based Pedestrian Localization with IMU and GPS Sensors"
"Landmark SLAM Using AprilTag Markers"

# insfilterErrorState

Estimate pose from IMU, GPS, and monocular visual odometry (MVO) data

## Description

The `insfilterErrorState` object implements sensor fusion of IMU, GPS, and monocular visual odometry (MVO) data to estimate pose in the NED (or ENU) reference frame. The filter uses a 17-element state vector to track the orientation `quaternion`, velocity, position, IMU sensor biases, and the MVO scaling factor. The `insfilterErrorState` object uses an error-state Kalman filter to estimate these quantities.

## Creation

### Syntax

```
filter = insfilterErrorState
filter = insfilterErrorState('ReferenceFrame',RF)
filter = insfilterErrorState( ___ ,Name,Value)
```

#### Description

`filter = insfilterErrorState` creates an `insfilterErrorState` object with default property values.

`filter = insfilterErrorState('ReferenceFrame',RF)` allows you to specify the reference frame, `RF`, of the `filter`. Specify `RF` as `'NED'` (North-East-Down) or `'ENU'` (East-North-Up). The default value is `'NED'`.

`filter = insfilterErrorState( ___ ,Name,Value)` also allows you set properties of the created `filter` using one or more name-value pairs. Enclose each property name in single quotes.

## Properties

**`IMUSampleRate` — Sample rate of IMU (Hz)**
`100` (default) | positive scalar

Sample rate of the inertial measurement unit (IMU) in Hz, specified as a positive scalar.

Data Types: `single` | `double`

**`ReferenceLocation` — Reference location (deg, deg, meters)**
`[0 0 0]` (default) | 3-element positive row vector

Reference location, specified as a 3-element row vector in geodetic coordinates (latitude, longitude, and altitude). Altitude is the height above the reference ellipsoid model, WGS84. The reference location units are [degrees degrees meters].

Data Types: `single` | `double`

**`GyroscopeNoise` — Multiplicative process noise variance from gyroscope ((rad/s)$^2$)**
`[1e-6 1e-6 1e-6]` (default) | scalar | 3-element row vector

Multiplicative process noise variance from the gyroscope in (rad/s)$^2$, specified as a scalar or 3-element row vector of positive real finite numbers.

- If `GyroscopeNoise` is specified as a row vector, the elements correspond to the noise in the *x*, *y*, and *z* axes of the gyroscope, respectively.
- If `GyroscopeNoise` is specified as a scalar, the single element is applied to each axis.

Data Types: `single` | `double`

**`GyroscopeBiasNoise` — Additive process noise variance from gyroscope bias ((rad/s)$^2$)**
`[1e-9 1e-9 1e-9]` (default) | scalar | 3-element row vector

Additive process noise variance from the gyroscope bias in (rad/s)$^2$, specified as a scalar or 3-element row vector of positive real finite numbers.

- If `GyroscopeBiasNoise` is specified as a row vector, the elements correspond to the noise in the *x*, *y*, and *z* axes of the gyroscope, respectively.
- If `GyroscopeBiasNoise` is specified as a scalar, the single element is applied to each axis

Data Types: `single` | `double`

**`AccelerometerNoise` — Multiplicative process noise variance from accelerometer ((m/s$^2$)$^2$)**
`[1e-4 1e-4 1e-4]` (default) | scalar | 3-element row vector

Multiplicative process noise variance from the accelerometer in (m/s$^2$)$^2$, specified as a scalar or 3-element row vector of positive real finite numbers.

- If `AccelerometerNoise` is specified as a row vector, the elements correspond to the noise in the *x*, *y*, and *z* axes of the accelerometer, respectively.
- If `AccelerometerNoise` is specified as a scalar, the single element is applied to each axis.

Data Types: `single` | `double`

**`AccelerometerBiasNoise` — Additive process noise variance from accelerometer bias ((m/s$^2$)$^2$)**
`[1e-4 1e-4 1e-4]` (default) | scalar | 3-element row vector

Additive process noise variance from accelerometer bias in (m/s$^2$)$^2$, specified as a scalar or 3-element row vector of positive real numbers.

- If `AccelerometerBiasNoise` is specified as a row vector, the elements correspond to the noise in the *x*, *y*, and *z* axes of the accelerometer, respectively.
- If `AccelerometerBiasNoise` is specified as a scalar, the single element is applied to each axis.

**`State` — State vector of Kalman filter**
`[1;zeros(15,1);1]` (default) | 17-element column vector

State vector of the extended Kalman filter, specified as a 17-element column vector. The state values represent:

| State | Units | Index |
| --- | --- | --- |
| Orientation (quaternion parts) | N/A | 1:4 |
| Position (NED or ENU) | m | 5:7 |
| Velocity (NED or ENU) | m/s | 8:10 |
| Gyroscope Bias (XYZ) | rad/s | 11:13 |
| Accelerometer Bias (XYZ) | m/s$^2$ | 14:16 |
| Visual Odometry Scale (XYZ) | N/A | 17 |

The default initial state corresponds to an object at rest located at `[0 0 0]` in geodetic LLA coordinates.

Data Types: `single` | `double`

**`StateCovariance` — State error covariance for Kalman filter**
`ones(16)` (default) | 16-by-16 matrix

State error covariance for the Kalman filter, specified as a 16-by-16-element matrix of real numbers. The state error covariance values represent:

| State Covariance | Row/Column Index |
| --- | --- |
| δ Rotation Vector (XYZ) | 1:3 |
| δ Position (NED or ENU) | 4:6 |
| δ Velocity (NED or ENU) | 7:9 |
| δ Gyroscope Bias (XYZ) | 10:12 |
| δ Accelerometer Bias (XYZ) | 13:15 |
| δ Visual Odometry Scale (XYZ) | 16 |

Note that because this is an error-state Kalman filter, it tracks the errors in the states. δ represents the error in the corresponding state.

Data Types: `single` | `double`

## Object Functions

| | |
| --- | --- |
| predict | Update states using accelerometer and gyroscope data for insfilterErrorState |
| correct | Correct states using direct state measurements for insfilterErrorState |
| residual | Residuals and residual covariances from direct state measurements for insfilterErrorState |
| fusegps | Correct states using GPS data for insfilterErrorState |
| residualgps | Residuals and residual covariance from GPS measurements for insfilterErrorState |
| fusemvo | Correct states using monocular visual odometry for insfilterErrorState |
| residualmvo | Residuals and residual covariance from monocular visual odometry measurements for insfilterErrorState |
| pose | Current orientation and position estimate for insfilterErrorState |
| reset | Reset internal states for insfilterErrorState |
| stateinfo | Display state vector information for insfilterErrorState |
| tune | Tune insfilterErrorState parameters to reduce estimation error |
| copy | Create copy of insfilterErrorState |

## Examples

### Estimate Pose of Ground Vehicle

Load logged data of a ground vehicle following a circular trajectory. The `.mat` file contains IMU and GPS sensor measurements and ground truth orientation and position.

```
load('loggedGroundVehicleCircle.mat', ...
    'imuFs','localOrigin', ...
    'initialStateCovariance', ...
    'accelData','gyroData', ...
    'gpsFs','gpsLLA','Rpos','gpsVel','Rvel', ...
    'trueOrient','truePos');
```

Create an INS filter to fuse IMU and GPS data using an error-state Kalman filter.

```
initialState = [compact(trueOrient(1)),truePos(1,:),-6.8e-3,2.5002,0,zeros(1,6),1].';
filt = insfilterErrorState;
filt.IMUSampleRate = imuFs;
filt.ReferenceLocation = localOrigin;
filt.State = initialState;
filt.StateCovariance = initialStateCovariance;
```

Preallocate variables for position and orientation. Allocate a variable for indexing into the GPS data.

```
numIMUSamples = size(accelData,1);
estOrient = ones(numIMUSamples,1,'quaternion');
estPos = zeros(numIMUSamples,3);

gpsIdx = 1;
```

Fuse accelerometer, gyroscope, and GPS data. The outer loop predicts the filter forward at the fastest sample rate (the IMU sample rate).

```
for idx = 1:numIMUSamples

    % Use predict to estimate the filter state based on the accelData and
    % gyroData arrays.
    predict(filt,accelData(idx,:),gyroData(idx,:));

    % GPS data is collected at a lower sample rate than IMU data. Fuse GPS
    % data at the lower rate.
    if mod(idx, imuFs / gpsFs) == 0
        % Correct the filter states based on the GPS data.
        fusegps(filt,gpsLLA(gpsIdx,:),Rpos,gpsVel(gpsIdx,:),Rvel);
        gpsIdx = gpsIdx + 1;
    end

    % Log the current pose estimate
    [estPos(idx,:), estOrient(idx,:)] = pose(filt);
end
```

Calculate the RMS errors between the known true position and orientation and the output from the error-state filter.

```
pErr = truePos - estPos;
qErr = rad2deg(dist(estOrient,trueOrient));
```

```
pRMS = sqrt(mean(pErr.^2));
qRMS = sqrt(mean(qErr.^2));

fprintf('Position RMS Error\n');
```

```
Position RMS Error
```

```
fprintf('\tX: %.2f, Y: %.2f, Z: %.2f (meters)\n\n',pRMS(1),pRMS(2),pRMS(3));
```

```
    X: 0.40, Y: 0.24, Z: 0.05 (meters)
```

```
fprintf('Quaternion Distance RMS Error\n');
```

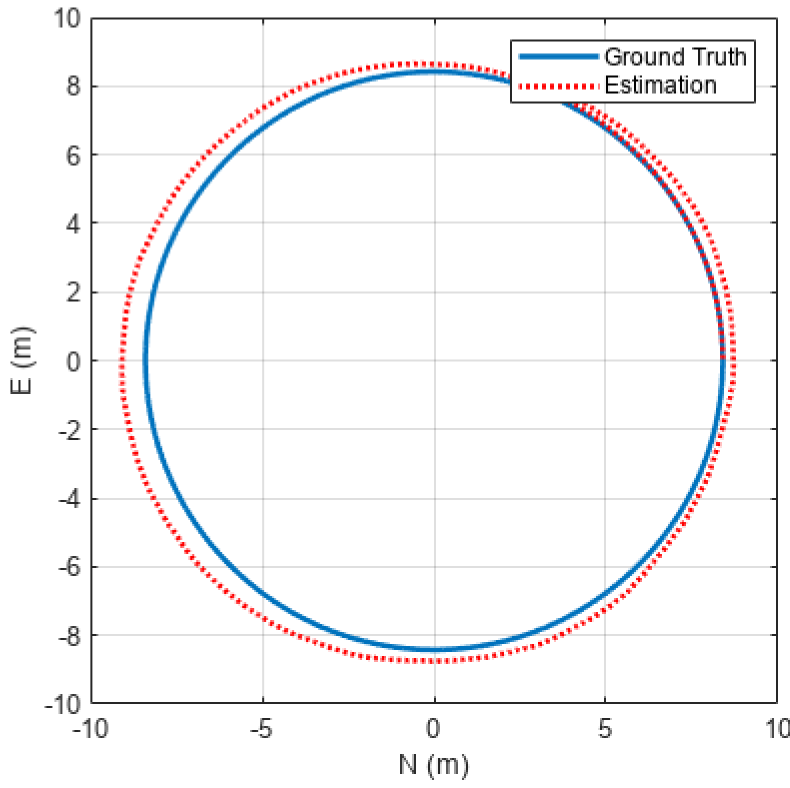
```
Quaternion Distance RMS Error
```

```
fprintf('\t%.2f (degrees)\n\n',qRMS);
```

```
    0.30 (degrees)
```

Visualize the true position and the estimated position.

```
plot(truePos(:,1),truePos(:,2),estPos(:,1),estPos(:,2),'r:','LineWidth',2)
grid on
axis square
xlabel('N (m)')
ylabel('E (m)')
legend('Ground Truth','Estimation')
```



## Algorithms

*Note: The following algorithm only applies to an NED reference frame.*

`insfilterErrorState` uses a 17-axis error state Kalman filter structure to estimate pose in the NED reference frame. The state is defined as:

$$x = \begin{bmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \\ position_N \\ position_E \\ position_D \\ v_N \\ v_E \\ v_D \\ gyrobias_X \\ gyrobias_Y \\ gyrobias_Z \\ accelbias_X \\ accelbias_Y \\ accelbias_Z \\ scaleFactor \end{bmatrix}$$

where

- $q_0$, $q_1$, $q_2$, $q_3$ –– Parts of orientation quaternion. The orientation quaternion represents a frame rotation from the platform's current orientation to the local NED coordinate system.
- $position_N$, $position_E$, $position_D$ –– Position of the platform in the local NED coordinate system.
- $gyrobias_X$, $gyrobias_Y$, $gyrobias_Z$ –– Bias in the gyroscope reading.
- $accelbias_X$, $accelbias_Y$, $accelbias_Z$ –– Bias in the accelerometer reading.
- *scaleFactor* –– Scale factor of the pose estimate.

Given the conventional formulation of the state transition function,

$$x_{k|k-1} = f(\widehat{x}_{k-1|k-1})$$

the predicted state estimate is:

$$x_{k|k-1} =$$

$$\left[\begin{array}{c}
q_0 + \Delta t * q_1(gyrobias_X/2 - gyro_X/2) + \Delta t * q_2 * (gyrobias_Y/2 - gyro_Y/2) + \Delta t * q_3 * (gyrobias_Z/2 - gyro_Z/2) \\
q_1 - \Delta t * q_0(gyrobias_X/2 - gyro_X/2) + \Delta t * q_3 * (gyrobias_Y/2 - gyro_Y/2) - \Delta t * q_2 * (gyrobias_Z/2 - gyro_Z/2) \\
q_2 - \Delta t * q_3(gyrobias_X/2 - gyro_X/2) - \Delta t * q_0 * (gyrobias_Y/2 - gyro_Y/2) + \Delta t * q_1 * (gyrobias_Z/2 - gyro_Z/2) \\
q_3 + \Delta t * q_2(gyrobias_X/2 - gyro_X/2) - \Delta t * q_1 * (gyrobias_Y/2 - gyro_Y/2) - \Delta t * q_0 * (gyrobias_Z/2 - gyro_Z/2) \\
position_N + \Delta t * v_N \\
position_E + \Delta t * v_E \\
position_D + \Delta t * v_D \\
v_N - \Delta t * \left\{\begin{array}{l}
q_0 * (q_0 * (accelbias_X - accel_X) - q_3 * (accelbias_Y - accel_Y) + q_2 * (accelbias_Z - accel_Z)) + g_N + \\
q_2 * (q_1 * (accelbias_Y - accel_Y) - q_2 * (accelbias_X - accel_X) + q_0 * (accelbias_Z - accel_Z)) + \\
q_1 * (q_1 * (accelbias_X - accel_X) + q_2 * (accelbias_Y - accel_Y) + q_3 * (accelbias_Z - accel_Z)) - \\
q_3 * (q_3 * (accelbias_X - accel_X) + q_0 * (accelbias_Y - accel_Y) - q_1 * (accelbias_Z - accel_Z))
\end{array}\right\} \\
v_E - \Delta t * \left\{\begin{array}{l}
q_0 * (q_3 * (accelbias_X - accel_X) + q_0 * (accelbias_Y - accel_Y) - q_1 * (accelbias_Z - accel_Z)) + g_E - \\
q_1 * (q_1 * (accelbias_Y - accel_Y) - q_2 * (accelbias_X - accel_X) + q_0 * (accelbias_Z - accel_Z)) + \\
q_2 * (q_1 * (accelbias_X - accel_X) + q_2 * (accelbias_Y - accel_Y) + q_3 * (accelbias_Z - accel_Z)) + \\
q_3 * (q_0 * (accelbias_X - accel_X) - q_3 * (accelbias_Y - accel_Y) + q_2 * (accelbias_Z - accel_Z))
\end{array}\right\} \\
\left\{\begin{array}{l}
q_0 * (q_1 * (accelbias_Y - accel_Y) - q_2 * (accelbias_X - accel_X) + q_0 * (accelbias_Z - accel_Z)) + g_D +
\end{array}\right.
\end{array}\right.$$

where

- $\Delta t$ –– IMU sample time.
- $g_N$, $g_E$, $g_D$ –– Constant gravity vector in the NED frame.

# Version History

**Introduced in R2019a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`insfilterAsync` | `insfilterMARG` | `insfilterNonholonomic`

# correct

Correct states using direct state measurements for `insfilterErrorState`

## Syntax

```
correct(FUSE,idx,measurement,measurementCovariance)
```

## Description

`correct(FUSE,idx,measurement,measurementCovariance)` corrects the state and state estimation error covariance of `FUSE`, an `insfilterErrorState` object, based on the measurement and measurement covariance. The measurement maps directly to the state specified by the indices `idx`.

## Input Arguments

**FUSE — INS filter object**
`insfilterErrorState`

`insfilterErrorState`, specified as an object.

**idx — State vector index of measurements to correct**
*N*-element vector of increasing integers in the range [1, 17]

State vector index of measurements to correct, specified as an *N*-element vector of increasing integers in the range [1, 17].

The state values represent:

| State | Units | Index |
|---|---|---|
| Orientation (quaternion parts) | N/A | 1:4 |
| Position (NED) | m | 5:7 |
| Velocity (NED) | m/s | 8:10 |
| Gyroscope Bias (XYZ) | rad/s | 11:13 |
| Accelerometer Bias (XYZ) | m/s$^2$ | 14:16 |
| Visual Odometry Scale (XYZ) | N/A | 17 |

Data Types: `single` | `double`

**`measurement` — Direct measurement of state**
*N*-element vector

Direct measurement of state, specified as a *N*-element vector. *N* is the number of elements of the index argument, `idx`.

Data Types: `single` | `double`

**`measurementCovariance` — Covariance of measurement**
scalar | *M*-element vector | *M*-by-*M* matrix

Covariance of measurement, specified as a scalar, *M*-element vector, or *M*-by-*M* matrix. If you correct orientation (state indices 1–4), then `M = numel(idx)-1`. If you do not correct orientation, then `M = numel(idx)`.

Data Types: `single` | `double`

# Version History

**Introduced in R2019a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`insfilterErrorState` | `insfilter`

# copy

Create copy of `insfilterErrorState`

## Syntax

`newFilter = copy(filter)`

## Description

`newFilter = copy(filter)` returns a copy of the `insfilterErrorState`, `filter`, with the exactly same property values.

## Input Arguments

**`filter` — Filter to be copied**
`insfilterErrorState`

Filter to be copied, specified as an `insfilterErrorState` object.

## Output Arguments

**`newFilter` — New copied filter**
`insfilterErrorState`

New copied filter, returned as an `insfilterErrorState` object.

# Version History

**Introduced in R2020b**

## See Also

`insfilterErrorState`

# fusegps

Correct states using GPS data for `insfilterErrorState`

## Syntax

```
[res,resCov] = fusegps(FUSE,position,positionCovariance)
[res,resCov] = fusegps(FUSE,position,positionCovariance,velocity,
velocityCovariance)
```

## Description

`[res,resCov] = fusegps(FUSE,position,positionCovariance)` fuses GPS position data to correct the state estimate.

`[res,resCov] = fusegps(FUSE,position,positionCovariance,velocity, velocityCovariance)` fuses GPS position and velocity data to correct the state estimate.

## Input Arguments

**FUSE — INS filter object**
`insfilterErrorState`

`insfilterErrorState`, specified as an object.

**`position` — Position of GPS receiver (LLA)**
3-element row vector

Position of GPS receiver in geodetic latitude, longitude, and altitude (LLA) specified as a real finite 3-element row vector. Latitude and longitude are in degrees with north and east being positive. Altitude is in meters.

Data Types: `single` | `double`

**`positionCovariance` — Position measurement covariance of GPS receiver ($m^2$)**
scalar | 3-element row vector | 3-by-3 matrix

Position measurement covariance of GPS receiver in $m^2$, specified as a 3-by-3 matrix.

Data Types: `single` | `double`

**`velocity` — Velocity of GPS receiver in local NED coordinate system (m/s)**
3-element row vector

Velocity of the GPS receiver in the local NED coordinate system in m/s, specified as a 3-element row vector.

Data Types: `single` | `double`

**`velocityCovariance` — Velocity measurement covariance of GPS receiver $(m/s)^2$**
scalar | 3-element row vector | 3-by-3 matrix

Velocity measurement covariance of the GPS receiver in the local NED coordinate system in $(m/s)^2$, specified as a 3-by-3 matrix.

Data Types: `single` | `double`

### Output Arguments

**`res` — Position and velocity residual**
1-by-6 vector of real values

Position and velocity residual, returned as a 1-by-6 vector of real values in m and m/s, respectively.

**`resCov` — Innovation residual**
6-by-6 matrix of real values

Innovation residual, returned as a 6-by-6 matrix of real values.

## Version History

**Introduced in R2019a**

### Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

### See Also

`insfilterErrorState` | `insfilter`

# fusemvo

Correct states using monocular visual odometry for `insfilterErrorState`

## Syntax

`[pResidual,oResidual,resCov] = fusemvo(FUSE,position,positionCovariance,ornt,orntCovariance)`

## Description

`[pResidual,oResidual,resCov] = fusemvo(FUSE,position,positionCovariance,ornt,orntCovariance)` fuses position and orientation data from monocular visual odometry (MVO) measurements to correct the state and state estimation error covariance.

## Input Arguments

**FUSE — INS filter object**
`insfilterErrorState`

`insfilterErrorState`, specified as an object.

**`position` — Position of camera in local NED coordinate system (m)**
3-element row vector

Position of camera in the local NED coordinate system in meters, specified as a real finite 3-element row vector.

Data Types: `single` | `double`

**`positionCovariance` — Position measurement covariance of MVO ($m^2$)**
scalar | 3-element vector | 3-by-3 matrix

Position measurement covariance of MVO in $m^2$, specified as a scalar, 3-element vector, or 3-by-3 matrix.

Data Types: `single` | `double`

**`ornt` — Orientation of camera with respect to local NED coordinate system**
scalar quaternion | rotation matrix

Orientation of the camera with respect to the local NED coordinate system, specified as a scalar quaternion or 3-by-3 rotation matrix. The quaternion or rotation matrix is a frame rotation from the NED coordinate system to the current camera coordinate system.

Data Types: `quaternion` | `single` | `double`

**`orntCovariance` — Orientation measurement covariance of monocular visual odometry ($rad^2$)**
scalar | 3-element vector | 3-by-3 matrix

Orientation measurement covariance of monocular visual odometry in $rad^2$, specified as a scalar, 3-element vector, or 3-by-3 matrix.

Data Types: `single` | `double`

## Output Arguments

### `pResidual` — Position residual

1-by-3 vector of real values

Position residual, returned as a 1-by-3 vector of real values in m.

### `oResidual` — Rotation vector residual

1-by-3 vector of real values

Rotation vector residual, returned as a 1-by-3 vector of real values in radians.

### `resCov` — Residual covariance

6-by-6 matrix of real values

Residual covariance, returned as a 6-by-6 matrix of real values.

# Version History

**Introduced in R2019a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`insfilterErrorState` | `insfilter`

# predict

Update states using accelerometer and gyroscope data for `insfilterErrorState`

## Syntax

```
predict(FUSE,accelReadings,gyroReadings)
```

## Description

`predict(FUSE,accelReadings,gyroReadings)` fuses accelerometer and gyroscope data to update the state estimate.

## Input Arguments

**FUSE — INS filter object**
`insfilterErrorState`

`insfilterErrorState`, specified as an object.

**`accelReadings` — Accelerometer readings in local sensor body coordinate system (m/s$^2$)**
3-element row vector

Accelerometer readings in m/s$^2$, specified as a 3-element row vector.

Data Types: `single` | `double`

**`gyroReadings` — Gyroscope readings in local sensor body coordinate system (rad/s)**
3-element row vector

Gyroscope readings in rad/s, specified as a 3-element row vector.

Data Types: `single` | `double`

# Version History

**Introduced in R2019a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

`insfilterErrorState` | `insfilter`

# reset

Reset internal states for `insfilterErrorState`

## Syntax

`reset(FUSE)`

## Description

`reset(FUSE)` resets the `State`, `StateCovariance`, and internal integrators of `FUSE`, an `insfilterErrorState` object, to their default values.

## Input Arguments

**FUSE — INS filter object**
`insfilterErrorState`

`insfilterErrorState`, specified as an object.

# Version History

**Introduced in R2019a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

`insfilterErrorState` | `insfilter`

# residual

Residuals and residual covariances from direct state measurements for `insfilterErrorState`

## Syntax

```
[res, resCov]= residual(FUSE,idx,measurement,measurementCovariance)
```

## Description

`[res, resCov]= residual(FUSE,idx,measurement,measurementCovariance)` computes the residual, `res`, and the residual covariance, `resCov`, based on the direct state measurement and measurement covariance. The `measurement` maps directly to the states specified by indices, `idx`.

## Input Arguments

**FUSE — INS filter object**
`insfilterErrorState`

`insfilterErrorState`, specified as an object.

**idx — State vector index of measurements to correct**
*N*-element vector of increasing integers in the range [1, 17]

State vector index of measurements to correct, specified as an *N*-element vector of increasing integers in the range [1, 17].

The state values represent:

| State | Units | Index |
|---|---|---|
| Orientation (quaternion parts) | N/A | 1:4 |
| Position (NED) | m | 5:7 |
| Velocity (NED) | m/s | 8:10 |
| Gyroscope Bias (XYZ) | rad/s | 11:13 |
| Accelerometer Bias (XYZ) | $m/s^2$ | 14:16 |
| Visual Odometry Scale (XYZ) | N/A | 17 |

Data Types: `single` | `double`

**`measurement` — Direct measurement of state**
*N*-element vector

Direct measurement of state, specified as a *N*-element vector. *N* is the number of elements of the index argument, `idx`.

**`measurementCovariance` — Covariance of measurement**
*N*-by-*N* matrix

Covariance of measurement, specified as an *N*-by-*N* matrix. *N* is the number of elements of the index argument, `idx`.

### Output Arguments

**`res` — Measurement residual**
1-by-*N* vector of real values

Measurement residual, returned as a 1-by-*N* vector of real values.

**`resCov` — Residual covariance**
*N*-by-*N* matrix of real values

Residual covariance, returned as a *N*-by-*N* matrix of real values.

## Version History

**Introduced in R2020a**

### Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

### See Also

`insfilterErrorState`

# residualgps

Residuals and residual covariance from GPS measurements for `insfilterErrorState`

## Syntax

```
[res,resCov] = residualgps(FUSE,position,positionCovariance)
[res,resCov] = residualgps(FUSE,position,positionCovariance,velocity,
velocityCovariance)
```

## Description

`[res,resCov] = residualgps(FUSE,position,positionCovariance)` computes the residual, `res`, and the residual covariance, `resCov`, based on the GPS position measurement and covariance.

`[res,resCov] = residualgps(FUSE,position,positionCovariance,velocity, velocityCovariance)` computes the residual, `res`, and the residual covariance, `resCov`, based on the GPS position measurement and covariance.

## Input Arguments

**FUSE — INS filter object**
`insfilterErrorState`

`insfilterErrorState`, specified as an object.

**`position` — Position of GPS receiver (LLA)**
3-element row vector

Position of GPS receiver in geodetic latitude, longitude, and altitude (LLA) specified as a real finite 3-element row vector. Latitude and longitude are in degrees with north and east being positive. Altitude is in meters.

Data Types: `single` | `double`

**`positionCovariance` — Position measurement covariance of GPS receiver ($m^2$)**
3-by-3 matrix

Position measurement covariance of GPS receiver in $m^2$, specified as a 3-by-3 matrix.

Data Types: `single` | `double`

**`velocity` — Velocity of GPS receiver in local NED coordinate system (m/s)**
3-element row vector

Velocity of the GPS receiver in the local NED coordinate system in m/s, specified as a 3-element row vector.

Data Types: `single` | `double`

**`velocityCovariance` — Velocity measurement covariance of GPS receiver ($m/s^2$)**
3-by-3 matrix

Velocity measurement covariance of the GPS receiver in the local NED coordinate system in $m/s^2$, specified as a 3-by-3 matrix.

Data Types: `single` | `double`

## Output Arguments

**`res` — Position and velocity residual**
1-by-3 vector of real values | 1-by-6 vector of real values

Position and velocity residual, returned as a 1-by-3 vector of real values if the inputs only contain position information, and returned as 1-by-6 vector of real values if the inputs also contain velocity information.

**`resCov` — Residual covariance**
3-by-3 matrix of real values | 6-by-6 matrix of real values

Residual covariance, returned as a 3-by-3 matrix of real values if the inputs only contain position information, and a 6-by-6 matrix of real values if the inputs also contain velocity information.

# Version History

**Introduced in R2020a**

## Extended Capabilities

### C/C++ Code Generation
Generate C and C++ code using MATLAB® Coder™.

## See Also
`insfilterErrorState`

# residualmvo

Residuals and residual covariance from monocular visual odometry measurements for `insfilterErrorState`

## Syntax

```
[pResidual,oResidual,resCov] = residualmvo(FUSE,position,positionCovariance,
ornt,orntCovariance)
```

## Description

`[pResidual,oResidual,resCov] = residualmvo(FUSE,position,positionCovariance, ornt,orntCovariance)` computes the residual information based on the monocular visual odometry measurements and covariance.

## Input Arguments

**FUSE — INS filter object**
`insfilterErrorState`

`insfilterErrorState`, specified as an object.

**`position` — Position of camera in local NED coordinate system (m)**
3-element row vector

Position of camera in the local NED coordinate system in meters, specified as a real finite 3-element row vector.

Data Types: `single` | `double`

**`positionCovariance` — Position measurement covariance of MVO ($m^2$)**
scalar | 3-element vector | 3-by-3 matrix

Position measurement covariance of MVO in $m^2$, specified as a scalar, 3-element vector, or 3-by-3 matrix.

Data Types: `single` | `double`

**`ornt` — Orientation of camera with respect to local NED coordinate system**
scalar quaternion | rotation matrix

Orientation of the camera with respect to the local NED coordinate system, specified as a scalar quaternion or 3-by-3 rotation matrix. The quaternion or rotation matrix is a frame rotation from the NED coordinate system to the current camera coordinate system.

Data Types: `quaternion` | `single` | `double`

**`orntCovariance` — Orientation measurement covariance of monocular visual odometry ($rad^2$)**
scalar | 3-element vector | 3-by-3 matrix

Orientation measurement covariance of monocular visual odometry in rad$^2$, specified as a scalar, 3-element vector, or 3-by-3 matrix.

Data Types: `single` | `double`

## Output Arguments

**`pResidual` — Position residual**
1-by-3 vector of real values

Position residual, returned as a 1-by-3 vector of real values in meters.

**`oResidual` — Rotation vector residual**
1-by-3 vector of real values

Rotation vector residual, returned a 1-by-3 vector of real values in radians.

**`resCov` — Residual covariance**
6-by-6 matrix of real values

Residual covariance, returned as a 6-by-6 matrix of real values.

# Version History

**Introduced in R2020a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

`insfilterErrorState` | `insfilter`

# stateinfo

Display state vector information for `insfilterErrorState`

## Syntax

```
stateinfo(FUSE)
info = stateinfo(FUSE)
```

## Description

`stateinfo(FUSE)` displays the meaning of each index of the `State` property of `FUSE`, an `insfilterErrorState` object, and the associated units.

`info = stateinfo(FUSE)` returns a structure with fields containing descriptions of the elements of the state vector of the filter, `FUSE`.

## Examples

### State Information of `insfilterErrorState`

Create an `insfilterErrorState` object.

```
filter = insfilterErrorState;
```

Display the state information of the created filter.

```
stateinfo(filter)
```

```
States                              Units    Index
Orientation (quaternion parts)               1:4
Position (NAV)                      m        5:7
Velocity (NAV)                      m/s      8:10
Gyroscope Bias (XYZ)                rad/s    11:13
Accelerometer Bias (XYZ)            m/s²     14:16
Visual Odometry Scale                        17
```

Output the state information of the filter as a structure.

```
info = stateinfo(filter)
```

```
info = struct with fields:
            Orientation: [1 2 3 4]
               Position: [5 6 7]
               Velocity: [8 9 10]
          GyroscopeBias: [11 12 13]
      AccelerometerBias: [14 15 16]
    VisualOdometryScale: 17
```

## Input Arguments

**FUSE — INS filter object**
`insfilterErrorState`

`insfilterErrorState`, specified as an object.

## Output Arguments

**`info` — State information**
structure

State information, returned as a structure. The field names of the structure are names of the elements of the state vector in the filter. The values of each field are the corresponding indices of the state vector.

# Version History

**Introduced in R2019a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

`insfilterErrorState` | `insfilter`

# pose

Current orientation and position estimate for `insfilterErrorState`

## Syntax

```
[position,orientation,velocity] = pose(FUSE)
[position,orientation,velocity] = pose(FUSE,format)
```

## Description

`[position,orientation,velocity] = pose(FUSE)` returns the current estimate of the pose of the object tracked by `FUSE`, an `insfilterErrorState` object.

`[position,orientation,velocity] = pose(FUSE,format)` returns the current estimate of the pose with orientation in the specified orientation format.

## Input Arguments

### FUSE — INS filter object
`insfilterErrorState`

`insfilterErrorState`, specified as an object.

### `format` — Output orientation format
`'quaternion'` (default) | `'rotmat'`

Output orientation format, specified as either `'quaternion'` for a `quaternion` or `'rotmat'` for a rotation matrix.

Data Types: `char` | `string`

## Output Arguments

### `position` — Position estimate expressed in the local coordinate system (m)
3-element row vector

Position estimate expressed in the local coordinate system of the filter in meters, returned as a 3-element row vector.

Data Types: `single` | `double`

### `orientation` — Orientation estimate expressed in the local coordinate system
quaternion (default) | 3-by-3 rotation matrix

Orientation estimate expressed in the local coordinate system of the filter, returned as a scalar quaternion or 3-by-3 rotation matrix. The quaternion or rotation matrix represents a frame rotation from the local reference frame of the filter to the body reference frame.

Data Types: `single` | `double` | `quaternion`

**`velocity` — Velocity estimate expressed in local coordinate system (m/s)**
3-element row vector

Velocity estimate expressed in the local coordinate system of the filter in m/s, returned as a 3-element row vector.

Data Types: `single` | `double`

# Version History

**Introduced in R2019a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

`insfilterErrorState` | `insfilter`

# tune

Tune `insfilterErrorState` parameters to reduce estimation error

## Syntax

```
tunedMeasureNoise = tune(filter,measureNoise,sensorData,groundTruth)
tunedMeasureNoise = tune( ___ ,config)
```

## Description

`tunedMeasureNoise = tune(filter,measureNoise,sensorData,groundTruth)` adjusts the properties of the `insfilterErrorState` filter object, `filter`, and measurement noises to reduce the root-mean-squared (RMS) state estimation error between the fused sensor data and the ground truth. The function also returns the tuned measurement noise, `tunedMeasureNoise`. The function uses the property values in the filter and the measurement noise provided in the `measureNoise` structure as the initial estimate for the optimization algorithm.

`tunedMeasureNoise = tune( ___ ,config)` specifies the tuning configuration based on a `tunerconfig` object, `config`.

## Examples

### Tune `insfilterErrorState` to Optimize Pose Estimate

Load the recorded sensor data and ground truth data.

```
load('insfilterErrorStateTuneData.mat');
```

Create tables for the sensor data and the truth data.

```
sensorData = table(Accelerometer,Gyroscope, ...
    GPSPosition,GPSVelocity,MVOOrientation, ...
    MVOPosition);
groundTruth = table(Orientation,Position);
```

Create an `insfilterErrorState` filter object.

```
filter = insfilterErrorState('State',initialState, ...
    'StateCovariance',initialStateCovariance);
```

Create a tuner configuration object for the filter. Use the tuner noise function to obtain a set of initial sensor noises used in the filter.

```
cfg = tunerconfig('insfilterErrorState','MaxIterations',40);
measNoise = tunernoise('insfilterErrorState')
```

```
measNoise = struct with fields:
    MVOOrientationNoise: 1
       MVOPositionNoise: 1
       GPSPositionNoise: 1
```

```
    GPSVelocityNoise: 1
```

Tune the filter and obtain the tuned parameters.

```
tunedmn = tune(filter,measNoise,sensorData, ...
    groundTruth,cfg);

    Iteration    Parameter                Metric
    _________    _________                ______
    1            AccelerometerNoise       4.1291
    1            GyroscopeNoise           4.1291
    1            AccelerometerBiasNoise   4.1290
    1            GyroscopeBiasNoise       4.1290
    1            GPSPositionNoise         4.0213
    1            GPSVelocityNoise         4.0051
    1            MVOPositionNoise         3.9949
    1            MVOOrientationNoise      3.9886
    2            AccelerometerNoise       3.9886
    2            GyroscopeNoise           3.9886
    2            AccelerometerBiasNoise   3.9886
    2            GyroscopeBiasNoise       3.9886
    2            GPSPositionNoise         3.8381
    2            GPSVelocityNoise         3.8268
    2            MVOPositionNoise         3.8219
    2            MVOOrientationNoise      3.8035
    3            AccelerometerNoise       3.8035
    3            GyroscopeNoise           3.8035
    3            AccelerometerBiasNoise   3.8035
    3            GyroscopeBiasNoise       3.8035
    3            GPSPositionNoise         3.6299
    3            GPSVelocityNoise         3.6276
    3            MVOPositionNoise         3.6241
    3            MVOOrientationNoise      3.5911
    4            AccelerometerNoise       3.5911
    4            GyroscopeNoise           3.5911
    4            AccelerometerBiasNoise   3.5911
    4            GyroscopeBiasNoise       3.5911
    4            GPSPositionNoise         3.1728
    4            GPSVelocityNoise         3.1401
    4            MVOPositionNoise         2.7686
    4            MVOOrientationNoise      2.6632
    5            AccelerometerNoise       2.6632
    5            GyroscopeNoise           2.6632
    5            AccelerometerBiasNoise   2.6632
    5            GyroscopeBiasNoise       2.6632
    5            GPSPositionNoise         2.3242
    5            GPSVelocityNoise         2.2291
    5            MVOPositionNoise         2.2291
    5            MVOOrientationNoise      2.0904
    6            AccelerometerNoise       2.0903
    6            GyroscopeNoise           2.0903
    6            AccelerometerBiasNoise   2.0903
    6            GyroscopeBiasNoise       2.0903
    6            GPSPositionNoise         2.0903
    6            GPSVelocityNoise         2.0141
    6            MVOPositionNoise         1.9952
    6            MVOOrientationNoise      1.8497
```

```
7            AccelerometerNoise        1.8497
7            GyroscopeNoise            1.8496
7            AccelerometerBiasNoise    1.8496
7            GyroscopeBiasNoise        1.8496
7            GPSPositionNoise          1.8398
7            GPSVelocityNoise          1.7528
7            MVOPositionNoise          1.7362
7            MVOOrientationNoise       1.5762
8            AccelerometerNoise        1.5762
8            GyroscopeNoise            1.5762
8            AccelerometerBiasNoise    1.5762
8            GyroscopeBiasNoise        1.5762
8            GPSPositionNoise          1.5762
8            GPSVelocityNoise          1.5107
8            MVOPositionNoise          1.4786
8            MVOOrientationNoise       1.3308
9            AccelerometerNoise        1.3308
9            GyroscopeNoise            1.3308
9            AccelerometerBiasNoise    1.3308
9            GyroscopeBiasNoise        1.3308
9            GPSPositionNoise          1.3308
9            GPSVelocityNoise          1.2934
9            MVOPositionNoise          1.2525
9            MVOOrientationNoise       1.1462
10           AccelerometerNoise        1.1462
10           GyroscopeNoise            1.1462
10           AccelerometerBiasNoise    1.1462
10           GyroscopeBiasNoise        1.1462
10           GPSPositionNoise          1.1443
10           GPSVelocityNoise          1.1332
10           MVOPositionNoise          1.0964
10           MVOOrientationNoise       1.0382
11           AccelerometerNoise        1.0382
11           GyroscopeNoise            1.0382
11           AccelerometerBiasNoise    1.0382
11           GyroscopeBiasNoise        1.0382
11           GPSPositionNoise          1.0348
11           GPSVelocityNoise          1.0348
11           MVOPositionNoise          1.0081
11           MVOOrientationNoise       0.9734
12           AccelerometerNoise        0.9734
12           GyroscopeNoise            0.9734
12           AccelerometerBiasNoise    0.9734
12           GyroscopeBiasNoise        0.9734
12           GPSPositionNoise          0.9693
12           GPSVelocityNoise          0.9682
12           MVOPositionNoise          0.9488
12           MVOOrientationNoise       0.9244
13           AccelerometerNoise        0.9244
13           GyroscopeNoise            0.9244
13           AccelerometerBiasNoise    0.9244
13           GyroscopeBiasNoise        0.9244
13           GPSPositionNoise          0.9203
13           GPSVelocityNoise          0.9199
13           MVOPositionNoise          0.9045
13           MVOOrientationNoise       0.8846
14           AccelerometerNoise        0.8846
14           GyroscopeNoise            0.8846
```

```
14          AccelerometerBiasNoise    0.8845
14          GyroscopeBiasNoise        0.8845
14          GPSPositionNoise          0.8807
14          GPSVelocityNoise          0.8807
14          MVOPositionNoise          0.8659
14          MVOOrientationNoise       0.8501
15          AccelerometerNoise        0.8501
15          GyroscopeNoise            0.8501
15          AccelerometerBiasNoise    0.8500
15          GyroscopeBiasNoise        0.8500
15          GPSPositionNoise          0.8457
15          GPSVelocityNoise          0.8453
15          MVOPositionNoise          0.8299
15          MVOOrientationNoise       0.8173
16          AccelerometerNoise        0.8173
16          GyroscopeNoise            0.8173
16          AccelerometerBiasNoise    0.8172
16          GyroscopeBiasNoise        0.8172
16          GPSPositionNoise          0.8122
16          GPSVelocityNoise          0.8116
16          MVOPositionNoise          0.7961
16          MVOOrientationNoise       0.7858
17          AccelerometerNoise        0.7858
17          GyroscopeNoise            0.7858
17          AccelerometerBiasNoise    0.7857
17          GyroscopeBiasNoise        0.7857
17          GPSPositionNoise          0.7807
17          GPSVelocityNoise          0.7800
17          MVOPositionNoise          0.7655
17          MVOOrientationNoise       0.7572
18          AccelerometerNoise        0.7572
18          GyroscopeNoise            0.7572
18          AccelerometerBiasNoise    0.7570
18          GyroscopeBiasNoise        0.7570
18          GPSPositionNoise          0.7525
18          GPSVelocityNoise          0.7520
18          MVOPositionNoise          0.7401
18          MVOOrientationNoise       0.7338
19          AccelerometerNoise        0.7337
19          GyroscopeNoise            0.7337
19          AccelerometerBiasNoise    0.7335
19          GyroscopeBiasNoise        0.7335
19          GPSPositionNoise          0.7293
19          GPSVelocityNoise          0.7290
19          MVOPositionNoise          0.7185
19          MVOOrientationNoise       0.7140
20          AccelerometerNoise        0.7138
20          GyroscopeNoise            0.7138
20          AccelerometerBiasNoise    0.7134
20          GyroscopeBiasNoise        0.7134
20          GPSPositionNoise          0.7086
20          GPSVelocityNoise          0.7068
20          MVOPositionNoise          0.6956
20          MVOOrientationNoise       0.6926
21          AccelerometerNoise        0.6922
21          GyroscopeNoise            0.6922
21          AccelerometerBiasNoise    0.6916
21          GyroscopeBiasNoise        0.6916
```

```
21          GPSPositionNoise        0.6862
21          GPSVelocityNoise        0.6822
21          MVOPositionNoise        0.6682
21          MVOOrientationNoise     0.6667
22          AccelerometerNoise      0.6660
22          GyroscopeNoise          0.6660
22          AccelerometerBiasNoise  0.6650
22          GyroscopeBiasNoise      0.6650
22          GPSPositionNoise        0.6605
22          GPSVelocityNoise        0.6541
22          MVOPositionNoise        0.6372
22          MVOOrientationNoise     0.6368
23          AccelerometerNoise      0.6356
23          GyroscopeNoise          0.6356
23          AccelerometerBiasNoise  0.6344
23          GyroscopeBiasNoise      0.6344
23          GPSPositionNoise        0.6324
23          GPSVelocityNoise        0.6252
23          MVOPositionNoise        0.6087
23          MVOOrientationNoise     0.6087
24          AccelerometerNoise      0.6075
24          GyroscopeNoise          0.6075
24          AccelerometerBiasNoise  0.6068
24          GyroscopeBiasNoise      0.6068
24          GPSPositionNoise        0.6061
24          GPSVelocityNoise        0.6032
24          MVOPositionNoise        0.6032
24          MVOOrientationNoise     0.6032
25          AccelerometerNoise      0.6017
25          GyroscopeNoise          0.6017
25          AccelerometerBiasNoise  0.6012
25          GyroscopeBiasNoise      0.6012
25          GPSPositionNoise        0.6010
25          GPSVelocityNoise        0.6005
25          MVOPositionNoise        0.6005
25          MVOOrientationNoise     0.6005
26          AccelerometerNoise      0.5992
26          GyroscopeNoise          0.5992
26          AccelerometerBiasNoise  0.5987
26          GyroscopeBiasNoise      0.5987
26          GPSPositionNoise        0.5983
26          GPSVelocityNoise        0.5983
26          MVOPositionNoise        0.5983
26          MVOOrientationNoise     0.5983
27          AccelerometerNoise      0.5975
27          GyroscopeNoise          0.5975
27          AccelerometerBiasNoise  0.5974
27          GyroscopeBiasNoise      0.5974
27          GPSPositionNoise        0.5973
27          GPSVelocityNoise        0.5972
27          MVOPositionNoise        0.5971
27          MVOOrientationNoise     0.5971
28          AccelerometerNoise      0.5971
28          GyroscopeNoise          0.5971
28          AccelerometerBiasNoise  0.5970
28          GyroscopeBiasNoise      0.5970
28          GPSPositionNoise        0.5970
28          GPSVelocityNoise        0.5970
```

```
28           MVOPositionNoise         0.5970
28           MVOOrientationNoise      0.5970
29           AccelerometerNoise       0.5970
29           GyroscopeNoise           0.5970
29           AccelerometerBiasNoise   0.5970
29           GyroscopeBiasNoise       0.5970
29           GPSPositionNoise         0.5970
29           GPSVelocityNoise         0.5970
29           MVOPositionNoise         0.5970
29           MVOOrientationNoise      0.5970
30           AccelerometerNoise       0.5969
30           GyroscopeNoise           0.5969
30           AccelerometerBiasNoise   0.5969
30           GyroscopeBiasNoise       0.5969
30           GPSPositionNoise         0.5969
30           GPSVelocityNoise         0.5969
30           MVOPositionNoise         0.5968
30           MVOOrientationNoise      0.5968
31           AccelerometerNoise       0.5968
31           GyroscopeNoise           0.5968
31           AccelerometerBiasNoise   0.5968
31           GyroscopeBiasNoise       0.5968
31           GPSPositionNoise         0.5968
31           GPSVelocityNoise         0.5968
31           MVOPositionNoise         0.5967
31           MVOOrientationNoise      0.5967
32           AccelerometerNoise       0.5967
32           GyroscopeNoise           0.5967
32           AccelerometerBiasNoise   0.5967
32           GyroscopeBiasNoise       0.5967
32           GPSPositionNoise         0.5967
32           GPSVelocityNoise         0.5967
32           MVOPositionNoise         0.5966
32           MVOOrientationNoise      0.5966
33           AccelerometerNoise       0.5966
33           GyroscopeNoise           0.5966
33           AccelerometerBiasNoise   0.5966
33           GyroscopeBiasNoise       0.5966
33           GPSPositionNoise         0.5966
33           GPSVelocityNoise         0.5966
33           MVOPositionNoise         0.5965
33           MVOOrientationNoise      0.5965
34           AccelerometerNoise       0.5965
34           GyroscopeNoise           0.5965
34           AccelerometerBiasNoise   0.5965
34           GyroscopeBiasNoise       0.5965
34           GPSPositionNoise         0.5965
34           GPSVelocityNoise         0.5964
34           MVOPositionNoise         0.5964
34           MVOOrientationNoise      0.5964
35           AccelerometerNoise       0.5964
35           GyroscopeNoise           0.5964
35           AccelerometerBiasNoise   0.5963
35           GyroscopeBiasNoise       0.5963
35           GPSPositionNoise         0.5963
35           GPSVelocityNoise         0.5963
35           MVOPositionNoise         0.5963
35           MVOOrientationNoise      0.5963
```

```
    36           AccelerometerNoise        0.5963
    36           GyroscopeNoise            0.5963
    36           AccelerometerBiasNoise    0.5963
    36           GyroscopeBiasNoise        0.5963
    36           GPSPositionNoise          0.5963
    36           GPSVelocityNoise          0.5963
    36           MVOPositionNoise          0.5963
    36           MVOOrientationNoise       0.5963
    37           AccelerometerNoise        0.5963
    37           GyroscopeNoise            0.5963
    37           AccelerometerBiasNoise    0.5963
    37           GyroscopeBiasNoise        0.5963
    37           GPSPositionNoise          0.5962
    37           GPSVelocityNoise          0.5962
    37           MVOPositionNoise          0.5962
    37           MVOOrientationNoise       0.5962
    38           AccelerometerNoise        0.5962
    38           GyroscopeNoise            0.5962
    38           AccelerometerBiasNoise    0.5962
    38           GyroscopeBiasNoise        0.5962
    38           GPSPositionNoise          0.5962
    38           GPSVelocityNoise          0.5961
    38           MVOPositionNoise          0.5961
    38           MVOOrientationNoise       0.5961
    39           AccelerometerNoise        0.5961
    39           GyroscopeNoise            0.5961
    39           AccelerometerBiasNoise    0.5961
    39           GyroscopeBiasNoise        0.5961
    39           GPSPositionNoise          0.5961
    39           GPSVelocityNoise          0.5960
    39           MVOPositionNoise          0.5960
    39           MVOOrientationNoise       0.5960
    40           AccelerometerNoise        0.5960
    40           GyroscopeNoise            0.5960
    40           AccelerometerBiasNoise    0.5960
    40           GyroscopeBiasNoise        0.5960
    40           GPSPositionNoise          0.5960
    40           GPSVelocityNoise          0.5959
    40           MVOPositionNoise          0.5959
    40           MVOOrientationNoise       0.5959
```

Fuse the sensor data using the tuned filter.

```
N = size(sensorData,1);
qEstTuned = quaternion.zeros(N,1);
posEstTuned = zeros(N,3);
for ii=1:N
    predict(filter, Accelerometer(ii,:),Gyroscope(ii,:));
    if all(~isnan(GPSPosition(ii,1)))
        fusegps(filter,GPSPosition(ii,:), ...
            tunedmn.GPSPositionNoise,GPSVelocity(ii,:), ...
            tunedmn.GPSVelocityNoise);
    end
    if all(~isnan(MVOPosition(ii,1)))
        fusemvo(filter,MVOPosition(ii,:),tunedmn.MVOPositionNoise, ...
            MVOOrientation{ii},tunedmn.MVOOrientationNoise);
    end
```

```
    [posEstTuned(ii,:),qEstTuned(ii,:)] = pose(filter);
end
```

Compute the RMS errors.

```
orientationErrorTuned = rad2deg(dist(qEstTuned,Orientation));
rmsOrientationErrorTuned = sqrt(mean(orientationErrorTuned.^2))
```

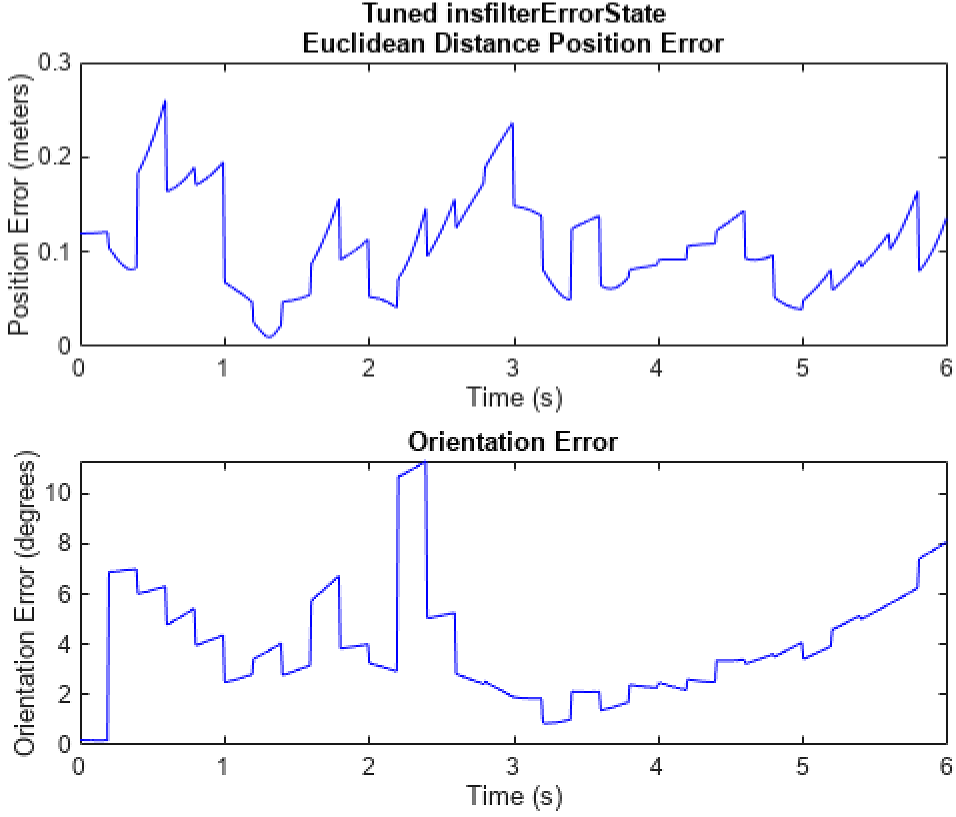
```
rmsOrientationErrorTuned = 4.4999
```

```
positionErrorTuned = sqrt(sum((posEstTuned - Position).^2,2));
rmsPositionErrorTuned = sqrt(mean( positionErrorTuned.^2))
```

```
rmsPositionErrorTuned = 0.1172
```

Visualize the results.

```
figure;
t = (0:N-1)./filter.IMUSampleRate;
subplot(2,1,1)
plot(t, positionErrorTuned,'b');
title("Tuned insfilterErrorState" + newline + ...
    "Euclidean Distance Position Error")
xlabel('Time (s)');
ylabel('Position Error (meters)')
subplot(2,1,2)
plot(t, orientationErrorTuned,'b');
title("Orientation Error")
xlabel('Time (s)');
ylabel('Orientation Error (degrees)');
```




## Input Arguments

**`filter` — Filter object**
`insfilterErrorState` object

Filter object, specified as an `insfilterErrorState` object.

**`measureNoise` — Measurement noise**
structure

Measurement noise, specified as a structure. The function uses the measurement noise input as the initial guess for tuning the measurement noise. The structure must contain these fields:

| Field name | Description |
| --- | --- |
| `MVOOrientationNoise` | Orientation measurement covariance of monocular visual odometry, specified as a scalar, 3-element vector, or 3-by-3 matrix in rad$^2$ |
| `MVOPositionNoise` | Position measurement covariance of MVO, specified as a scalar, 3-element vector, or 3-by-3 matrix in m$^2$ |
| `GPSPositionNoise` | Variance of GPS position noise, specified as a scalar in m$^2$ |

| Field name | Description |
| --- | --- |
| GPSVelocityNoise | Variance of GPS velocity noise, specified as a scalar in $(m/s)^2$ |

**sensorData — Sensor data**
table

Sensor data, specified as a table. In each row, the sensor data is specified as:

- Accelerometer — Accelerometer data, specified as a 1-by-3 vector of scalars in $m^2/s$.
- Gyroscope— Gyroscope data, specified as a 1-by-3 vector of scalars in rad/s.
- MVOOrienation — Orientation of the camera with respect to the local navigation frame, specified as a scalar quaternion or 3-by-3 rotation matrix. The quaternion or rotation matrix is a frame rotation from the local navigation frame to the current camera coordinate system.
- MVOPosition — Position of camera in the local navigation frame, specified as a real 3-element row vector in meters.
- GPSPosition — GPS position data, specified as a 1-by-3 vector of latitude in degrees, longitude in degrees, and altitude in meters.
- GPSVelocity — GPS velocity data, specified as a 1-by-3 vector of scalars in m/s.

If the GPS sensor does not produce complete measurements, specify the corresponding entry for GPSPosition and/or GPSVelocity as NaN. If you set the Cost property of the tuner configuration input, config, to Custom, then you can use other data types for the sensorData input based on your choice.

**groundTruth — Ground truth data**
table

Ground truth data, specified as a table. In each row, the table can optionally contain any of these variables:

- Orientation — Orientation from the navigation frame to the body frame, specified as a quaternion or a 3-by-3 rotation matrix.
- Position — Position in navigation frame, specified as a 1-by-3 vector of scalars in meters.
- Velocity — Velocity in navigation frame, specified as a 1-by-3 vector of scalars in m/s.
- AccelerometerBias — Accelerometer delta angle bias in body frame, specified as a 1-by-3 vector of scalars in $m^2/s$.
- VisualOdometryScale — Visual odometry scale factor, specified as a scalar.

The function processes each row of the sensorData and groundTruth tables sequentially to calculate the state estimate and RMS error from the ground truth. State variables not present in groundTruth input are ignored for the comparison. The sensorData and the groundTruth tables must have the same number of rows.

If you set the Cost property of the tuner configuration input, config, to Custom, then you can use other data types for the groundTruth input based on your choice.

**config — Tuner configuration**
tunerconfig object

Tuner configuration, specified as a tunerconfig object.

## Output Arguments

**`tunedMeasureNoise` — Tuned measurement noise**
structure

Tuned measurement noise, returned as a structure. The structure contains these fields.

| Field name | Description |
| --- | --- |
| `MVOOrientationNoise` | Orientation measurement covariance of monocular visual odometry, specified as a scalar, 3-element vector, or 3-by-3 matrix in $rad^2$ |
| `MVOPositionNoise` | Position measurement covariance of MVO, specified as a scalar, 3-element vector, or 3-by-3 matrix in $m^2$ |
| `GPSPositionNoise` | Variance of GPS position noise, specified as a scalar in $m^2$ |
| `GPSVelocityNoise` | Variance of GPS velocity noise, specified as a scalar in $(m/s)^2$ |

# Version History

**Introduced in R2021a**

## References

[1] Abbeel, P., Coates, A., Montemerlo, M., Ng, A.Y. and Thrun, S. Discriminative Training of Kalman Filters. In *Robotics: Science and systems*, Vol. 2, pp. 1, 2005.

## See Also

`tunerconfig` | `tunernoise`

# gpsSensor

GPS receiver simulation model

## Description

The gpsSensor System object models data output from a Global Positioning System (GPS) receiver. The object models the position noise as a first order Gauss Markov process, in which the sigma values are specified in the HorizontalPositionAccuracy and the VerticalPositionAccuracy properties. The object models the velocity noise as Gaussian noise with its sigma value specified in the VelocityAccuracy property.

To model a GPS receiver:

1. Create the gpsSensor object and set its properties.
2. Call the object with arguments, as if it were a function.

To learn more about how System objects work, see What Are System Objects?

# Creation

## Syntax

```
GPS = gpsSensor
GPS = gpsSensor('ReferenceFrame',RF)
GPS = gpsSensor( ___ ,Name,Value)
```

### Description

GPS = gpsSensor returns a gpsSensor System object that computes a Global Positioning System receiver reading based on a local position and velocity input signal. The default reference position in geodetic coordinates is

- latitude: 0º N
- longitude: 0º E
- altitude: 0 m

GPS = gpsSensor('ReferenceFrame',RF) returns a gpsSensor System object that computes a global positioning system receiver reading relative to the reference frame RF. Specify RF as 'NED' (North-East-Down) or 'ENU' (East-North-Up). The default value is 'NED'.

GPS = gpsSensor( ___ ,Name,Value) sets each property Name to the specified Value. Unspecified properties have default values.

## Properties

Unless otherwise indicated, properties are *nontunable*, which means you cannot change their values after calling the object. Objects lock when you call them, and the release function unlocks them.

If a property is *tunable*, you can change its value at any time.

For more information on changing property values, see System Design in MATLAB Using System Objects.

**SampleRate — Update rate of receiver (Hz)**
1 (default) | positive real scalar

Update rate of the receiver in Hz, specified as a positive real scalar.

Data Types: single | double

**ReferenceLocation — Origin of local navigation reference frame**
[0 0 0] (default) | [latitude longitude altitude]

Reference location, specified as a 3-element row vector in geodetic coordinates (latitude, longitude, and altitude). Altitude is the height above the reference ellipsoid model, WGS84. The reference location is in [degrees degrees meters]. The degree format is decimal degrees (DD).

Data Types: single | double

**PositionInputFormat — Position coordinate input format**
'Local' (default) | 'Geodetic'

Position coordinate input format, specified as 'Local' or 'Geodetic'.

- If you set the property as 'Local', then you need to specify the truePosition input as Cartesian coordinates with respect to the local navigation frame whose origin is fixed and defined by the ReferenceLcation property. Additionally, when you specify the trueVelocity input, you need to specify it with respect to this local navigation frame.
- If you set the property as 'Geodetic', then you need to specify the truePosition input as geodetic coordinates in latitude, longitude, and altitude. Additionally, when you specify the trueVelocity input, you need to specify it with respect to the navigation frame (NED or ENU) whose origin corresponds to the truePosition input. When setting the property as 'Geodetic', the gpsSensor object neglects the ReferenceLocation property.

Data Types: character vector

**HorizontalPositionAccuracy — Horizontal position accuracy (m)**
1.6 (default) | nonnegative real scalar

Horizontal position accuracy in meters, specified as a nonnegative real scalar. The horizontal position accuracy specifies the standard deviation of the noise in the horizontal position measurement.

**Tunable:** Yes

Data Types: single | double

**VerticalPositionAccuracy — Vertical position accuracy (m)**
3 (default) | nonnegative real scalar

Vertical position accuracy in meters, specified as a nonnegative real scalar. The vertical position accuracy specifies the standard deviation of the noise in the vertical position measurement.

**Tunable:** Yes

Data Types: single | double

**`VelocityAccuracy` — Velocity accuracy (m/s)**
`0.1` (default) | nonnegative real scalar

Velocity accuracy in meters per second, specified as a nonnegative real scalar. The velocity accuracy specifies the standard deviation of the noise in the velocity measurement.

**Tunable:** Yes

Data Types: `single` | `double`

**`DecayFactor` — Global position noise decay factor**
`0.999` (default) | scalar in the range [0,1]

Global position noise decay factor, specified as a scalar in the range [0,1].

A decay factor of 0 models the global position noise as a white noise process. A decay factor of 1 models the global position noise as a random walk process.

**Tunable:** Yes

Data Types: `single` | `double`

**`RandomStream` — Random number source**
`'Global stream'` (default) | `'mt19937ar with seed'`

Random number source, specified as a character vector or string:

- `'Global stream'` –– Random numbers are generated using the current global random number stream.
- `'mt19937ar with seed'` –– Random numbers are generated using the mt19937ar algorithm with the seed specified by the `Seed` property.

Data Types: `char` | `string`

**`Seed` — Initial seed**
`67` (default) | nonnegative integer scalar

Initial seed of an mt19937ar random number generator algorithm, specified as a nonnegative integer scalar.

#### Dependencies

To enable this property, set `RandomStream` to `'mt19937ar with seed'`.

Data Types: `single` | `double` | `int8` | `int16` | `int32` | `int64` | `uint8` | `uint16` | `uint32` | `uint64`

## Usage

## Syntax

```
[position,velocity,groundspeed,course] = GPS(truePosition,trueVelocity)
```

### Description

`[position,velocity,groundspeed,course] = GPS(truePosition,trueVelocity)` computes global navigation satellite system receiver readings from the position and velocity inputs.

### Input Arguments

**`truePosition` — Position of GPS receiver in navigation coordinate system**
*N*-by-3 matrix

Position of the GPS receiver in the navigation coordinate system, specified as a real finite *N*-by-3 matrix. *N* is the number of samples in the current frame.

- When the `PositionInputFormat` property is specified as `'Local'`, specify `truePosition` as Cartesian coordinates with respect to the local navigation frame whose origin is fixed at `ReferenceLocation`.
- When the `PositionInputFormat` property is specified as `'Geodetic'`, specify `truePosition` as geodetic coordinates in `[latitude longitude altitude]`. `Latitude` and `longitude` are in meters. `altitude` is the height above the WGS84 ellipsoid model in meters.

Data Types: `single` | `double`

**`trueVelocity` — Velocity of GPS receiver in navigation coordinate system (m/s)**
*N*-by-3 matrix

Velocity of GPS receiver in the navigation coordinate system in meters per second, specified as a real finite *N*-by-3 matrix. *N* is the number of samples in the current frame.

- When the `PositionInputFormat` property is specified as `'Local'`, specify `trueVelocity` with respect to the local navigation frame (NED or ENU) whose origin is fixed at `ReferenceLocation`.
- When the `PositionInputFormat` property is specified as `'Geodetic'`, specify `trueVelocity` with respect to the navigation frame (NED or ENU) whose origin corresponds to the `truePosition` input.

Data Types: `single` | `double`

### Output Arguments

**`position` — Position in LLA coordinate system**
*N*-by-3 matrix

Position of the GPS receiver in the geodetic latitude, longitude, and altitude (LLA) coordinate system, returned as a real finite *N*-by-3 array. Latitude and longitude are in degrees with North and East being positive. Altitude is in meters.

*N* is the number of samples in the current frame.

Data Types: `single` | `double`

**`velocity` — Velocity in local navigation coordinate system (m/s)**
*N*-by-3 matrix

Velocity of the GPS receiver in the local navigation coordinate system in meters per second, returned as a real finite *N*-by-3 array. *N* is the number of samples in the current frame.

- When the `PositionInputFormat` property is specified as `'Local'`, the returned velocity is with respect to the local navigation frame whose origin is fixed at `ReferenceLocation`.

- When the PositionInputFormat property is specified as 'Geodetic', the returned velocity is with respect to the navigation frame (NED or ENU) whose origin corresponds to the position output.

Data Types: single | double

**groundspeed — Magnitude of horizontal velocity in local navigation coordinate system (m/s)**
*N*-by-1 column vector

Magnitude of the horizontal velocity of the GPS receiver in the local navigation coordinate system in meters per second, returned as a real finite *N*-by-1 column vector.

*N* is the number of samples in the current frame.

Data Types: single | double

**course — Direction of horizontal velocity in local navigation coordinate system (°)**
*N*-by-1 column vector

Direction of the horizontal velocity of the GPS receiver in the local navigation coordinate system in degrees, returned as a real finite *N*-by-1 column of values between 0 and 360. North corresponds to 360 degrees and East corresponds to 90 degrees.

*N* is the number of samples in the current frame.

Data Types: single | double

## Object Functions

To use an object function, specify the System object as the first input argument. For example, to release system resources of a System object named obj, use this syntax:

```
release(obj)
```

## Common to All System Objects

| | |
|---|---|
| step | Run System object algorithm |
| release | Release resources and allow changes to System object property values and input characteristics |
| reset | Reset internal states of System object |

## Examples

### Generate GPS Position Measurements From Stationary Input

Create a gpsSensor System object™ to model GPS receiver data. Assume a typical one Hz sample rate and a 1000-second simulation time. Define the reference location in terms of latitude, longitude, and altitude (LLA) of Natick, MA (USA). Define the sensor as stationary by specifying the true position and velocity with zeros.

```
fs = 1;
duration = 1000;
numSamples = duration*fs;
```

```
refLoc = [42.2825 -71.343 53.0352];

truePosition = zeros(numSamples,3);
trueVelocity = zeros(numSamples,3);

gps = gpsSensor('SampleRate',fs,'ReferenceLocation',refLoc);
```

Call `gps` with the specified `truePosition` and `trueVelocity` to simulate receiving GPS data for a stationary platform.

```
position = gps(truePosition,trueVelocity);
```

Plot the true position and the GPS sensor readings for position.

```
t = (0:(numSamples-1))/fs;

subplot(3, 1, 1)
plot(t, position(:,1), ...
     t, ones(numSamples)*refLoc(1))
title('GPS Sensor Readings')
ylabel('Latitude (degrees)')

subplot(3, 1, 2)
plot(t, position(:,2), ...
     t, ones(numSamples)*refLoc(2))
ylabel('Longitude (degrees)')

subplot(3, 1, 3)
plot(t, position(:,3), ...
     t, ones(numSamples)*refLoc(3))
ylabel('Altitude (m)')
xlabel('Time (s)')
```

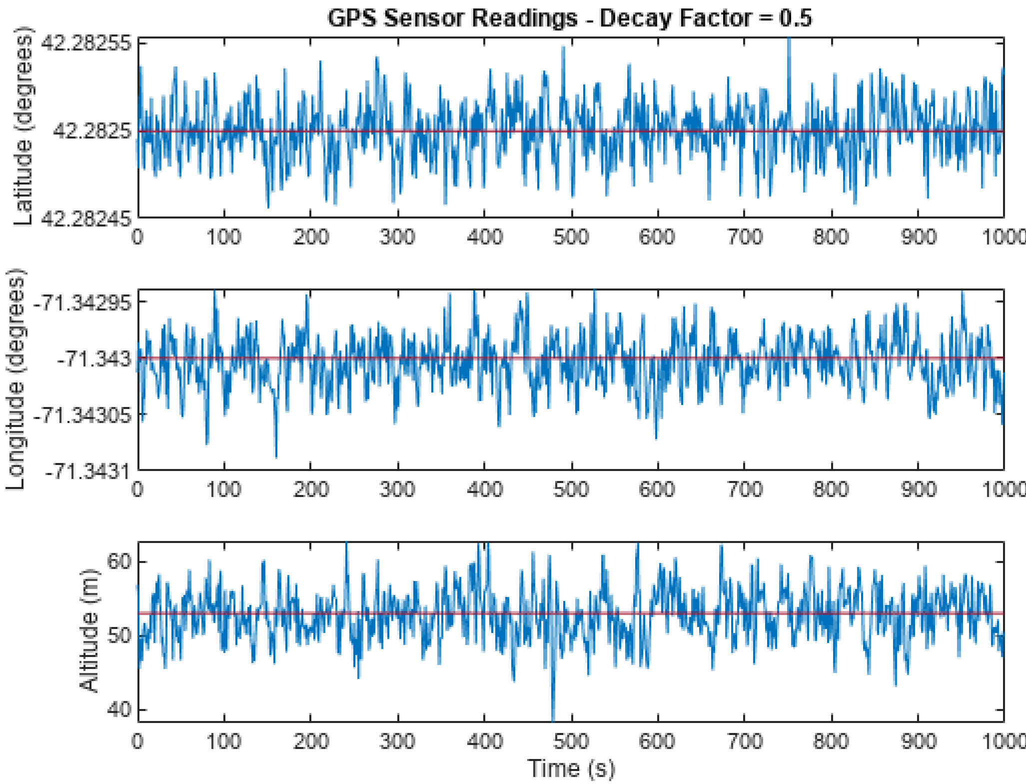
The position readings have noise controlled by `HorizontalPositionAccuracy`, `VerticalPositionAccuracy`, `VelocityAccuracy`, and `DecayFactor`. The `DecayFactor` property controls the drift in the noise model. By default, `DecayFactor` is set to `0.999`, which approaches a random walk process. To observe the effect of the `DecayFactor` property:

1. Reset the `gps` object.
2. Set `DecayFactor` to `0.5`.
3. Call `gps` with variables specifying a stationary position.
4. Plot the results.

The `GPS` position readings now oscillate around the true position.

```
reset(gps)
gps.DecayFactor = 0.5;
position = gps(truePosition,trueVelocity);

subplot(3, 1, 1)
plot(t, position(:,1), ...
     t, ones(numSamples)*refLoc(1))
title('GPS Sensor Readings - Decay Factor = 0.5')
ylabel('Latitude (degrees)')

subplot(3, 1, 2)
plot(t, position(:,2), ...
     t, ones(numSamples)*refLoc(2))
ylabel('Longitude (degrees)')
```

```
subplot(3, 1, 3)
plot(t, position(:,3), ...
     t, ones(numSamples)*refLoc(3))
ylabel('Altitude (m)')
xlabel('Time (s)')
```




**Relationship Between Groundspeed and Course Accuracy**

GPS receivers achieve greater course accuracy as groundspeed increases. In this example, you create a GPS receiver simulation object and simulate the data received from a platform that is accelerating from a stationary position.

Create a default `gpsSensor` System object™ to model data returned by a GPS receiver.

```
GPS = gpsSensor
```

```
GPS = 
  gpsSensor with properties:

                   SampleRate: 1                  Hz
          PositionInputFormat: 'Local'
            ReferenceLocation: [0 0 0]            [deg deg m]
    HorizontalPositionAccuracy: 1.6               m
      VerticalPositionAccuracy: 3                 m
```

```
    VelocityAccuracy: 0.1                m/s
        RandomStream: 'Global stream'
         DecayFactor: 0.999
```

Create matrices to describe the position and velocity of a platform in the NED coordinate system. The platform begins from a stationary position and accelerates to 60 m/s North-East over 60 seconds, then has a vertical acceleration to 2 m/s over 2 seconds, followed by a 2 m/s rate of climb for another 8 seconds. Assume a constant velocity, such that the velocity is the simple derivative of the position.

```
duration = 70;
numSamples = duration*GPS.SampleRate;

course = 45*ones(duration,1);
groundspeed = [(1:60)';60*ones(10,1)];

Nvelocity   = groundspeed.*sind(course);
Evelocity   = groundspeed.*cosd(course);
Dvelocity   = [zeros(60,1);-1;-2*ones(9,1)];
NEDvelocity = [Nvelocity,Evelocity,Dvelocity];

Ndistance   = cumsum(Nvelocity);
Edistance   = cumsum(Evelocity);
Ddistance   = cumsum(Dvelocity);
NEDposition = [Ndistance,Edistance,Ddistance];
```

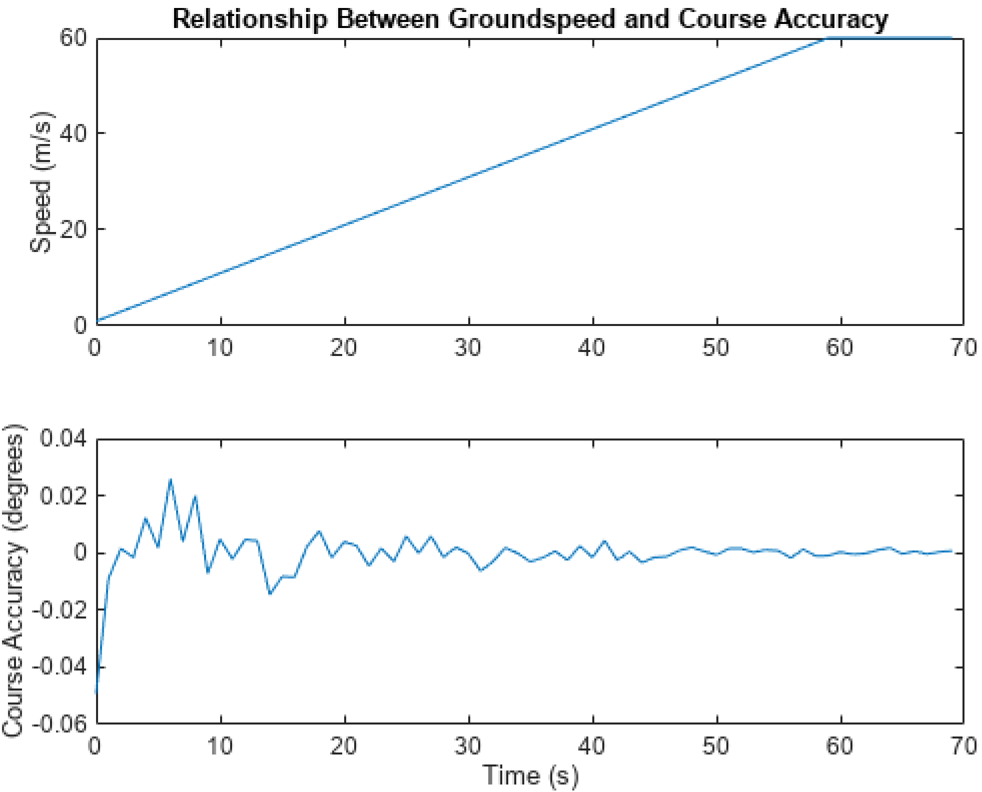
Model GPS measurement data by calling the `GPS` object with your velocity and position matrices.

```
[~,~,groundspeedMeasurement,courseMeasurement] = GPS(NEDposition,NEDvelocity);
```

Plot the groundspeed and the difference between the true course and the course returned by the GPS simulator.

As groundspeed increases, the accuracy of the course increases. Note that the velocity increase during the last ten seconds has no effect, because the additional velocity is not in the ground plane.

```
t = (0:numSamples-1)/GPS.SampleRate;

subplot(2,1,1)
plot(t,groundspeed);
ylabel('Speed (m/s)')
title('Relationship Between Groundspeed and Course Accuracy')

subplot(2,1,2)
courseAccuracy = courseMeasurement - course;
plot(t,courseAccuracy)
xlabel('Time (s)');
ylabel('Course Accuracy (degrees)')
```




**Model GPS Receiver Data**

Simulate GPS data received during a trajectory from the city of Natick, MA, to Boston, MA.

Define the decimal degree latitude and longitude for the city of Natick, MA USA, and Boston, MA USA. For simplicity, set the altitude for both locations to zero.

```
NatickLLA = [42.27752809999999, -71.34680909999997, 0];
BostonLLA = [42.3600825, -71.05888010000001, 0];
```

Define a motion that can take a platform from Natick to Boston in 20 minutes. Set the origin of the local NED coordinate system as Natick. Create a `waypointTrajectory` object to output the trajectory 10 samples at a time.

```
fs = 1;
duration = 60*20;

bearing = 68; % degrees
distance = 25.39e3; % meters
distanceEast = distance*sind(bearing);
distanceNorth = distance*cosd(bearing);

NatickNED = [0,0,0];
BostonNED = [distanceNorth,distanceEast,0];
```

```
trajectory = waypointTrajectory( ...
    'Waypoints', [NatickNED;BostonNED], ...
    'TimeOfArrival',[0;duration], ...
    'SamplesPerFrame',10, ...
    'SampleRate',fs);
```

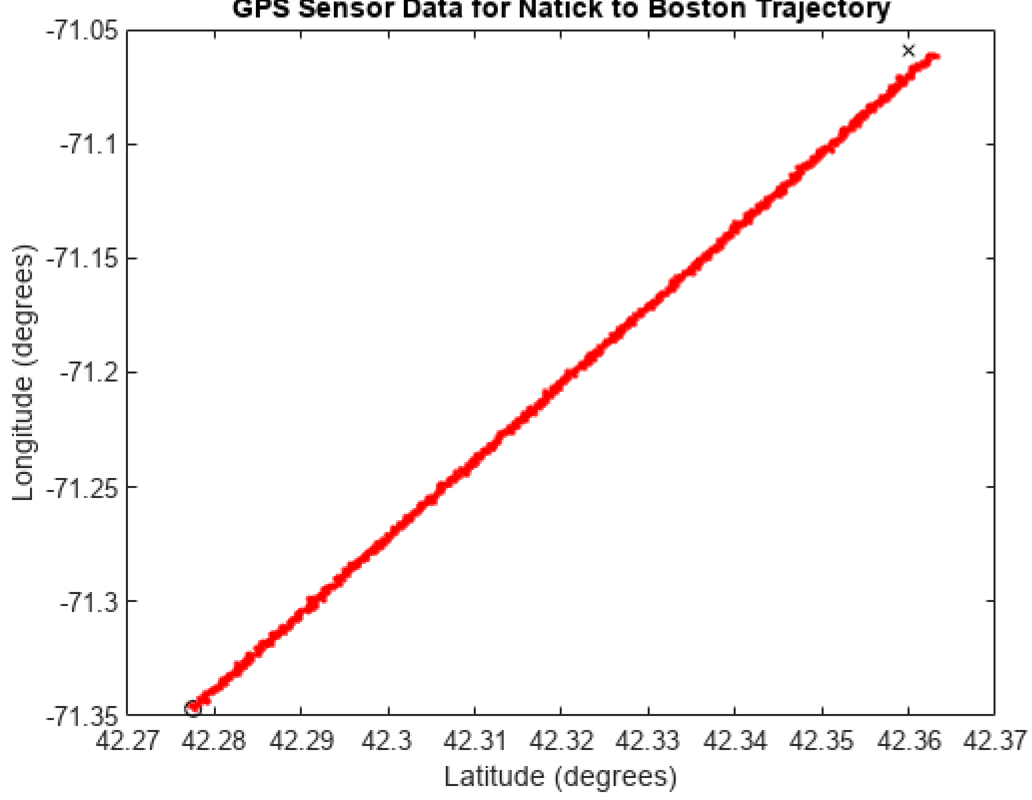
Create a `gpsSensor` object to model receiving GPS data for the platform. Set the `HorizontalPositionalAccuracy` to `25` and the `DecayFactor` to `0.25` to emphasize the noise. Set the `ReferenceLocation` to the Natick coordinates in LLA.

```
GPS = gpsSensor( ...
    'HorizontalPositionAccuracy',25, ...
    'DecayFactor',0.25, ...
    'SampleRate',fs, ...
    'ReferenceLocation',NatickLLA);
```

Open a figure and plot the position of Natick and Boston in LLA. Ignore altitude for simplicity.

In a loop, call the `gpsSensor` object with the ground-truth trajectory to simulate the received GPS data. Plot the ground-truth trajectory and the model of received GPS data.

```
figure(1)
plot(NatickLLA(1),NatickLLA(2),'ko', ...
     BostonLLA(1),BostonLLA(2),'kx')
xlabel('Latitude (degrees)')
ylabel('Longitude (degrees)')
title('GPS Sensor Data for Natick to Boston Trajectory')
hold on

while ~isDone(trajectory)
    [truePositionNED,~,trueVelocityNED] = trajectory();
    reportedPositionLLA = GPS(truePositionNED,trueVelocityNED);

    figure(1)
    plot(reportedPositionLLA(:,1),reportedPositionLLA(:,2),'r.')
end
```




As a best practice, release System objects when complete.

```
release(GPS)
release(trajectory)
```

# Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

Usage notes and limitations:

See “System Objects in MATLAB Code Generation” (MATLAB Coder).

## See Also

### Objects

`imuSensor` | `insSensor`

**Topics**

"Model IMU, GPS, and INS/GPS"

# gyroparams

Gyroscope sensor parameters

## Description

The `gyroparams` class creates a gyroscope sensor parameters object. You can use this object to model a gyroscope when simulating an IMU with `imuSensor`. See the “Algorithms” on page 2-545 section of `imuSensor` for details of `gyroparams` modeling.

## Creation

### Syntax

```
params = gyroparams
params = gyroparams(Name,Value)
```

#### Description

`params = gyroparams` returns an ideal gyroscope sensor parameters object with default values.

`params = gyroparams(Name,Value)` configures `gyroparams` object properties using one or more `Name,Value` pair arguments. `Name` is a property name and `Value` is the corresponding value. `Name` must appear inside single quotes (`''`). You can specify several name-value pair arguments in any order as `Name1,Value1,...,NameN,ValueN`. Any unspecified properties take default values.

### Properties

**`MeasurementRange` — Maximum sensor reading (rad/s)**
`Inf` (default) | real positive scalar

Maximum sensor reading in rad/s, specified as a real positive scalar.

Data Types: `single` | `double`

**`Resolution` — Resolution of sensor measurements ((rad/s)/LSB)**
`0` (default) | real nonnegative scalar

Resolution of sensor measurements in (rad/s)/LSB, specified as a real nonnegative scalar. Here, LSB is the acronym for least significant bit.

Data Types: `single` | `double`

**`ConstantBias` — Constant sensor offset bias (rad/s)**
`[0 0 0]` (default) | real scalar | real 3-element row vector

Constant sensor offset bias in rad/s, specified as a real scalar or 3-element row vector. Any scalar input is converted into a real 3-element row vector where each element has the input scalar value.

Data Types: `single` | `double`

**`AxesMisalignment` — Sensor axes skew (%)**
`diag([100 100 100])` (default) | scalar in the range [0,100] | 3-element row vector in the range [0,100] | 3-by-3 matrix in the range [0,100]

Sensor axes skew in percentage, specified as a scalar, a 3-element row vector, or a 3-by-3 matrix with values ranging from `0` to `100`. The diagonal elements of the matrix account for the misalignment effects for each axes. The off-diagonal elements account for the cross-axes misalignment effects. The measured state $v_{measure}$ is obtained from the true state $v_{true}$ via the misalignment matrix as:

$$v_{measure} = \frac{1}{100} M v_{true} = \frac{1}{100} \begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{bmatrix} v_{true}$$

- If you specify the property as a scalar, then all the off-diagonal elements of the matrix take the value of the specified scalar and all the diagonal elements are 100.
- If you specify the property as a vector [$a$ $b$ $c$], then $m_{21} = m_{31} = a$, $m_{12} = m_{32} = b$, and $m_{13} = m_{23} = c$. All the diagonal elements are 100.

Data Types: `single` | `double`

**`NoiseDensity` — Power spectral density of sensor noise ((rad/s)/√Hz)**
`[0 0 0]` (default) | real scalar | real 3-element row vector

Power spectral density of sensor noise in (rad/s)/√Hz, specified as a real scalar or 3-element row vector. This property corresponds to the angle random walk (ARW). Any scalar input is converted into a real 3-element row vector where each element has the input scalar value.

Data Types: `single` | `double`

**`BiasInstability` — Instability of the bias offset (rad/s)**
`[0 0 0]` (default) | real scalar | real 3-element row vector

Instability of the bias offset in rad/s, specified as a real scalar or 3-element row vector. Any scalar input is converted into a real 3-element row vector where each element has the input scalar value.

Data Types: `single` | `double`

**`RandomWalk` — Integrated white noise of sensor ((rad/s)(√Hz))**
`[0 0 0]` (default) | real scalar | real 3-element row vector

Integrated white noise of sensor in (rad/s)(√Hz), specified as a real scalar or 3-element row vector. Any scalar input is converted into a real 3-element row vector where each element has the input scalar value.

Data Types: `single` | `double`

**`TemperatureBias` — Sensor bias from temperature ((rad/s)/°C)**
`[0 0 0]` (default) | real scalar | real 3-element row vector

Sensor bias from temperature in ((rad/s)/℃), specified as a real scalar or 3-element row vector. Any scalar input is converted into a real 3-element row vector where each element has the input scalar value.

Data Types: `single` | `double`

**`TemperatureScaleFactor` — Scale factor error from temperature (%/°C)**
`[0 0 0]` (default) | real scalar in the range [0,100] | real 3-element row vector in the range [0,100]

Scale factor error from temperature in (%/℃), specified as a real scalar or 3-element row vector with values ranging from 0 to 100. Any scalar input is converted into a real 3-element row vector where each element has the input scalar value.

Data Types: `single` | `double`

**`AccelerationBias` — Sensor bias from linear acceleration (rad/s)/(m/s²)**
`[0 0 0]` (default) | real scalar | real 3-element row vector

Sensor bias from linear acceleration in (rad/s)/(m/s$^2$), specified as a real scalar or 3-element row vector. Any scalar input is converted into a real 3-element row vector where each element has the input scalar value.

Data Types: `single` | `double`

## Examples

### Generate Gyroscope Data from Stationary Inputs

Generate gyroscope data for an imuSensor object from stationary inputs.

Generate a gyroscope parameter object with a maximum sensor reading of 4.363 rad/s and a resolution of 1.332e-4 (rad/s)/LSB. The constant offset bias is 0.349 rad/s. The sensor has a power spectral density of 8.727e-4 $\mathrm{rad/s}/\sqrt{\mathrm{Hz}}$. The bias from temperature is 0.349 $\mathrm{rad/s}/{}^0C$. The bias from temperature is 0.349 $\left(\mathrm{rad/s}^2\right)/{}^0\mathrm{C}$. The scale factor error from temperature is 0.2%/$^0$C. The sensor axes are skewed by 2%. The sensor bias from linear acceleration is 0.178e-3 (rad/s)/(m/s$^2$)

```
params = gyroparams('MeasurementRange',4.363,'Resolution',1.332e-04,'ConstantBias',0.349,'NoiseDe
```

Use a sample rate of 100 Hz spaced out over 1000 samples. Create the imuSensor object using the gyroscope parameter object.

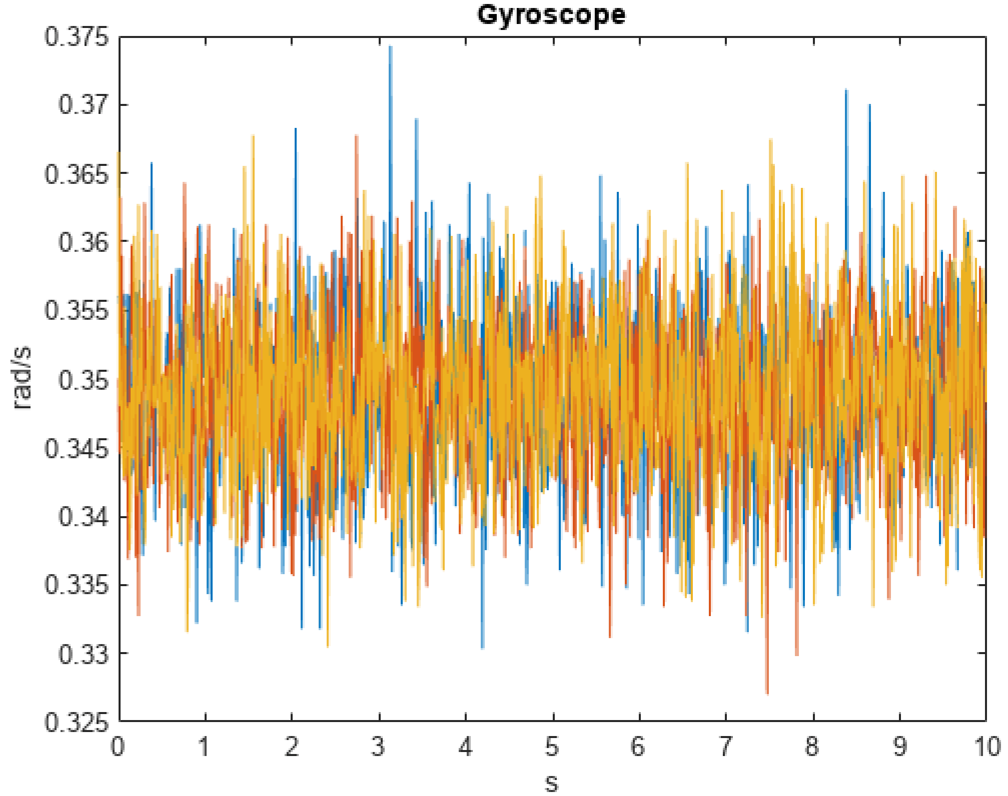
```
Fs = 100;
numSamples = 1000;
t = 0:1/Fs:(numSamples-1)/Fs;

imu = imuSensor('accel-gyro','SampleRate', Fs, 'Gyroscope', params);
```

Generate gyroscope data from the imuSensor object.

```
orient = quaternion.ones(numSamples, 1);
acc = zeros(numSamples, 3);
angvel = zeros(numSamples, 3);

[~, gyroData] = imu(acc, angvel, orient);
```

Plot the resultant gyroscope data.

```
plot(t, gyroData)
title('Gyroscope')
xlabel('s')
ylabel('rad/s')
```




# Version History

**Introduced in R2018b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`accelparams` | `magparams` | `imuSensor`

# imufilter

Orientation from accelerometer and gyroscope readings

## Description

The `imufilter` System object fuses accelerometer and gyroscope sensor data to estimate device orientation.

To estimate device orientation:

1. Create the `imufilter` object and set its properties.
2. Call the object with arguments, as if it were a function.

To learn more about how System objects work, see What Are System Objects?

# Creation

## Syntax

```
FUSE = imufilter
FUSE = imufilter('ReferenceFrame',RF)
FUSE = imufilter( ___ ,Name,Value)
```

### Description

`FUSE = imufilter` returns an indirect Kalman filter System object, `FUSE`, for fusion of accelerometer and gyroscope data to estimate device orientation. The filter uses a nine-element state vector to track error in the orientation estimate, the gyroscope bias estimate, and the linear acceleration estimate.

`FUSE = imufilter('ReferenceFrame',RF)` returns an `imufilter` filter System object that fuses accelerometer and gyroscope data to estimate device orientation relative to the reference frame `RF`. Specify `RF` as `'NED'` (North-East-Down) or `'ENU'` (East-North-Up). The default value is `'NED'`.

`FUSE = imufilter( ___ ,Name,Value)` sets each property `Name` to the specified `Value`. Unspecified properties have default values.

Example: `FUSE = imufilter('SampleRate',200,'GyroscopeNoise',1e-6)` creates a System object, `FUSE`, with a 200 Hz sample rate and gyroscope noise set to 1e-6 radians per second squared.

## Properties

Unless otherwise indicated, properties are *nontunable*, which means you cannot change their values after calling the object. Objects lock when you call them, and the `release` function unlocks them.

If a property is *tunable*, you can change its value at any time.

For more information on changing property values, see System Design in MATLAB Using System Objects.

**SampleRate — Sample rate of input sensor data (Hz)**
100 (default) | positive finite scalar

Sample rate of the input sensor data in Hz, specified as a positive finite scalar.

**Tunable:** No

Data Types: single | double | uint8 | uint16 | uint32 | uint64 | int8 | int16 | int32 | int64

**DecimationFactor — Decimation factor**
1 (default) | positive integer scalar

Decimation factor by which to reduce the sample rate of the input sensor data, specified as a positive integer scalar.

The number of rows of the inputs, `accelReadings` and `gyroReadings`, must be a multiple of the decimation factor.

**Tunable:** No

Data Types: single | double | uint8 | uint16 | uint32 | uint64 | int8 | int16 | int32 | int64

**AccelerometerNoise — Variance of accelerometer signal noise ($(m/s^2)^2$)**
0.00019247 (default) | positive real scalar

Variance of accelerometer signal noise in $(m/s^2)^2$, specified as a positive real scalar.

**Tunable:** Yes

Data Types: single | double | uint8 | uint16 | uint32 | uint64 | int8 | int16 | int32 | int64

**GyroscopeNoise — Variance of gyroscope signal noise ($(rad/s)^2$)**
9.1385e-5 (default) | positive real scalar

Variance of gyroscope signal noise in $(rad/s)^2$, specified as a positive real scalar.

**Tunable:** Yes

Data Types: single | double | uint8 | uint16 | uint32 | uint64 | int8 | int16 | int32 | int64

**GyroscopeDriftNoise — Variance of gyroscope offset drift ($(rad/s)^2$)**
3.0462e-13 (default) | positive real scalar

Variance of gyroscope offset drift in $(rad/s)^2$, specified as a positive real scalar.

**Tunable:** Yes

Data Types: single | double | uint8 | uint16 | uint32 | uint64 | int8 | int16 | int32 | int64

**LinearAccelerationNoise — Variance of linear acceleration noise ($(m/s^2)^2$)**
0.0096236 (default) | positive real scalar

Variance of linear acceleration noise in $(m/s^2)^2$, specified as a positive real scalar. Linear acceleration is modeled as a lowpass filtered white noise process.

**Tunable:** Yes

Data Types: `single` | `double` | `uint8` | `uint16` | `uint32` | `uint64` | `int8` | `int16` | `int32` | `int64`

### `LinearAcclerationDecayFactor` — Decay factor for linear acceleration drift

`0.5` (default) | scalar in the range [0,1]

Decay factor for linear acceleration drift, specified as a scalar in the range [0,1]. If linear acceleration is changing quickly, set `LinearAccelerationDecayFactor` to a lower value. If linear acceleration changes slowly, set `LinearAccelerationDecayFactor` to a higher value. Linear acceleration drift is modeled as a lowpass-filtered white noise process.

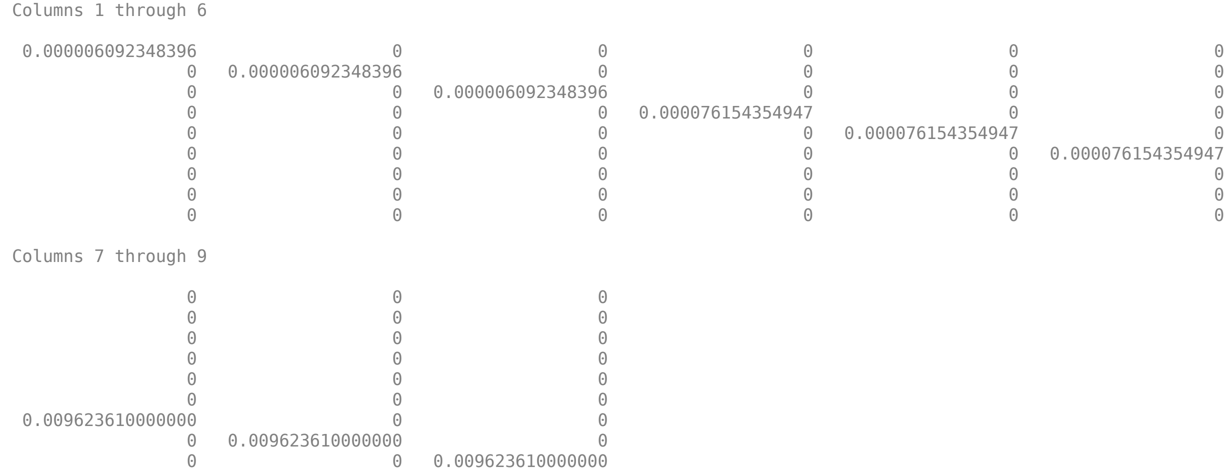
**Tunable:** Yes

Data Types: `single` | `double` | `uint8` | `uint16` | `uint32` | `uint64` | `int8` | `int16` | `int32` | `int64`

### `InitialProcessNoise` — Covariance matrix for process noise

9-by-9 matrix

Covariance matrix for process noise, specified as a 9-by-9 matrix. The default is:



```
  Columns 1 through 6

   0.000006092348396                   0                   0                   0                   0                   0
                   0   0.000006092348396                   0                   0                   0                   0
                   0                   0   0.000006092348396                   0                   0                   0
                   0                   0                   0   0.000076154354947                   0                   0
                   0                   0                   0                   0   0.000076154354947                   0
                   0                   0                   0                   0                   0   0.000076154354947
                   0                   0                   0                   0                   0                   0
                   0                   0                   0                   0                   0                   0
                   0                   0                   0                   0                   0                   0

  Columns 7 through 9

                   0                   0                   0
                   0                   0                   0
                   0                   0                   0
                   0                   0                   0
                   0                   0                   0
                   0                   0                   0
   0.009623610000000                   0                   0
                   0   0.009623610000000                   0
                   0                   0   0.009623610000000
```

The initial process covariance matrix accounts for the error in the process model.

Data Types: `single` | `double` | `uint8` | `uint16` | `uint32` | `uint64` | `int8` | `int16` | `int32` | `int64`

### `OrientationFormat` — Output orientation format

`'quaternion'` (default) | `'Rotation matrix'`

Output orientation format, specified as `'quaternion'` or `'Rotation matrix'`. The size of the output depends on the input size, *N*, and the output orientation format:

- `'quaternion'` –– Output is an *N*-by-1 `quaternion`.
- `'Rotation matrix'` –– Output is a 3-by-3-by-*N* rotation matrix.

Data Types: `char` | `string`

## Usage

## Syntax

`[orientation,angularVelocity] = FUSE(accelReadings,gyroReadings)`

### Description

`[orientation,angularVelocity] = FUSE(accelReadings,gyroReadings)` fuses accelerometer and gyroscope readings to compute orientation and angular velocity measurements. The algorithm assumes that the device is stationary before the first call.

### Input Arguments

**`accelReadings` — Accelerometer readings in sensor body coordinate system (m/s²)**
*N*-by-3 matrix

Accelerometer readings in the sensor body coordinate system in $m/s^2$, specified as an *N*-by-3 matrix. *N* is the number of samples, and the three columns of `accelReadings` represent the [*x y z*] measurements. Accelerometer readings are assumed to correspond to the sample rate specified by the SampleRate property.

Data Types: `single` | `double`

**`gyroReadings` — Gyroscope readings in sensor body coordinate system (rad/s)**
*N*-by-3 matrix

Gyroscope readings in the sensor body coordinate system in rad/s, specified as an *N*-by-3 matrix. *N* is the number of samples, and the three columns of `gyroReadings` represent the [*x y z*] measurements. Gyroscope readings are assumed to correspond to the sample rate specified by the SampleRate property.

Data Types: `single` | `double`

### Output Arguments

**`orientation` — Orientation that rotates quantities from global coordinate system to sensor body coordinate system**
*M*-by-1 vector of quaternions (default) | 3-by-3-by-*M* array

Orientation that can rotate quantities from a global coordinate system to a body coordinate system, returned as quaternions or an array. The size and type of `orientation` depends on whether the OrienationFormat property is set to `'quaternion'` or `'Rotation matrix'`:

- `'quaternion'` -– The output is an *M*-by-1 vector of quaternions, with the same underlying data type as the inputs.
- `'Rotation matrix'` -– The output is a 3-by-3-by-*M* array of rotation matrices the same data type as the inputs.

The number of input samples, *N*, and the DecimationFactor property determine *M*.

You can use `orientation` in a `rotateframe` function to rotate quantities from a global coordinate system to a sensor body coordinate system.

Data Types: `quaternion` | `single` | `double`

**`angularVelocity` — Angular velocity in sensor body coordinate system (rad/s)**
*M*-by-3 array (default)

Angular velocity with gyroscope bias removed in the sensor body coordinate system in rad/s, returned as an *M*-by-3 array. The number of input samples, *N*, and the DecimationFactor property determine *M*.

Data Types: `single` | `double`

## Object Functions

To use an object function, specify the System object as the first input argument. For example, to release system resources of a System object named `obj`, use this syntax:

```
release(obj)
```

### Specific to `imufilter`

| | |
|---|---|
| tune | Tune imufilter parameters to reduce estimation error |

### Common to All System Objects

| | |
|---|---|
| step | Run System object algorithm |
| release | Release resources and allow changes to System object property values and input characteristics |
| reset | Reset internal states of System object |

## Examples

#### Estimate Orientation from IMU data

Load the `rpy_9axis` file, which contains recorded accelerometer, gyroscope, and magnetometer sensor data from a device oscillating in pitch (around *y*-axis), then yaw (around *z*-axis), and then roll (around *x*-axis). The file also contains the sample rate of the recording.

```
load 'rpy_9axis.mat' sensorData Fs

accelerometerReadings = sensorData.Acceleration;
gyroscopeReadings = sensorData.AngularVelocity;
```

Create an `imufilter` System object™ with sample rate set to the sample rate of the sensor data. Specify a decimation factor of two to reduce the computational cost of the algorithm.

```
decim = 2;
fuse = imufilter('SampleRate',Fs,'DecimationFactor',decim);
```

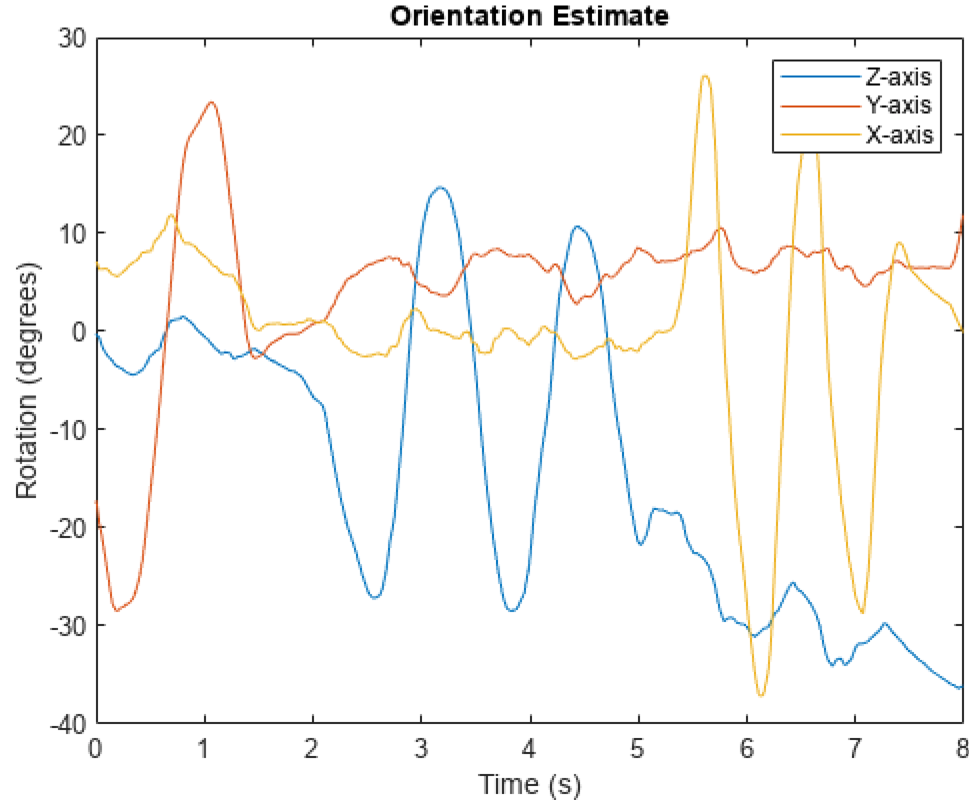
Pass the accelerometer readings and gyroscope readings to the `imufilter` object, `fuse`, to output an estimate of the sensor body orientation over time. By default, the orientation is output as a vector of quaternions.

```
q = fuse(accelerometerReadings,gyroscopeReadings);
```

Orientation is defined by the angular displacement required to rotate a parent coordinate system to a child coordinate system. Plot the orientation in Euler angles in degrees over time.

`imufilter` fusion correctly estimates the change in orientation from an assumed north-facing initial orientation. However, the device's *x*-axis was pointing southward when recorded. To correctly estimate the orientation relative to the true initial orientation or relative to NED, use `ahrsfilter`.

```
time = (0:decim:size(accelerometerReadings,1)-1)/Fs;

plot(time,eulerd(q,'ZYX','frame'))
title('Orientation Estimate')
legend('Z-axis', 'Y-axis', 'X-axis')
xlabel('Time (s)')
ylabel('Rotation (degrees)')
```




**Model Tilt Using Gyroscope and Accelerometer Readings**

Model a tilting IMU that contains an accelerometer and gyroscope using the `imuSensor` System object™. Use ideal and realistic models to compare the results of orientation tracking using the `imufilter` System object.

Load a struct describing ground-truth motion and a sample rate. The motion struct describes sequential rotations:

1. yaw: 120 degrees over two seconds
2. pitch: 60 degrees over one second

3. roll: 30 degrees over one-half second
4. roll: -30 degrees over one-half second
5. pitch: -60 degrees over one second
6. yaw: -120 degrees over two seconds

In the last stage, the motion struct combines the 1st, 2nd, and 3rd rotations into a single-axis rotation. The acceleration, angular velocity, and orientation are defined in the local NED coordinate system.

```
load y120p60r30.mat motion fs
accNED = motion.Acceleration;
angVelNED = motion.AngularVelocity;
orientationNED = motion.Orientation;

numSamples = size(motion.Orientation,1);
t = (0:(numSamples-1)).'/fs;
```

Create an ideal IMU sensor object and a default IMU filter object.

```
IMU = imuSensor('accel-gyro','SampleRate',fs);

aFilter = imufilter('SampleRate',fs);
```

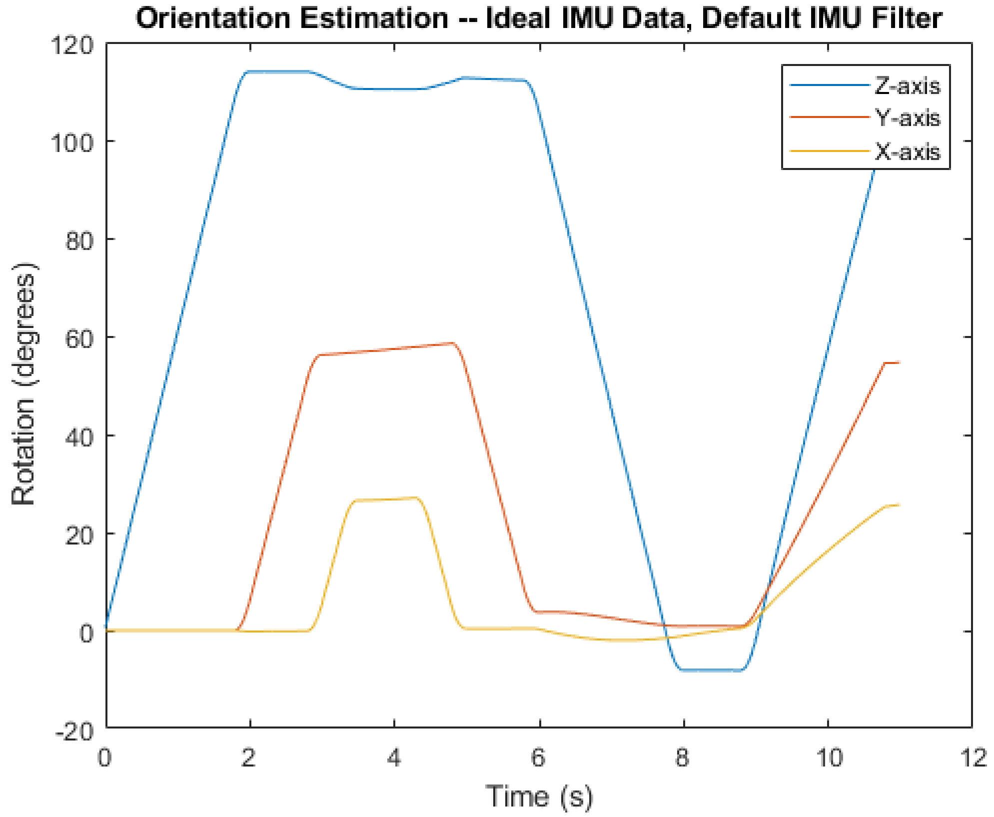
In a loop:

1. Simulate IMU output by feeding the ground-truth motion to the IMU sensor object.
2. Filter the IMU output using the default IMU filter object.

```
orientation = zeros(numSamples,1,'quaternion');
for i = 1:numSamples

    [accelBody,gyroBody] = IMU(accNED(i,:),angVelNED(i,:),orientationNED(i,:));

    orientation(i) = aFilter(accelBody,gyroBody);

end
release(aFilter)
```

Plot the orientation over time.

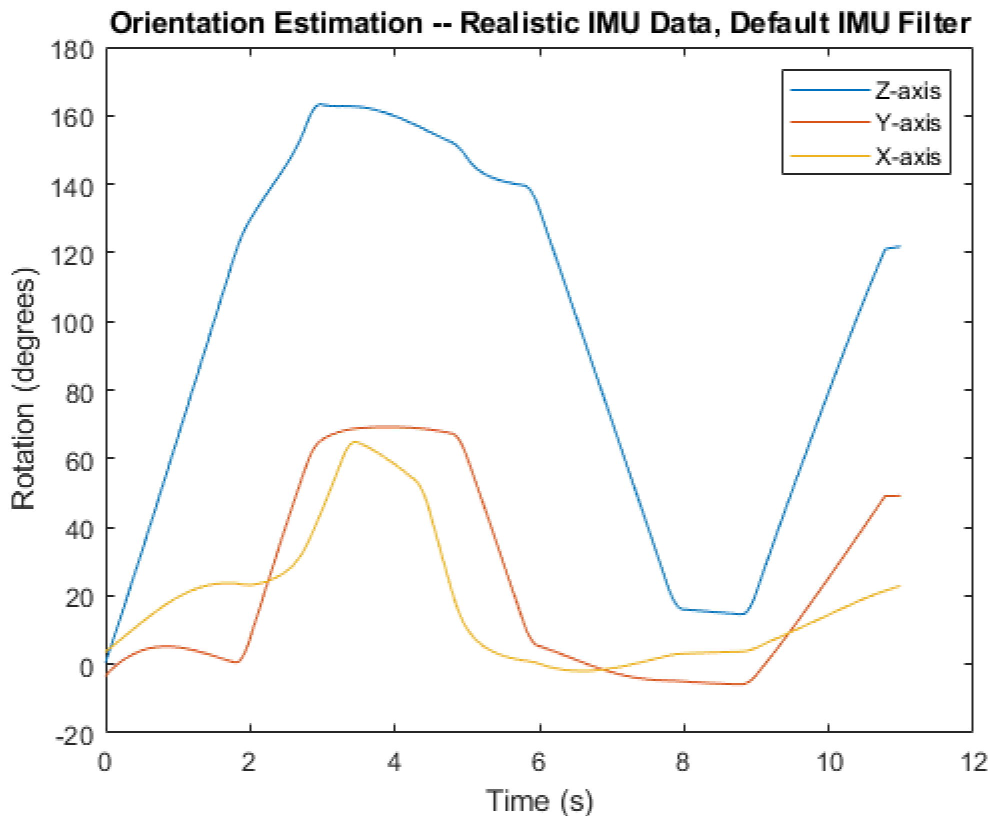
```
figure(1)
plot(t,eulerd(orientation,'ZYX','frame'))
xlabel('Time (s)')
ylabel('Rotation (degrees)')
title('Orientation Estimation -- Ideal IMU Data, Default IMU Filter')
legend('Z-axis','Y-axis','X-axis')
```




Modify properties of your `imuSensor` to model real-world sensors. Run the loop again and plot the orientation estimate over time.

```
IMU.Accelerometer = accelparams( ...
    'MeasurementRange',19.62, ...
    'Resolution',0.00059875, ...
    'ConstantBias',0.4905, ...
    'AxesMisalignment',2, ...
    'NoiseDensity',0.003924, ...
    'BiasInstability',0, ...
    'TemperatureBias', [0.34335 0.34335 0.5886], ...
    'TemperatureScaleFactor',0.02);
IMU.Gyroscope = gyroparams( ...
    'MeasurementRange',4.3633, ...
    'Resolution',0.00013323, ...
    'AxesMisalignment',2, ...
    'NoiseDensity',8.7266e-05, ...
    'TemperatureBias',0.34907, ...
    'TemperatureScaleFactor',0.02, ...
    'AccelerationBias',0.00017809, ...
    'ConstantBias',[0.3491,0.5,0]);

orientationDefault = zeros(numSamples,1,'quaternion');
for i = 1:numSamples

    [accelBody,gyroBody] = IMU(accNED(i,:),angVelNED(i,:),orientationNED(i,:));
```

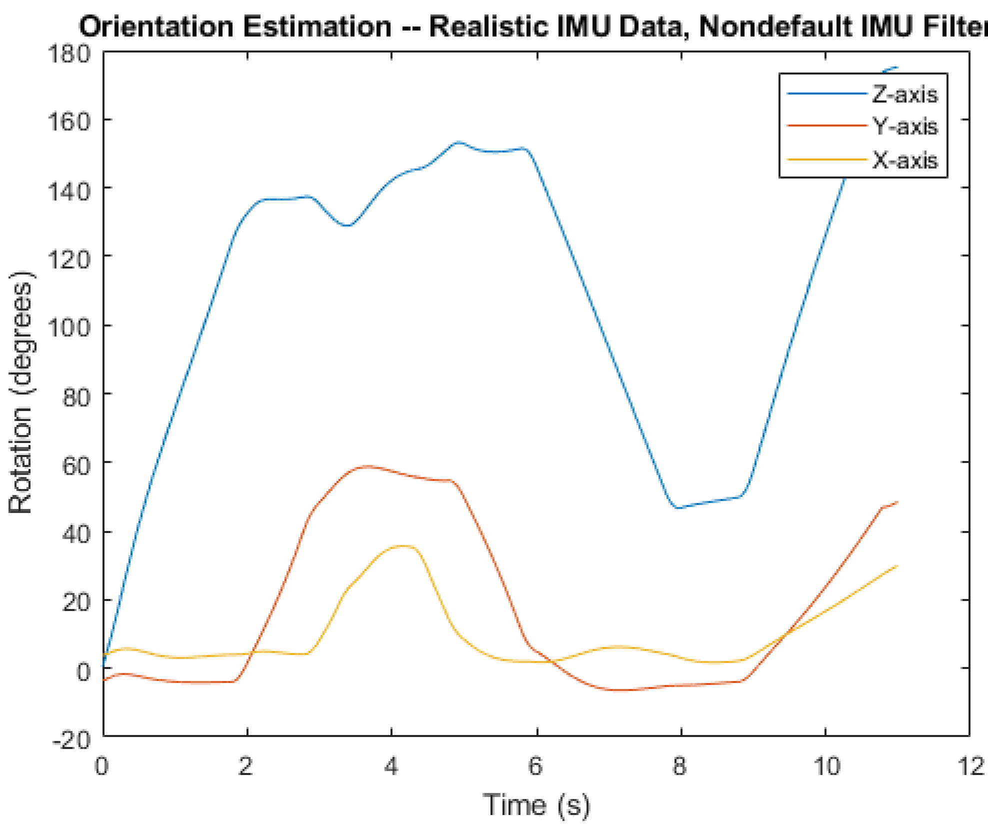
```
    orientationDefault(i) = aFilter(accelBody,gyroBody);

end
release(aFilter)

figure(2)
plot(t,eulerd(orientationDefault,'ZYX','frame'))
xlabel('Time (s)')
ylabel('Rotation (degrees)')
title('Orientation Estimation -- Realistic IMU Data, Default IMU Filter')
legend('Z-axis','Y-axis','X-axis')
```




The ability of the `imufilter` to track the ground-truth data is significantly reduced when modeling a realistic IMU. To improve performance, modify properties of your `imufilter` object. These values were determined empirically. Run the loop again and plot the orientation estimate over time.

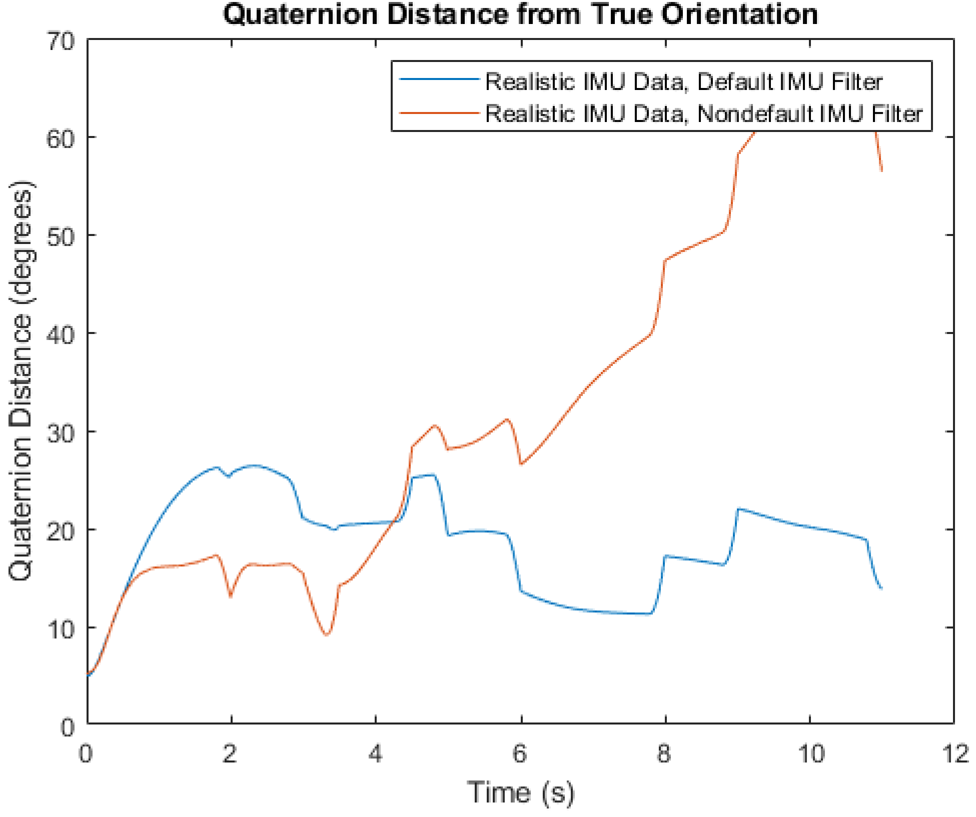
```
aFilter.GyroscopeNoise          = 7.6154e-7;
aFilter.AccelerometerNoise      = 0.0015398;
aFilter.GyroscopeDriftNoise     = 3.0462e-12;
aFilter.LinearAccelerationNoise = 0.00096236;
aFilter.InitialProcessNoise     = aFilter.InitialProcessNoise*10;

orientationNondefault = zeros(numSamples,1,'quaternion');
for i = 1:numSamples
    [accelBody,gyroBody] = IMU(accNED(i,:),angVelNED(i,:),orientationNED(i,:));

    orientationNondefault(i) = aFilter(accelBody,gyroBody);
```

```
end
release(aFilter)

figure(3)
plot(t,eulerd(orientationNondefault,'ZYX','frame'))
xlabel('Time (s)')
ylabel('Rotation (degrees)')
title('Orientation Estimation -- Realistic IMU Data, Nondefault IMU Filter')
legend('Z-axis','Y-axis','X-axis')
```




To quantify the improved performance of the modified `imufilter`, plot the quaternion distance between the ground-truth motion and the orientation as returned by the `imufilter` with default and nondefault properties.

```
qDistDefault = rad2deg(dist(orientationNED,orientationDefault));
qDistNondefault = rad2deg(dist(orientationNED,orientationNondefault));

figure(4)
plot(t,[qDistDefault,qDistNondefault])
title('Quaternion Distance from True Orientation')
legend('Realistic IMU Data, Default IMU Filter', ...
       'Realistic IMU Data, Nondefault IMU Filter')
xlabel('Time (s)')
ylabel('Quaternion Distance (degrees)')
```




#### Remove Bias from Angular Velocity Measurement

This example shows how to remove gyroscope bias from an IMU using `imufilter`.

Use `kinematicTrajectory` to create a trajectory with two parts. The first part has a constant angular velocity about the *y*- and *z*-axes. The second part has a varying angular velocity in all three axes.

```
duration = 60*8;
fs = 20;
numSamples = duration * fs;
rng('default') % Seed the RNG to reproduce noisy sensor measurements.

initialAngVel = [0,0.5,0.25];
finalAngVel = [-0.2,0.6,0.5];
constantAngVel = repmat(initialAngVel,floor(numSamples/2),1);
varyingAngVel = [linspace(initialAngVel(1), finalAngVel(1), ceil(numSamples/2)).', ...
    linspace(initialAngVel(2), finalAngVel(2), ceil(numSamples/2)).', ...
    linspace(initialAngVel(3), finalAngVel(3), ceil(numSamples/2)).'];

angVelBody = [constantAngVel; varyingAngVel];
accBody = zeros(numSamples,3);

traj = kinematicTrajectory('SampleRate',fs);

[~,qNED,~,accNED,angVelNED] = traj(accBody,angVelBody);
```

Create an `imuSensor` System object™, `IMU`, with a nonideal gyroscope. Call `IMU` with the ground-truth acceleration, angular velocity, and orientation.

```
IMU = imuSensor('accel-gyro', ...
    'Gyroscope',gyroparams('RandomWalk',0.003,'ConstantBias',0.3), ...
    'SampleRate',fs);

[accelReadings, gyroReadingsBody] = IMU(accNED,angVelNED,qNED);
```

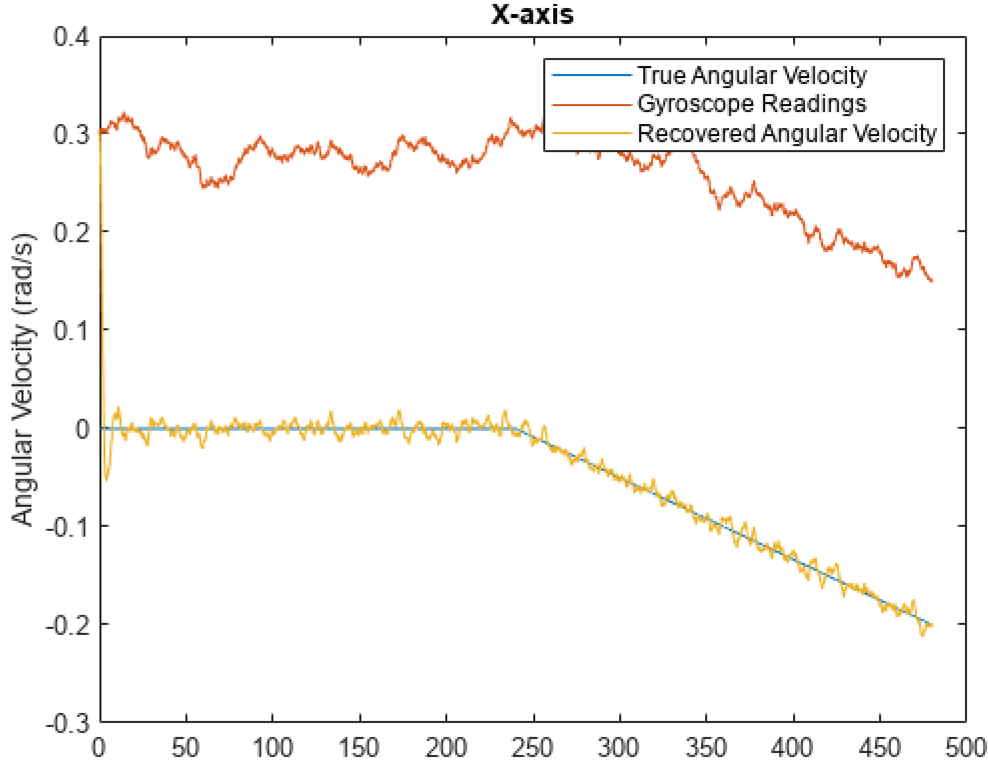
Create an `imufilter` System object, `fuse`. Call `fuse` with the modeled accelerometer readings and gyroscope readings.

```
fuse = imufilter('SampleRate',fs, 'GyroscopeDriftNoise', 1e-6);

[~,angVelBodyRecovered] = fuse(accelReadings,gyroReadingsBody);
```

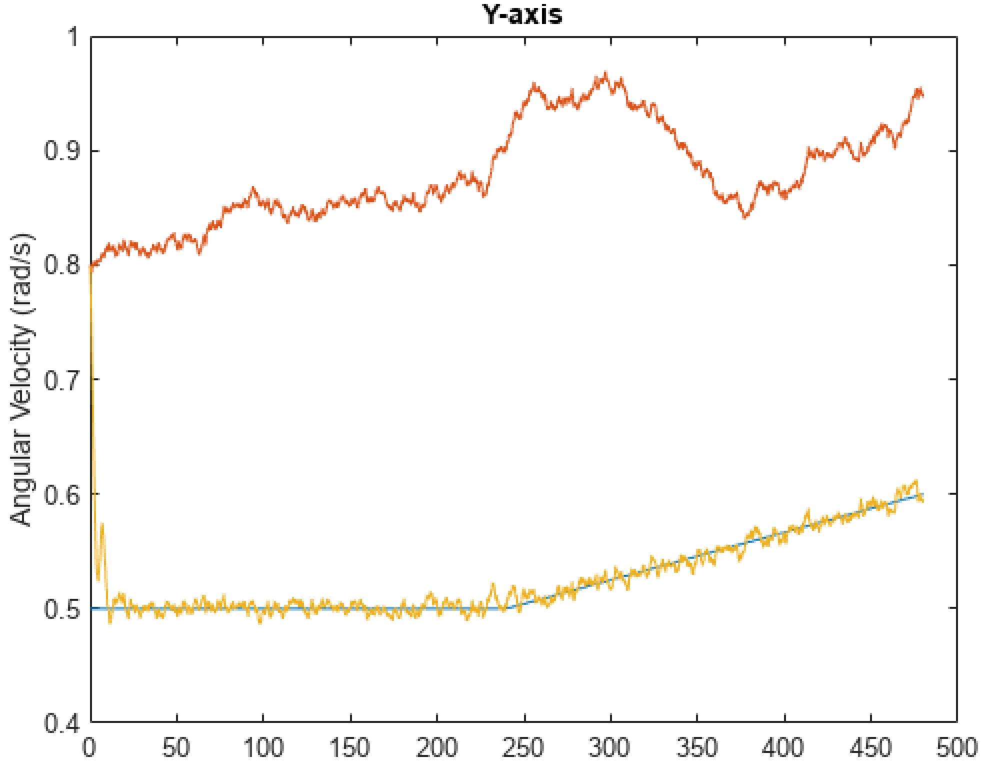
Plot the ground-truth angular velocity, the gyroscope readings, and the recovered angular velocity for each axis.

The angular velocity returned from the `imufilter` compensates for the effect of the gyroscope bias over time and converges to the true angular velocity.

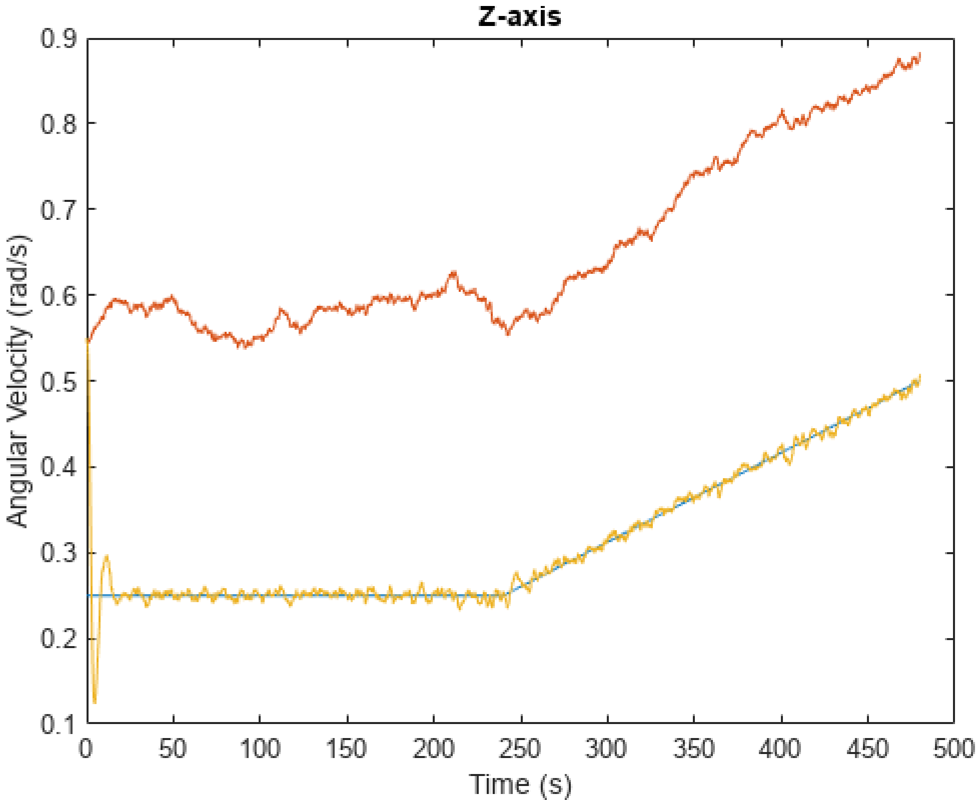
```
time = (0:numSamples-1)'/fs;

figure(1)
plot(time,angVelBody(:,1), ...
     time,gyroReadingsBody(:,1), ...
     time,angVelBodyRecovered(:,1))
title('X-axis')
legend('True Angular Velocity', ...
       'Gyroscope Readings', ...
       'Recovered Angular Velocity')
ylabel('Angular Velocity (rad/s)')
```




```
figure(2)
plot(time,angVelBody(:,2), ...
     time,gyroReadingsBody(:,2), ...
     time,angVelBodyRecovered(:,2))
title('Y-axis')
ylabel('Angular Velocity (rad/s)')
```




```
figure(3)
plot(time,angVelBody(:,3), ...
     time,gyroReadingsBody(:,3), ...
     time,angVelBodyRecovered(:,3))
title('Z-axis')
ylabel('Angular Velocity (rad/s)')
xlabel('Time (s)')
```




## Algorithms

*Note: The following algorithm only applies to an NED reference frame.*

The `imufilter` uses the six-axis Kalman filter structure described in [1]. The algorithm attempts to track the errors in orientation, gyroscope offset, and linear acceleration to output the final orientation and angular velocity. Instead of tracking the orientation directly, the indirect Kalman filter models the error process, $x$, with a recursive update:

$$x_k = \begin{bmatrix} \theta_k \\ b_k \\ a_k \end{bmatrix} = F_k \begin{bmatrix} \theta_{k-1} \\ b_{k-1} \\ a_{k-1} \end{bmatrix} + w_k$$

where $x_k$ is a 9-by-1 vector consisting of:

- $\theta_k$ -- 3-by-1 orientation error vector, in degrees, at time $k$
- $b_k$ -- 3-by-1 gyroscope zero angular rate bias vector, in deg/s, at time $k$
- $a_k$ -- 3-by-1 acceleration error vector measured in the sensor frame, in g, at time $k$
- $w_k$ -- 9-by-1 additive noise vector
- $F_k$ -- state transition model

Because $x_k$ is defined as the error process, the *a priori* estimate is always zero, and therefore the state transition model, $F_k$, is zero. This insight results in the following reduction of the standard Kalman equations:

Standard Kalman equations:

$$x_k^- = F_k x_{k-1}^+$$

$$P_k^- = F_k P_{k-1}^+ F_k^T + Q_k$$

$$y_k = z_k - H_k x_k^-$$

$$S_k = R_k + H_k P_k^- H_k^T$$

$$K_k = P_k^- H_k^T (S_k)^{-1}$$

$$x_k^+ = x_k^- + K_k y_k$$

$$P_k^+ = P_k^- - K_k H_k P_k^-$$

Kalman equations used in this algorithm:

$$x_k^- = 0$$

$$P_k^- = Q_k$$

$$y_k = z_k$$

$$S_k = R_k + H_k P_k^- H_k^T$$

$$K_k = P_k^- H_k^T (S_k)^{-1}$$

$$x_k^+ = K_k y_k$$

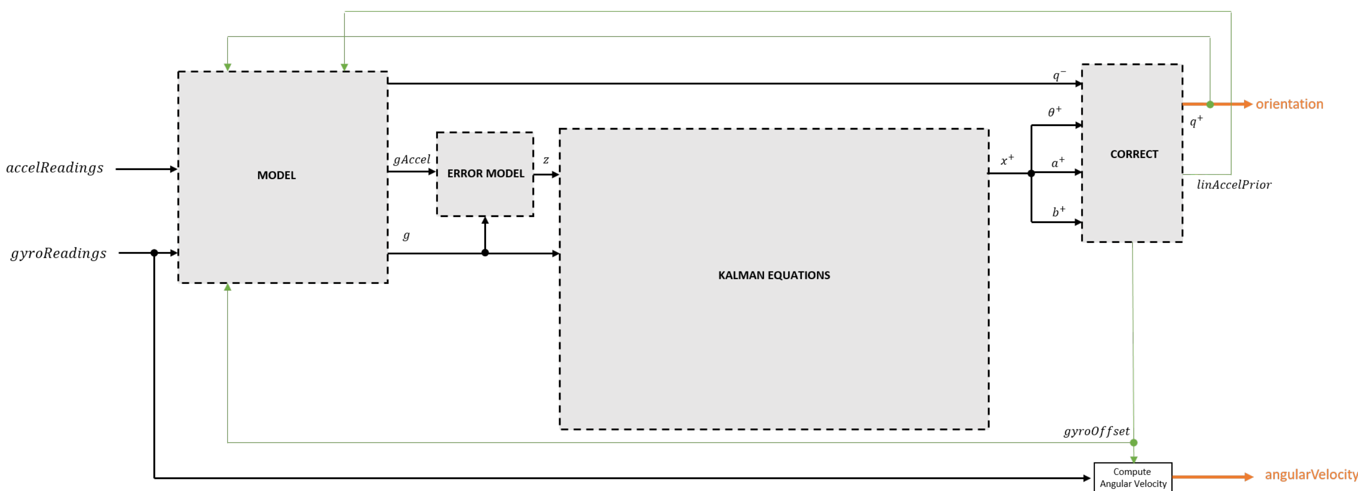
$$P_k^+ = P_k^- - K_k H_k P_k^-$$

where

- $x_k^-$ –– predicted (*a priori*) state estimate; the error process
- $P_k^-$ –– predicted (*a priori*) estimate covariance
- $y_k$ –– innovation
- $S_k$ –– innovation covariance
- $K_k$ –– Kalman gain
- $x_k^+$ –– updated (*a posteriori*) state estimate
- $P_k^+$ –– updated (*a posteriori*) estimate covariance

*k* represents the iteration, the superscript $^+$ represents an *a posteriori* estimate, and the superscript $^-$ represents an *a priori* estimate.

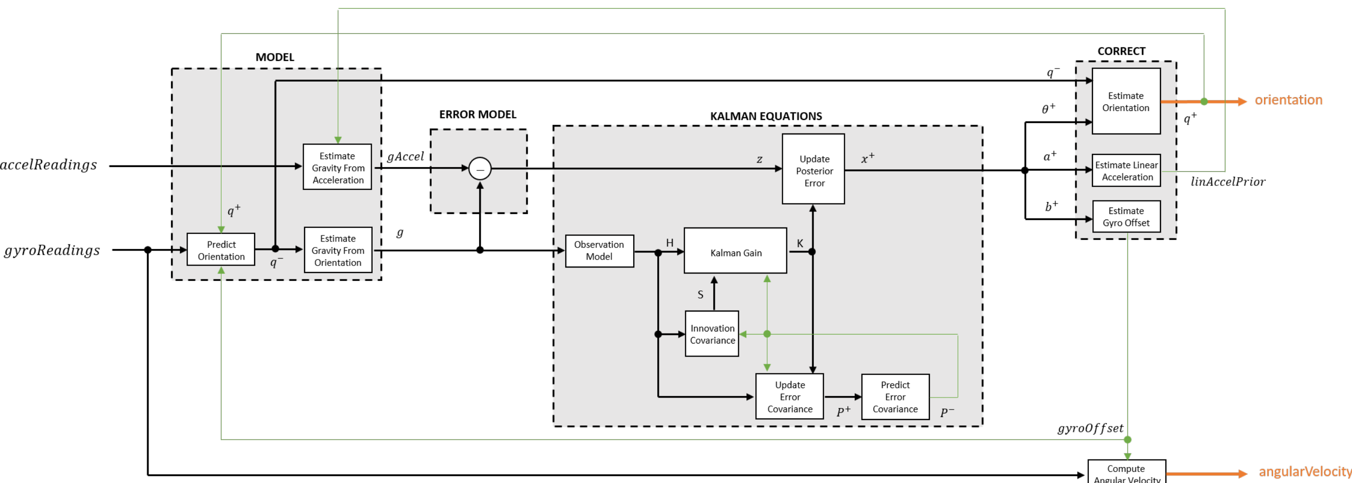
The graphic and following steps describe a single frame-based iteration through the algorithm.




Before the first iteration, the `accelReadings` and `gyroReadings` inputs are chunked into 1-by-3 frames and `DecimationFactor`-by-3 frames, respectively. The algorithm uses the most current accelerometer readings corresponding to the chunk of gyroscope readings.

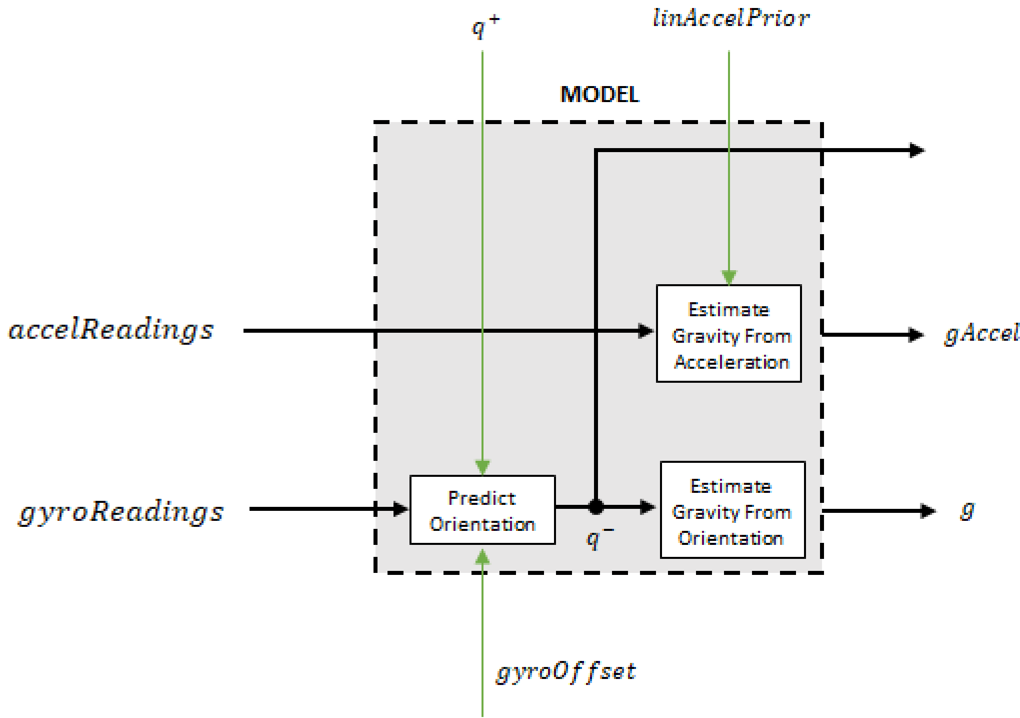
### Detailed Overview

Step through the algorithm for an explanation of each stage of the detailed overview.




### Model

The algorithm models acceleration and angular change as linear processes.




**Predict Orientation**

The orientation for the current frame is predicted by first estimating the angular change from the previous frame:

$$\Delta\varphi_{N\times 3} = \frac{(gyroReadings_{N\times 3} - gyroOffset_{1\times 3})}{fs}$$

where $N$ is the decimation factor specified by the `DecimationFactor` property, and $fs$ is the sample rate specified by the `SampleRate` property.

The angular change is converted into quaternions using the `rotvec` `quaternion` construction syntax:

$$\Delta Q_{N\times 1} = \text{quaternion}(\Delta\varphi_{N\times 3}, 'rotvec')$$

The previous orientation estimate is updated by rotating it by $\Delta Q$:

$$q^-_{1\times 1} = \left(q^+_{1\times 1}\right)\left(\prod_{n=1}^{N} \Delta Q_n\right)$$

During the first iteration, the orientation estimate, $q^-$, is initialized by `ecompass` with an assumption that the $x$-axis points north.

**Estimate Gravity from Orientation**

The gravity vector is interpreted as the third column of the quaternion, $q^-$, in rotation matrix form:

$$g_{1\times 3} = (rPrior(:,3))^T$$

See `ecompass` for an explanation of why the third column of *rPrior* can be interpreted as the gravity vector.

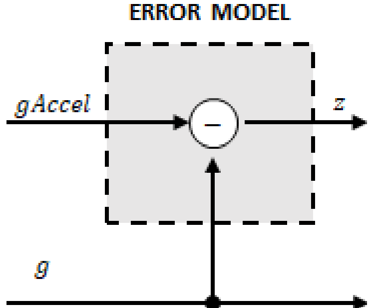
#### Estimate Gravity from Acceleration

A second gravity vector estimation is made by subtracting the decayed linear acceleration estimate of the previous iteration from the accelerometer readings:

$$gAccel_{1\times 3} = accelReadings_{1\times 3} - linAccelprior_{1\times 3}$$

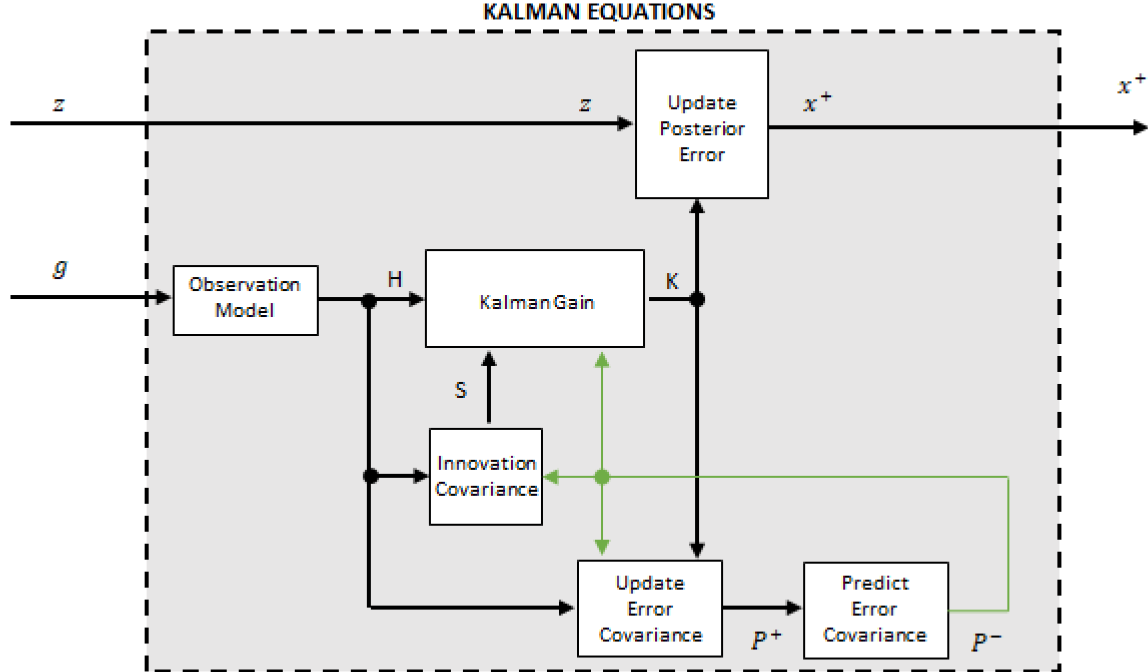
### Error Model

The error model is the difference between the gravity estimate from the accelerometer readings and the gravity estimate from the gyroscope readings: $z = g - gAccel$.




### Kalman Equations

The Kalman equations use the gravity estimate derived from the gyroscope readings, $g$, and the observation of the error process, $z$, to update the Kalman gain and intermediary covariance matrices. The Kalman gain is applied to the error signal, $z$, to output an *a posteriori* error estimate, $x^+$.




**Observation Model**

The observation model maps the 1-by-3 observed state, $g$, into the 3-by-9 true state, $H$.

The observation model is constructed as:

$$H_{3\times 9} = \begin{bmatrix} 0 & g_z & -g_y & 0 & -\kappa g_z & \kappa g_y & 1 & 0 & 0 \\ -g_z & 0 & g_x & \kappa g_z & 0 & -\kappa g_x & 0 & 1 & 0 \\ g_y & -g_x & 0 & -\kappa g_y & \kappa g_x & 0 & 0 & 0 & 1 \end{bmatrix}$$

where $g_x$, $g_y$, and $g_z$ are the $x$-, $y$-, and $z$-elements of the gravity vector estimated from the orientation, respectively. $\kappa$ is a constant determined by the SampleRate and DecimationFactor properties: $\kappa$ = `DecimationFactor/SampleRate`.

See sections 7.3 and 7.4 of [1] for a derivation of the observation model.

**Innovation Covariance**

The innovation covariance is a 3-by-3 matrix used to track the variability in the measurements. The innovation covariance matrix is calculated as:

$$S_{3x3} = R_{3x3} + (H_{3x9})\left(P_{9x9}^{-}\right)(H_{3x9})^T$$

where

- $H$ is the observation model matrix
- $P^-$ is the predicted (*a priori*) estimate of the covariance of the observation model calculated in the previous iteration

- $R$ is the covariance of the observation model noise, calculated as:

  $$R_{3 \times 3} = (\lambda + \xi + \kappa(\beta + \eta))\begin{bmatrix}1 & 0 & 0\\0 & 1 & 0\\0 & 0 & 1\end{bmatrix}.$$

  The following properties define the observation model noise variance:

  - $\kappa$ –– (DecimationFactor/SampleRate)$^2$
  - $\beta$ –– GyroscopeDriftNoise
  - $\eta$ –– GyroscopeNoise
  - $\lambda$ –– AccelerometerNoise
  - $\xi$ –– LinearAccelerationNoise

#### Update Error Estimate Covariance

The error estimate covariance is a 9-by-9 matrix used to track the variability in the state.

The error estimate covariance matrix is updated as:

$$P^{+}_{9 \times 9} = P^{-}_{9 \times 9} - (K_{9 \times 3})(H_{3 \times 9})\left(P^{-}_{9 \times 9}\right)$$

where $K$ is the Kalman gain, $H$ is the measurement matrix, and $P^{-}$ is the error estimate covariance calculated during the previous iteration.

#### Predict Error Estimate Covariance

The error estimate covariance is a 9-by-9 matrix used to track the variability in the state. The *a priori* error estimate covariance, $P^{-}$, is set to the process noise covariance, $Q$, determined during the previous iteration. $Q$ is calculated as a function of the *a posteriori* error estimate covariance, $P^{+}$. When calculating $Q$, the cross-correlation terms are assumed to be negligible compared to the autocorrelation terms, and are set to zero:

$Q =$

$$\begin{bmatrix} P^+(1)+\kappa^2\left(P^+(31)+\beta+\eta\right) & 0 & 0 & -\kappa\left(P^+(31)+\beta\right) & 0 \\ 0 & P^+(11)+\kappa^2\left(P^+(41)+\beta+\eta\right) & 0 & 0 & -\kappa(P^+(4 \\ 0 & 0 & P^+(21)+\kappa^2\left(P^+(51)+\beta+\eta\right) & 0 & 0 \\ -\kappa\left(P^+(31)+\beta\right) & 0 & 0 & P^+(31)+\beta & 0 \\ 0 & -\kappa(P^+(41)+\beta) & 0 & 0 & P^+(41 \\ 0 & 0 & -\kappa(P^+(51)+\beta) & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

where

- $P^+$ -- is the updated (*a posteriori*) error estimate covariance
- $\kappa$ -- DecimationFactor/SampleRate
- $\beta$ -- GyroscopeDriftNoise
- $\eta$ -- GyroscopeNoise
- $\nu$ -- LinearAcclerationDecayFactor

- $\xi$ –– LinearAccelerationNoise

See section 10.1 of [1] for a derivation of the terms of the process error matrix.

**Kalman Gain**

The Kalman gain matrix is a 9-by-3 matrix used to weight the innovation. In this algorithm, the innovation is interpreted as the error process, $z$.

The Kalman gain matrix is constructed as:

$$K_{9\times3} = \left(P^{-}_{9\times9}\right)\left(H_{3\times9}\right)^{T}\left(\left(S_{3\times3}\right)^{T}\right)^{-1}$$

where

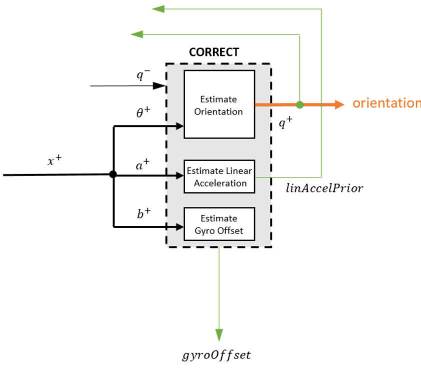
- $P^{-}$ –– predicted error covariance
- $H$ –– observation model
- $S$ –– innovation covariance

**Update a Posteriori Error**

The *a posterior* error estimate is determined by combining the Kalman gain matrix with the error in the gravity vector estimations:

$$x_{9\times1} = \left(K_{9\times3}\right)\left(z_{1\times3}\right)^{T}$$

## Correct




**Estimate Orientation**

The orientation estimate is updated by multiplying the previous estimation by the error:

$$q^{+} = \left(q^{-}\right)\left(\theta^{+}\right)$$

**Estimate Linear Acceleration**

The linear acceleration estimation is updated by decaying the linear acceleration estimation from the previous iteration and subtracting the error:

$$linAccelPrior = \left(linAccelPrior_{k-1}\right)\nu - a^{+}$$

where

- $\nu$ –– LinearAcclerationDecayFactor

#### Estimate Gyroscope Offset

The gyroscope offset estimation is updated by subtracting the gyroscope offset error from the gyroscope offset from the previous iteration:

$$gyroOffset = gyroOffset_{k-1} - b^{+}$$

#### Compute Angular Velocity

To estimate angular velocity, the frame of `gyroReadings` are averaged and the gyroscope offset computed in the previous iteration is subtracted:

$$angularVelocity_{1 \times 3} = \frac{\sum gyroReadings_{N \times 3}}{N} - gyroOffset_{1 \times 3}$$

where $N$ is the decimation factor specified by the `DecimationFactor` property.

The gyroscope offset estimation is initialized to zeros for the first iteration.

# Version History

**Introduced in R2018b**

## References

[1] Open Source Sensor Fusion. https://github.com/memsindustrygroup/Open-Source-Sensor-Fusion/tree/master/docs

[2] Roetenberg, D., H.J. Luinge, C.T.M. Baten, and P.H. Veltink. "Compensation of Magnetic Disturbances Improves Inertial and Magnetic Sensing of Human Body Segment Orientation." *IEEE Transactions on Neural Systems and Rehabilitation Engineering*. Vol. 13. Issue 3, 2005, pp. 395-405.

## Extended Capabilities

#### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

Usage notes and limitations:

See “System Objects in MATLAB Code Generation” (MATLAB Coder).

## See Also

`ecompass` | `imuSensor` | `ahrsfilter` | `gpsSensor`

# tune

Tune `imufilter` parameters to reduce estimation error

## Syntax

```
tune(filter,sensorData,groundTruth)
tune( ___ ,config)
```

## Description

`tune(filter,sensorData,groundTruth)` adjusts the properties of the `imufilter` filter object, `filter`, to reduce the root-mean-squared (RMS) quaternion distance error between the fused sensor data and the ground truth. The function fuses the sensor data to estimate the orientation, which is compared to the orientation in the ground truth. The function uses the property values in the filter as the initial estimate for the optimization algorithm.

`tune( ___ ,config)` specifies the tuning configuration based on a `tunerconfig` object, `config`.

## Examples

### Tune `imufilter` to Optimize Orientation Estimate

Load recorded sensor data and ground truth data.

```
ld = load('imufilterTuneData.mat');
qTrue = ld.groundTruth.Orientation; % true orientation
```

Create an `imufilter` object and fuse the filter with the sensor data.

```
fuse = imufilter;
qEstUntuned = fuse(ld.sensorData.Accelerometer, ...
    ld.sensorData.Gyroscope);
```

Create a `tunerconfig` object and tune the imufilter to improve the orientation estimate.

```
cfg = tunerconfig('imufilter');
tune(fuse, ld.sensorData, ld.groundTruth, cfg);
```

```
    Iteration    Parameter                       Metric
    _________    _________                       ______
    1            AccelerometerNoise              0.1149
    1            GyroscopeNoise                  0.1146
    1            GyroscopeDriftNoise             0.1146
    1            LinearAccelerationNoise         0.1122
    1            LinearAccelerationDecayFactor   0.1103
    2            AccelerometerNoise              0.1102
    2            GyroscopeNoise                  0.1098
    2            GyroscopeDriftNoise             0.1098
    2            LinearAccelerationNoise         0.1070
    2            LinearAccelerationDecayFactor   0.1053
    3            AccelerometerNoise              0.1053
```

```
3            GyroscopeNoise                    0.1048
3            GyroscopeDriftNoise               0.1048
3            LinearAccelerationNoise           0.1016
3            LinearAccelerationDecayFactor     0.1002
4            AccelerometerNoise                0.1001
4            GyroscopeNoise                    0.0996
4            GyroscopeDriftNoise               0.0996
4            LinearAccelerationNoise           0.0962
4            LinearAccelerationDecayFactor     0.0950
5            AccelerometerNoise                0.0950
5            GyroscopeNoise                    0.0943
5            GyroscopeDriftNoise               0.0943
5            LinearAccelerationNoise           0.0910
5            LinearAccelerationDecayFactor     0.0901
6            AccelerometerNoise                0.0900
6            GyroscopeNoise                    0.0893
6            GyroscopeDriftNoise               0.0893
6            LinearAccelerationNoise           0.0862
6            LinearAccelerationDecayFactor     0.0855
7            AccelerometerNoise                0.0855
7            GyroscopeNoise                    0.0848
7            GyroscopeDriftNoise               0.0848
7            LinearAccelerationNoise           0.0822
7            LinearAccelerationDecayFactor     0.0818
8            AccelerometerNoise                0.0817
8            GyroscopeNoise                    0.0811
8            GyroscopeDriftNoise               0.0811
8            LinearAccelerationNoise           0.0791
8            LinearAccelerationDecayFactor     0.0789
9            AccelerometerNoise                0.0788
9            GyroscopeNoise                    0.0782
9            GyroscopeDriftNoise               0.0782
9            LinearAccelerationNoise           0.0769
9            LinearAccelerationDecayFactor     0.0768
10           AccelerometerNoise                0.0768
10           GyroscopeNoise                    0.0762
10           GyroscopeDriftNoise               0.0762
10           LinearAccelerationNoise           0.0754
10           LinearAccelerationDecayFactor     0.0753
11           AccelerometerNoise                0.0753
11           GyroscopeNoise                    0.0747
11           GyroscopeDriftNoise               0.0747
11           LinearAccelerationNoise           0.0741
11           LinearAccelerationDecayFactor     0.0740
12           AccelerometerNoise                0.0740
12           GyroscopeNoise                    0.0734
12           GyroscopeDriftNoise               0.0734
12           LinearAccelerationNoise           0.0728
12           LinearAccelerationDecayFactor     0.0728
13           AccelerometerNoise                0.0728
13           GyroscopeNoise                    0.0721
13           GyroscopeDriftNoise               0.0721
13           LinearAccelerationNoise           0.0715
13           LinearAccelerationDecayFactor     0.0715
14           AccelerometerNoise                0.0715
14           GyroscopeNoise                    0.0706
14           GyroscopeDriftNoise               0.0706
14           LinearAccelerationNoise           0.0700
```

```
    14          LinearAccelerationDecayFactor    0.0700
    15          AccelerometerNoise               0.0700
    15          GyroscopeNoise                   0.0690
    15          GyroscopeDriftNoise              0.0690
    15          LinearAccelerationNoise          0.0684
    15          LinearAccelerationDecayFactor    0.0684
    16          AccelerometerNoise               0.0684
    16          GyroscopeNoise                   0.0672
    16          GyroscopeDriftNoise              0.0672
    16          LinearAccelerationNoise          0.0668
    16          LinearAccelerationDecayFactor    0.0667
    17          AccelerometerNoise               0.0667
    17          GyroscopeNoise                   0.0655
    17          GyroscopeDriftNoise              0.0655
    17          LinearAccelerationNoise          0.0654
    17          LinearAccelerationDecayFactor    0.0654
    18          AccelerometerNoise               0.0654
    18          GyroscopeNoise                   0.0641
    18          GyroscopeDriftNoise              0.0641
    18          LinearAccelerationNoise          0.0640
    18          LinearAccelerationDecayFactor    0.0639
    19          AccelerometerNoise               0.0639
    19          GyroscopeNoise                   0.0627
    19          GyroscopeDriftNoise              0.0627
    19          LinearAccelerationNoise          0.0627
    19          LinearAccelerationDecayFactor    0.0624
    20          AccelerometerNoise               0.0624
    20          GyroscopeNoise                   0.0614
    20          GyroscopeDriftNoise              0.0614
    20          LinearAccelerationNoise          0.0613
    20          LinearAccelerationDecayFactor    0.0613
```

Fuse the sensor data again using the tuned filter.

```
qEstTuned = fuse(ld.sensorData.Accelerometer, ...
    ld.sensorData.Gyroscope);
```

Compare the tuned and untuned filter RMS error performances.

```
dUntuned = rad2deg(dist(qEstUntuned, qTrue));
dTuned = rad2deg(dist(qEstTuned, qTrue));
rmsUntuned = sqrt(mean(dUntuned.^2))
```

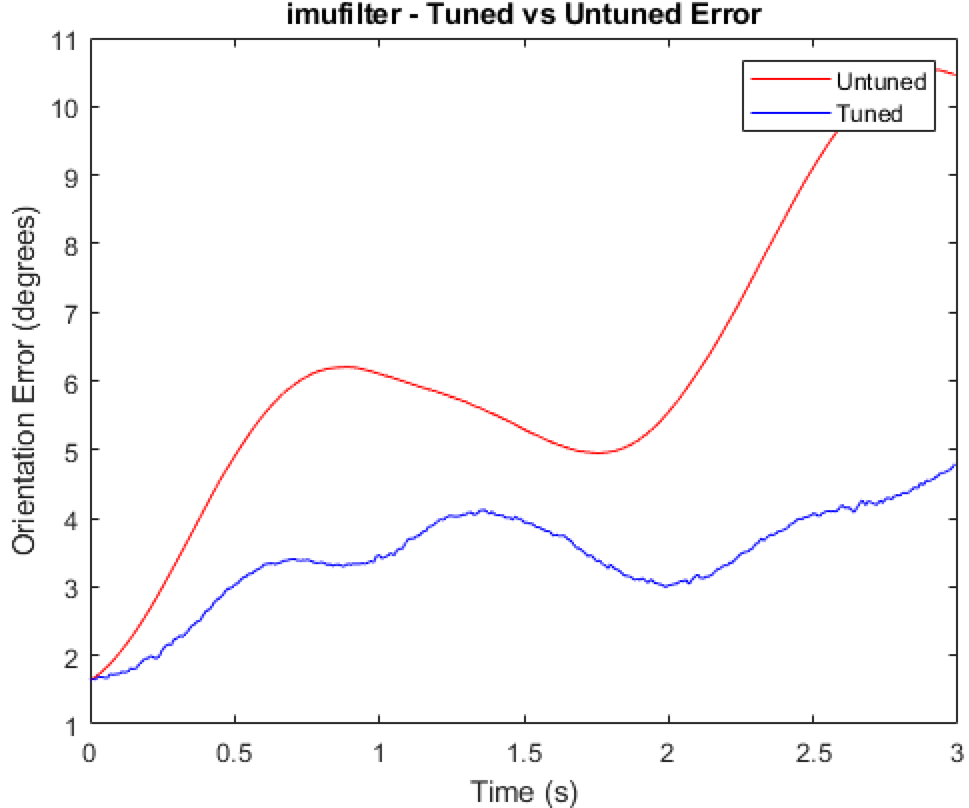
```
rmsUntuned = 6.5864
```

```
rmsTuned = sqrt(mean(dTuned.^2))
```

```
rmsTuned = 3.5098
```

Visualize the results.

```
N = numel(dUntuned);
t = (0:N-1)./ fuse.SampleRate;
plot(t, dUntuned, 'r', t, dTuned, 'b');
legend('Untuned', 'Tuned');
title('imufilter - Tuned vs Untuned Error')
xlabel('Time (s)');
ylabel('Orientation Error (degrees)');
```




## Input Arguments

**`filter` — Filter object**
`imufilter` object

Filter object, specified as an `imufilter` object.

**`sensorData` — Sensor data**
`table`

Sensor data, specified as a `table`. In each row, the sensor data is specified as:

- `Accelerometer` — Accelerometer data, specified as a 1-by-3 vector of scalars in $m^2/s$.
- `Gyroscope` — Gyroscope data, specified as a 1-by-3 vector of scalars in rad/s.

If you set the `Cost` property of the tuner configuration input, `config`, to `Custom`, then you can use other data types for the `sensorData` input based on your choice.

**`groundTruth` — Ground truth data**
`table`

Ground truth data, specified as a `table`. The table has only one column of `Orientation` data. In each row, the orientation is specified as a `quaternion` object or a 3-by-3 rotation matrix.

The function processes each row of the `sensorData` and `groundTruth` tables sequentially to calculate the state estimate and RMS error from the ground truth. Each row of the `sensorData` and the `groundTruth` tables must correspond to each other.

If you set the `Cost` property of the tuner configuration input, `config`, to `Custom`, then you can use other data types for the `groundTruth` input based on your choice.

**`config` — Tuner configuration**
`tunerconfig` object

Tuner configuration, specified as a `tunerconfig` object.

# Version History

**Introduced in R2020b**

## References

[1] Abbeel, P., Coates, A., Montemerlo, M., Ng, A.Y. and Thrun, S. Discriminative Training of Kalman Filters. In *Robotics: Science and systems*, Vol. 2, pp. 1, 2005.

# imuSensor

IMU simulation model

## Description

The `imuSensor` System object models receiving data from an inertial measurement unit (IMU). You can specify the reference frame of the block inputs as the `NED` (North-East-Down) or `ENU` (East-North-Up) frame by using the `ReferenceFrame` argument.

To model an IMU:

1. Create the `imuSensor` object and set its properties.
2. Call the object with arguments, as if it were a function.

To learn more about how System objects work, see What Are System Objects?

# Creation

## Syntax

```
IMU = imuSensor
IMU = imuSensor('accel-gyro')
IMU = imuSensor('accel-mag')
IMU = imuSensor('accel-gyro-mag')
IMU = imuSensor( ___ ,'ReferenceFrame',RF)
IMU = imuSensor( ___ ,Name,Value)
```

### Description

`IMU = imuSensor` returns a System object, `IMU`, that computes an inertial measurement unit reading based on an inertial input signal. `IMU` has an ideal accelerometer and gyroscope.

`IMU = imuSensor('accel-gyro')` returns an `imuSensor` System object with an ideal accelerometer and gyroscope. `imuSensor` and `imuSensor('accel-gyro')` are equivalent creation syntaxes.

`IMU = imuSensor('accel-mag')` returns an `imuSensor` System object with an ideal accelerometer and magnetometer.

`IMU = imuSensor('accel-gyro-mag')` returns an `imuSensor` System object with an ideal accelerometer, gyroscope, and magnetometer.

`IMU = imuSensor( ___ ,'ReferenceFrame',RF)` returns an `imuSensor` System object that computes an inertial measurement unit reading relative to the reference frame `RF`. Specify `RF` as `'NED'` (North-East-Down) or `'ENU'` (East-North-Up). The default value is `'NED'`.

**Note**

- If you choose the NED reference frame, specify the sensor inputs in the NED reference frame. Additionally, the sensor models the gravitational acceleration as [0 0 9.81] m/s$^2$.
- If you choose the ENU reference frame, specify the sensor inputs in the ENU reference frame. Additionally, the sensor models the gravitational acceleration as [0 0 −9.81] m/s$^2$.

---

`IMU = imuSensor( ___ ,Name,Value)` sets each property `Name` to the specified `Value`. Unspecified properties have default values. This syntax can be used in combination with any of the previous input arguments.

## Properties

Unless otherwise indicated, properties are *nontunable*, which means you cannot change their values after calling the object. Objects lock when you call them, and the `release` function unlocks them.

If a property is *tunable*, you can change its value at any time.

For more information on changing property values, see System Design in MATLAB Using System Objects.

**`IMUType` — Type of inertial measurement unit**
`'accel-gyro'` (default) | `'accel-mag'` | `'accel-gyro-mag'`

Type of inertial measurement unit, specified as a `'accel-gyro'`, `'accel-mag'`, or `'accel-gyro-mag'`.

The type of inertial measurement unit specifies which sensor readings to model:

- `'accel-gyro'` –– Accelerometer and gyroscope
- `'accel-mag'` –– Accelerometer and magnetometer
- `'accel-gyro-mag'` –– Accelerometer, gyroscope, and magnetometer

You can specify `IMUType` as a value-only argument during creation or as a `Name,Value` pair.

Data Types: `char` | `string`

**`SampleRate` — Sample rate of sensor (Hz)**
`100` (default) | positive scalar

Sample rate of the sensor model in Hz, specified as a positive scalar.

Data Types: `single` | `double`

**`Temperature` — Temperature of IMU (°C)**
`25` (default) | real scalar

Operating temperature of the IMU in degrees Celsius, specified as a real scalar.

When the object calculates temperature scale factors and environmental drift noises, 25 °C is used as the nominal temperature.

**Tunable:** Yes

Data Types: `single` | `double`

**MagneticField — Magnetic field vector in local navigation coordinate system (µT)**
[27.5550 -2.4169 -16.0849] (default) | real scalar

Magnetic field vector in microtesla, specified as a three-element row vector in the local navigation coordinate system.

The default magnetic field corresponds to the magnetic field at latitude zero, longitude zero, and altitude zero.

**Tunable:** Yes

Data Types: single | double

**Accelerometer — Accelerometer sensor parameters**
accelparams object (default)

Accelerometer sensor parameters, specified by an accelparams object.

**Tunable:** Yes

**Gyroscope — Gyroscope sensor parameters**
gyroparams object (default)

Gyroscope sensor parameters, specified by a gyroparams object.

**Tunable:** Yes

**Magnetometer — Magnetometer sensor parameters**
magparams object (default)

Magnetometer sensor parameters, specified by a magparams object.

**Tunable:** Yes

**RandomStream — Random number source**
'Global stream' (default) | 'mt19937ar with seed'

Random number source, specified as a character vector or string:

- 'Global stream' –- Random numbers are generated using the current global random number stream.
- 'mt19937ar with seed' –- Random numbers are generated using the mt19937ar algorithm with the seed specified by the Seed property.

Data Types: char | string

**Seed — Initial seed**
67 (default) | nonnegative integer scalar

Initial seed of an mt19937ar random number generator algorithm, specified as a real, nonnegative integer scalar.

**Dependencies**

To enable this property, set RandomStream to 'mt19937ar with seed'.

Data Types: single | double | int8 | int16 | int32 | int64 | uint8 | uint16 | uint32 | uint64

## Usage

## Syntax

```
[accelReadings,gyroReadings] = IMU(acc,angVel)
[accelReadings,gyroReadings] = IMU(acc,angVel,orientation)

[accelReadings,magReadings] = IMU(acc,angVel)
[accelReadings,magReadings] = IMU(acc,angVel,orientation)

[accelReadings,gyroReadings,magReadings] = IMU(acc,angVel)
[accelReadings,gyroReadings,magReadings] = IMU(acc,angVel,orientation)
```

### Description

`[accelReadings,gyroReadings] = IMU(acc,angVel)` generates accelerometer and gyroscope readings from the acceleration and angular velocity inputs.

This syntax is only valid if `IMUType` is set to `'accel-gyro'` or `'accel-gyro-mag'`.

`[accelReadings,gyroReadings] = IMU(acc,angVel,orientation)` generates accelerometer and gyroscope readings from the acceleration, angular velocity, and orientation inputs.

This syntax is only valid if `IMUType` is set to `'accel-gyro'` or `'accel-gyro-mag'`.

`[accelReadings,magReadings] = IMU(acc,angVel)` generates accelerometer and magnetometer readings from the acceleration and angular velocity inputs.

This syntax is only valid if `IMUType` is set to `'accel-mag'`.

`[accelReadings,magReadings] = IMU(acc,angVel,orientation)` generates accelerometer and magnetometer readings from the acceleration, angular velocity, and orientation inputs.

This syntax is only valid if `IMUType` is set to `'accel-mag'`.

`[accelReadings,gyroReadings,magReadings] = IMU(acc,angVel)` generates accelerometer, gyroscope, and magnetometer readings from the acceleration and angular velocity inputs.

This syntax is only valid if `IMUType` is set to `'accel-gyro-mag'`.

`[accelReadings,gyroReadings,magReadings] = IMU(acc,angVel,orientation)` generates accelerometer, gyroscope, and magnetometer readings from the acceleration, angular velocity, and orientation inputs.

This syntax is only valid if `IMUType` is set to `'accel-gyro-mag'`.

### Input Arguments

**acc — Acceleration of IMU in local navigation coordinate system (m/s$^2$)**
*N*-by-3 matrix

Acceleration of the IMU in the local navigation coordinate system, specified as a real, finite *N*-by-3 array in meters per second squared. *N* is the number of samples in the current frame. Do not include the gravitational acceleration in this input since the sensor models gravitational acceleration by default.

To specify the orientation of the IMU sensor body frame with respect to the local navigation frame, use the `orientation` input argument.

Data Types: `single` | `double`

**`angVel` — Angular velocity of IMU in local navigation coordinate system (rad/s)**
*N*-by-3 matrix

Angular velocity of the IMU in the local navigation coordinate system, specified as a real, finite *N*-by-3 array in radians per second. *N* is the number of samples in the current frame. To specify the orientation of the IMU sensor body frame with respect to the local navigation frame, use the `orientation` input argument.

Data Types: `single` | `double`

**`orientation` — Orientation of IMU in local navigation coordinate system**
*N*-element quaternion column vector | 3-by-3-by-*N*-element rotation matrix

Orientation of the IMU with respect to the local navigation coordinate system, specified as a `quaternion` *N*-element column vector or a 3-by-3-by-*N* rotation matrix. Each `quaternion` or rotation matrix represents a frame rotation from the local navigation coordinate system to the current IMU sensor body coordinate system. *N* is the number of samples in the current frame.

Data Types: `single` | `double` | `quaternion`

**Output Arguments**

**`accelReadings` — Accelerometer measurement of IMU in sensor body coordinate system (m/s$^2$)**
*N*-by-3 matrix

Accelerometer measurement of the IMU in the sensor body coordinate system, specified as a real, finite *N*-by-3 array in meters per second squared. *N* is the number of samples in the current frame.

Data Types: `single` | `double`

**`gyroReadings` — Gyroscope measurement of IMU in sensor body coordinate system (rad/s)**
*N*-by-3 matrix

Gyroscope measurement of the IMU in the sensor body coordinate system, specified as a real, finite *N*-by-3 array in radians per second. *N* is the number of samples in the current frame.

Data Types: `single` | `double`

**`magReadings` — Magnetometer measurement of IMU in sensor body coordinate system (μT)**
*N*-by-3 matrix (default)

Magnetometer measurement of the IMU in the sensor body coordinate system, specified as a real, finite *N*-by-3 array in microtelsa. *N* is the number of samples in the current frame.

Data Types: `single` | `double`

## Object Functions

To use an object function, specify the System object as the first input argument. For example, to release system resources of a System object named `obj`, use this syntax:

```
release(obj)
```

## Specific to `imuSensor`

| | |
|---|---|
| loadparams | Load sensor parameters from JSON file |
| perturbations | Perturbation defined on object |
| perturb | Apply perturbations to object |

## Common to All System Objects

| | |
|---|---|
| step | Run System object algorithm |
| release | Release resources and allow changes to System object property values and input characteristics |
| reset | Reset internal states of System object |

## Examples

### Create Default `imuSensor` System object

The `imuSensor` System object™ enables you to model the data received from an inertial measurement unit consisting of a combination of gyroscope, accelerometer, and magnetometer.

Create a default `imuSensor` object.

```
IMU = imuSensor
```

```
IMU = 
  imuSensor with properties:

          IMUType: 'accel-gyro'
       SampleRate: 100
      Temperature: 25
    Accelerometer: [1x1 accelparams]
        Gyroscope: [1x1 gyroparams]
     RandomStream: 'Global stream'
```

The `imuSensor` object, `IMU`, contains an idealized gyroscope and accelerometer. Use dot notation to view properties of the gyroscope.

```
IMU.Gyroscope
```

```
ans = 
  gyroparams with properties:

    MeasurementRange: Inf              rad/s
          Resolution: 0                (rad/s)/LSB
        ConstantBias: [0 0 0]          rad/s
    AxesMisalignment: [3x3 double]     %

       NoiseDensity: [0 0 0]    (rad/s)/√Hz
    BiasInstability: [0 0 0]    rad/s
         RandomWalk: [0 0 0]    (rad/s)*√Hz

           TemperatureBias: [0 0 0]    (rad/s)/°C
    TemperatureScaleFactor: [0 0 0]    %/°C
```

```
        AccelerationBias: [0 0 0]    (rad/s)/(m/s²)
```

Sensor properties are defined by corresponding parameter objects. For example, the gyroscope model used by the `imuSensor` is defined by an instance of the `gyroparams` class. You can modify properties of the gyroscope model using dot notation. Set the gyroscope measurement range to 4.3 rad/s.

```
IMU.Gyroscope.MeasurementRange = 4.3;
```

You can also set sensor properties to preset parameter objects. Create an `accelparams` object to mimic specific hardware, and then set the IMU `Accelerometer` property to the `accelparams` object. Display the `Accelerometer` property to verify the properties are correctly set.

```
SpecSheet1 = accelparams( ...
    'MeasurementRange',19.62, ...
    'Resolution',0.00059875, ...
    'ConstantBias',0.4905, ...
    'AxesMisalignment',2, ...
    'NoiseDensity',0.003924, ...
    'BiasInstability',0, ...
    'TemperatureBias', [0.34335 0.34335 0.5886], ...
    'TemperatureScaleFactor', 0.02);

IMU.Accelerometer = SpecSheet1;

IMU.Accelerometer
```

```
ans = 
  accelparams with properties:

    MeasurementRange: 19.62                     m/s²
          Resolution: 0.00059875                (m/s²)/LSB
        ConstantBias: [0.4905 0.4905 0.4905]    m/s²
    AxesMisalignment: [3x3 double]              %

       NoiseDensity: [0.003924 0.003924 0.003924]    (m/s²)/√Hz
    BiasInstability: [0 0 0]                         m/s²
         RandomWalk: [0 0 0]                         (m/s²)*√Hz

           TemperatureBias: [0.34335 0.34335 0.5886]    (m/s²)/°C
    TemperatureScaleFactor: [0.02 0.02 0.02]            %/°C
```

### Generate IMU Data from Stationary Input

Use the `imuSensor` System object™ to model receiving data from a stationary ideal IMU containing an accelerometer, gyroscope, and magnetometer.

Create an ideal IMU sensor model that contains an accelerometer, gyroscope, and magnetometer.

```
IMU = imuSensor('accel-gyro-mag')
```

```
IMU = 
  imuSensor with properties:
```

```
         IMUType: 'accel-gyro-mag'
      SampleRate: 100
     Temperature: 25
   MagneticField: [27.5550 -2.4169 -16.0849]
   Accelerometer: [1x1 accelparams]
       Gyroscope: [1x1 gyroparams]
    Magnetometer: [1x1 magparams]
    RandomStream: 'Global stream'
```

Define the ground-truth, underlying motion of the IMU you are modeling. The acceleration and angular velocity are defined relative to the local NED coordinate system.

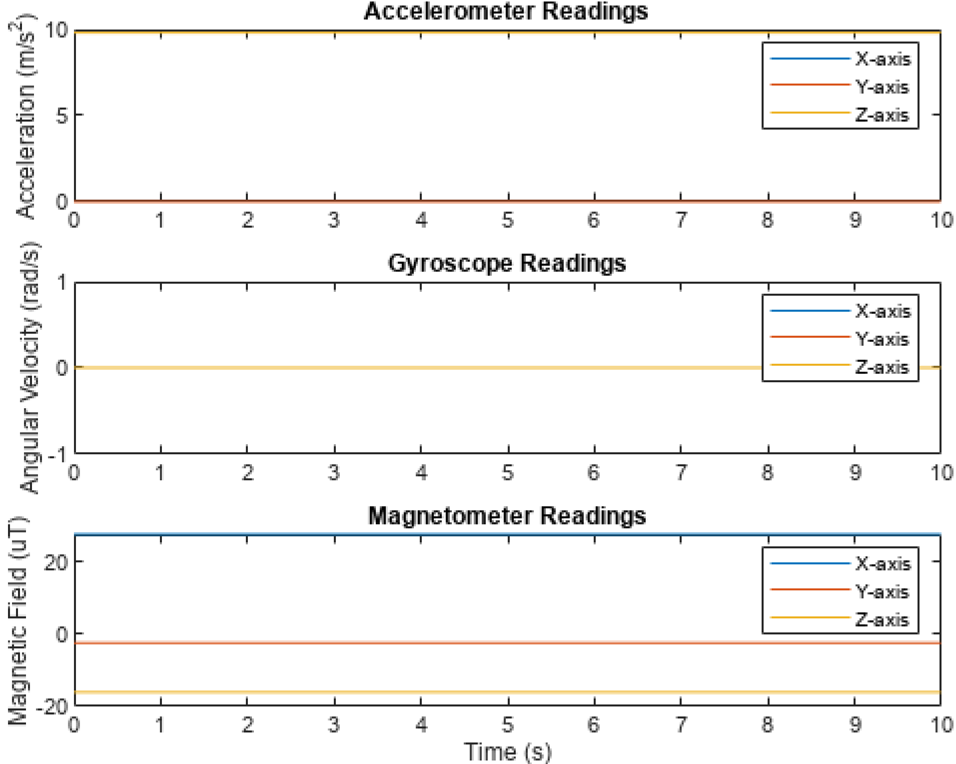
```
numSamples = 1000;
acceleration = zeros(numSamples,3);
angularVelocity = zeros(numSamples,3);
```

Call `IMU` with the ground-truth acceleration and angular velocity. The object outputs accelerometer readings, gyroscope readings, and magnetometer readings, as modeled by the properties of the `imuSensor` System object. The accelerometer readings, gyroscope readings, and magnetometer readings are relative to the IMU sensor body coordinate system.

```
[accelReading,gyroReading,magReading] = IMU(acceleration,angularVelocity);
```

Plot the accelerometer readings, gyroscope readings, and magnetometer readings.

```
t = (0:(numSamples-1))/IMU.SampleRate;
subplot(3,1,1)
plot(t,accelReading)
legend('X-axis','Y-axis','Z-axis')
title('Accelerometer Readings')
ylabel('Acceleration (m/s^2)')

subplot(3,1,2)
plot(t,gyroReading)
legend('X-axis','Y-axis','Z-axis')
title('Gyroscope Readings')
ylabel('Angular Velocity (rad/s)')

subplot(3,1,3)
plot(t,magReading)
legend('X-axis','Y-axis','Z-axis')
title('Magnetometer Readings')
xlabel('Time (s)')
ylabel('Magnetic Field (uT)')
```




Orientation is not specified and the ground-truth motion is stationary, so the IMU sensor body coordinate system and the local NED coordinate system overlap for the entire simulation.

- Accelerometer readings: The *z*-axis of the sensor body corresponds to the Down-axis. The 9.8 m/s^2 acceleration along the *z*-axis is due to gravity.
- Gyroscope readings: The gyroscope readings are zero along each axis, as expected.
- Magnetometer readings: Because the sensor body coordinate system is aligned with the local NED coordinate system, the magnetometer readings correspond to the `MagneticField` property of `imuSensor`. The `MagneticField` property is defined in the local NED coordinate system.

### Model Rotating Six-Axis IMU Data

Use `imuSensor` to model data obtained from a rotating IMU containing an ideal accelerometer and an ideal magnetometer. Use `kinematicTrajectory` to define the ground-truth motion. Fuse the `imuSensor` model output using the `ecompass` function to determine orientation over time.

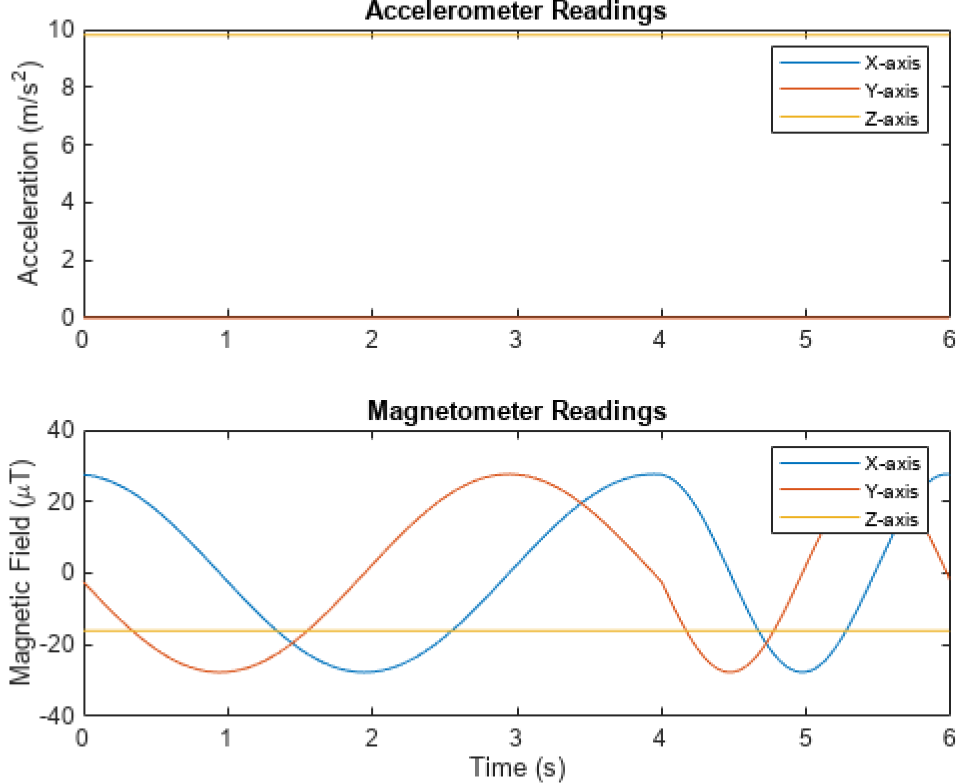
Define the ground-truth motion for a platform that rotates 360 degrees in four seconds, and then another 360 degrees in two seconds. Use `kinematicTrajectory` to output the orientation, acceleration, and angular velocity in the NED coordinate system.

```
fs = 100;
firstLoopNumSamples = fs*4;
secondLoopNumSamples = fs*2;
```

```
totalNumSamples = firstLoopNumSamples + secondLoopNumSamples;

traj = kinematicTrajectory('SampleRate',fs);

accBody = zeros(totalNumSamples,3);
angVelBody = zeros(totalNumSamples,3);
angVelBody(1:firstLoopNumSamples,3) = (2*pi)/4;
angVelBody(firstLoopNumSamples+1:end,3) = (2*pi)/2;

[~,orientationNED,~,accNED,angVelNED] = traj(accBody,angVelBody);
```

Create an `imuSensor` object with an ideal accelerometer and an ideal magnetometer. Call `IMU` with the ground-truth acceleration, angular velocity, and orientation to output accelerometer readings and magnetometer readings. Plot the results.

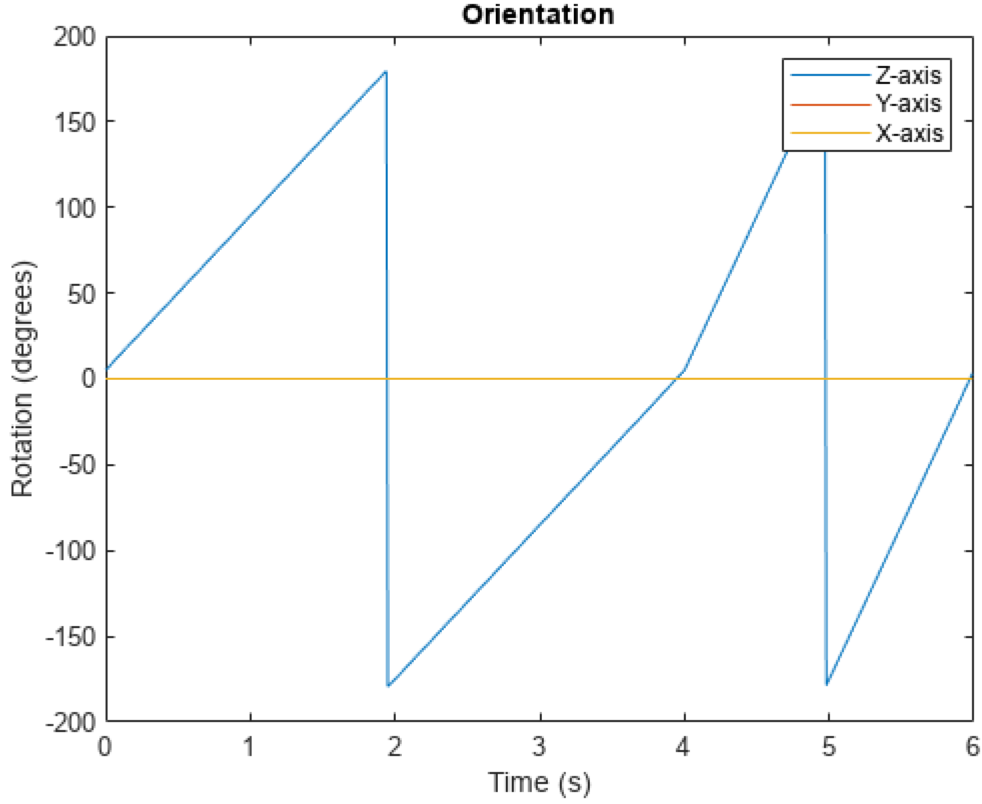
```
IMU = imuSensor('accel-mag','SampleRate',fs);

[accelReadings,magReadings] = IMU(accNED,angVelNED,orientationNED);

figure(1)
t = (0:(totalNumSamples-1))/fs;
subplot(2,1,1)
plot(t,accelReadings)
legend('X-axis','Y-axis','Z-axis')
ylabel('Acceleration (m/s^2)')
title('Accelerometer Readings')

subplot(2,1,2)
plot(t,magReadings)
legend('X-axis','Y-axis','Z-axis')
ylabel('Magnetic Field (\muT)')
xlabel('Time (s)')
title('Magnetometer Readings')
```




The accelerometer readings indicate that the platform has no translation. The magnetometer readings indicate that the platform is rotating around the *z*-axis.

Feed the accelerometer and magnetometer readings into the `ecompass` function to estimate the orientation over time. The `ecompass` function returns orientation in quaternion format. Convert orientation to Euler angles and plot the results. The orientation plot indicates that the platform rotates about the *z*-axis only.

```
orientation = ecompass(accelReadings,magReadings);

orientationEuler = eulerd(orientation,'ZYX','frame');

figure(2)
plot(t,orientationEuler)
legend('Z-axis','Y-axis','X-axis')
xlabel('Time (s)')
ylabel('Rotation (degrees)')
title('Orientation')
```




#### Model Rotating Six-Axis IMU Data with Noise

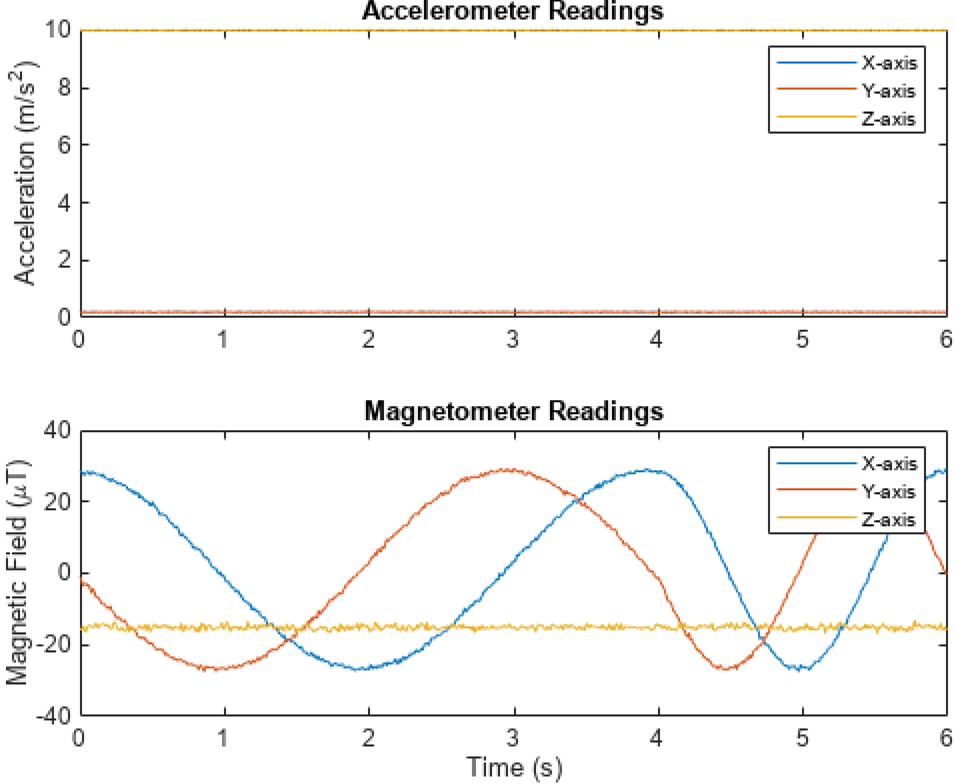
Use `imuSensor` to model data obtained from a rotating IMU containing a realistic accelerometer and a realistic magnetometer. Use `kinematicTrajectory` to define the ground-truth motion. Fuse the `imuSensor` model output using the `ecompass` function to determine orientation over time.

Define the ground-truth motion for a platform that rotates 360 degrees in four seconds, and then another 360 degrees in two seconds. Use `kinematicTrajectory` to output the orientation, acceleration, and angular velocity in the NED coordinate system.

```
fs = 100;
firstLoopNumSamples = fs*4;
secondLoopNumSamples = fs*2;
totalNumSamples = firstLoopNumSamples + secondLoopNumSamples;

traj = kinematicTrajectory('SampleRate',fs);

accBody = zeros(totalNumSamples,3);
angVelBody = zeros(totalNumSamples,3);
angVelBody(1:firstLoopNumSamples,3) = (2*pi)/4;
angVelBody(firstLoopNumSamples+1:end,3) = (2*pi)/2;

[~,orientationNED,~,accNED,angVelNED] = traj(accBody,angVelBody);
```

Create an `imuSensor` object with a realistic accelerometer and a realistic magnetometer. Call `IMU` with the ground-truth acceleration, angular velocity, and orientation to output accelerometer readings and magnetometer readings. Plot the results.

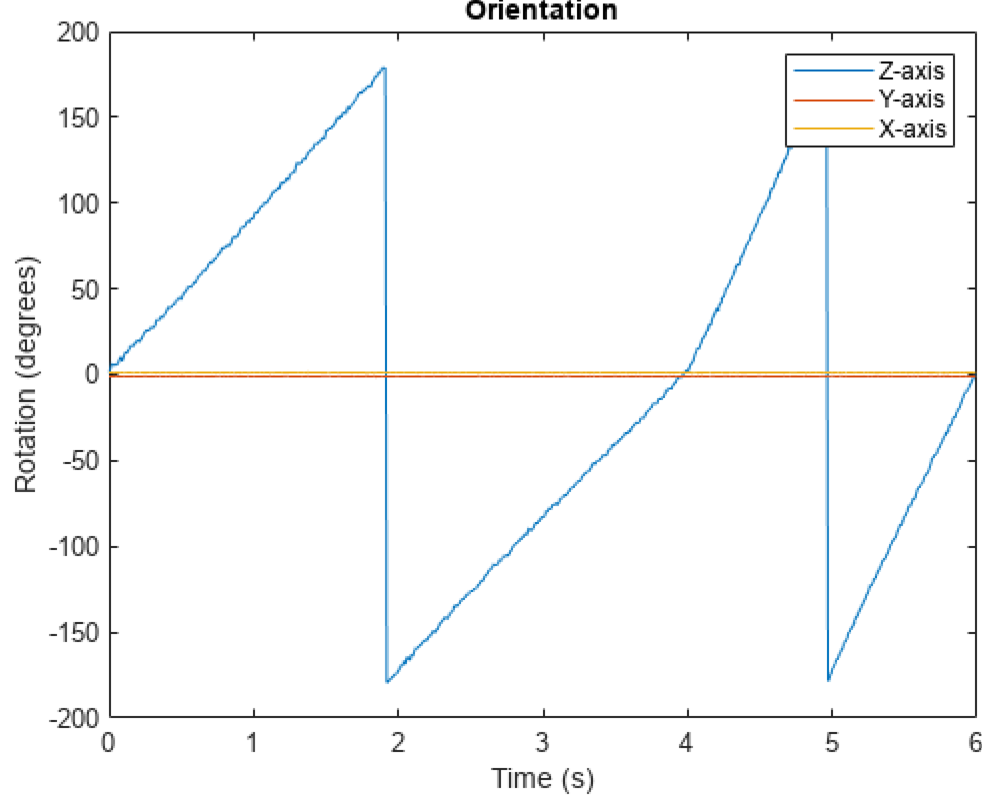
```
IMU = imuSensor('accel-mag','SampleRate',fs);

IMU.Accelerometer = accelparams( ...
    'MeasurementRange',19.62, ...            % m/s^2
    'Resolution',0.0023936, ...              % m/s^2 / LSB
    'TemperatureScaleFactor',0.008, ...      % % / degree C
    'ConstantBias',0.1962, ...               % m/s^2
    'TemperatureBias',0.0014715, ...         % m/s^2 / degree C
    'NoiseDensity',0.0012361);               % m/s^2 / Hz^(1/2)

IMU.Magnetometer = magparams( ...
    'MeasurementRange',1200, ...             % uT
    'Resolution',0.1, ...                    % uT / LSB
    'TemperatureScaleFactor',0.1, ...        % % / degree C
    'ConstantBias',1, ...                    % uT
    'TemperatureBias',[0.8 0.8 2.4], ...     % uT / degree C
    'NoiseDensity',[0.6 0.6 0.9]/sqrt(100)); % uT / Hz^(1/2)

[accelReadings,magReadings] = IMU(accNED,angVelNED,orientationNED);

figure(1)
t = (0:(totalNumSamples-1))/fs;
subplot(2,1,1)
plot(t,accelReadings)
legend('X-axis','Y-axis','Z-axis')
ylabel('Acceleration (m/s^2)')
title('Accelerometer Readings')

subplot(2,1,2)
plot(t,magReadings)
legend('X-axis','Y-axis','Z-axis')
ylabel('Magnetic Field (\muT)')
xlabel('Time (s)')
title('Magnetometer Readings')
```




The accelerometer readings indicate that the platform has no translation. The magnetometer readings indicate that the platform is rotating around the *z*-axis.

Feed the accelerometer and magnetometer readings into the `ecompass` function to estimate the orientation over time. The `ecompass` function returns orientation in quaternion format. Convert orientation to Euler angles and plot the results. The orientation plot indicates that the platform rotates about the *z*-axis only.

```
orientation = ecompass(accelReadings,magReadings);

orientationEuler = eulerd(orientation,'ZYX','frame');

figure(2)
plot(t,orientationEuler)
legend('Z-axis','Y-axis','X-axis')
xlabel('Time (s)')
ylabel('Rotation (degrees)')
title('Orientation')
```




%

#### Model Tilt Using Gyroscope and Accelerometer Readings

Model a tilting IMU that contains an accelerometer and gyroscope using the `imuSensor` System object™. Use ideal and realistic models to compare the results of orientation tracking using the `imufilter` System object.

Load a struct describing ground-truth motion and a sample rate. The motion struct describes sequential rotations:

1. yaw: 120 degrees over two seconds
2. pitch: 60 degrees over one second
3. roll: 30 degrees over one-half second
4. roll: -30 degrees over one-half second
5. pitch: -60 degrees over one second
6. yaw: -120 degrees over two seconds

In the last stage, the motion struct combines the 1st, 2nd, and 3rd rotations into a single-axis rotation. The acceleration, angular velocity, and orientation are defined in the local NED coordinate system.

```
load y120p60r30.mat motion fs
accNED = motion.Acceleration;
angVelNED = motion.AngularVelocity;
orientationNED = motion.Orientation;

numSamples = size(motion.Orientation,1);
t = (0:(numSamples-1)).'/fs;
```

Create an ideal IMU sensor object and a default IMU filter object.

```
IMU = imuSensor('accel-gyro','SampleRate',fs);

aFilter = imufilter('SampleRate',fs);
```

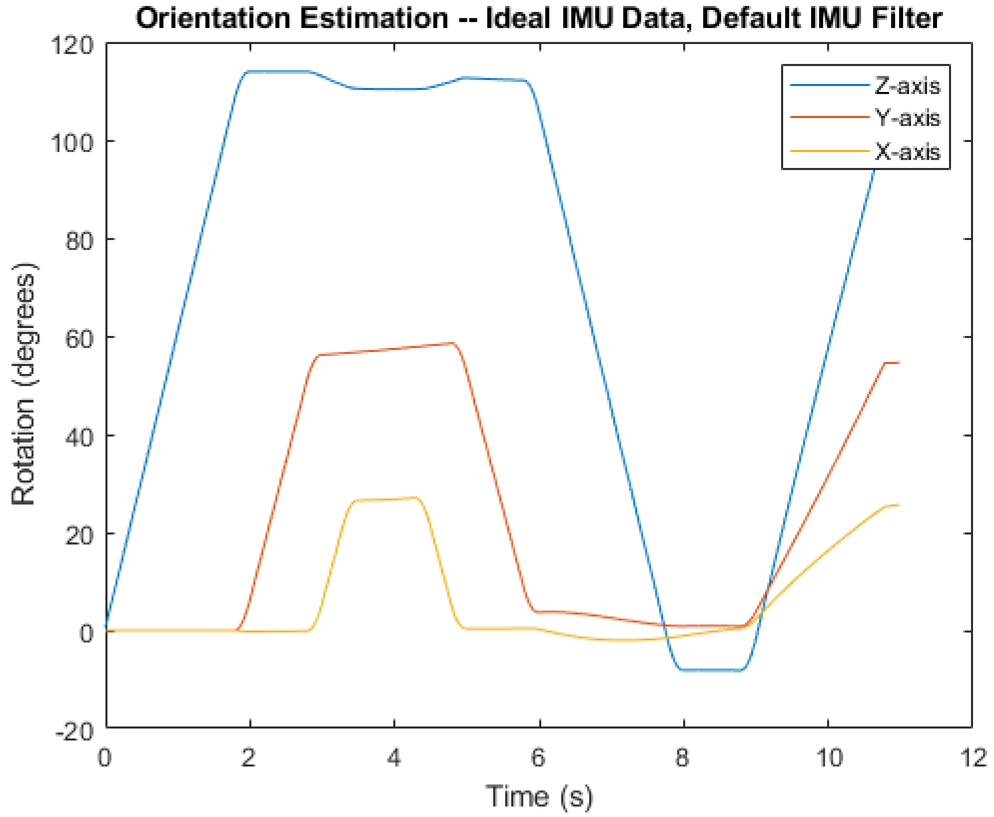
In a loop:

1. Simulate IMU output by feeding the ground-truth motion to the IMU sensor object.
2. Filter the IMU output using the default IMU filter object.

```
orientation = zeros(numSamples,1,'quaternion');
for i = 1:numSamples

    [accelBody,gyroBody] = IMU(accNED(i,:),angVelNED(i,:),orientationNED(i,:));

    orientation(i) = aFilter(accelBody,gyroBody);

end
release(aFilter)
```

Plot the orientation over time.

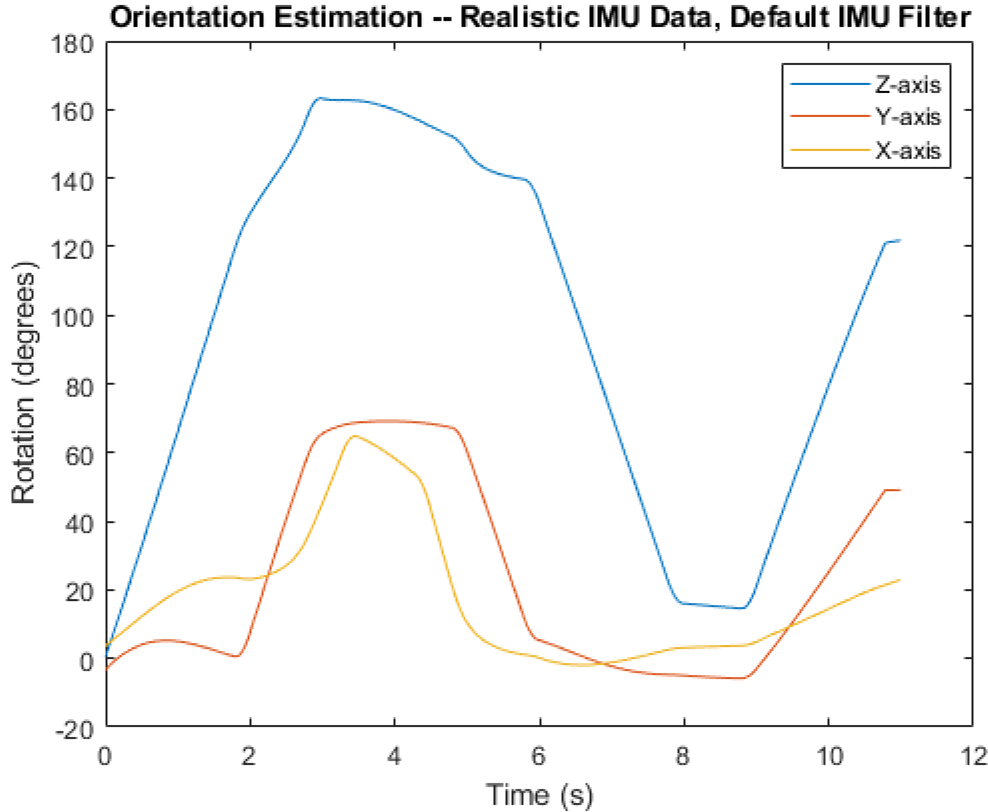
```
figure(1)
plot(t,eulerd(orientation,'ZYX','frame'))
xlabel('Time (s)')
ylabel('Rotation (degrees)')
title('Orientation Estimation -- Ideal IMU Data, Default IMU Filter')
legend('Z-axis','Y-axis','X-axis')
```




Modify properties of your `imuSensor` to model real-world sensors. Run the loop again and plot the orientation estimate over time.

```
IMU.Accelerometer = accelparams( ...
    'MeasurementRange',19.62, ...
    'Resolution',0.00059875, ...
    'ConstantBias',0.4905, ...
    'AxesMisalignment',2, ...
    'NoiseDensity',0.003924, ...
    'BiasInstability',0, ...
    'TemperatureBias', [0.34335 0.34335 0.5886], ...
    'TemperatureScaleFactor',0.02);
IMU.Gyroscope = gyroparams( ...
    'MeasurementRange',4.3633, ...
    'Resolution',0.00013323, ...
    'AxesMisalignment',2, ...
    'NoiseDensity',8.7266e-05, ...
    'TemperatureBias',0.34907, ...
    'TemperatureScaleFactor',0.02, ...
    'AccelerationBias',0.00017809, ...
    'ConstantBias',[0.3491,0.5,0]);

orientationDefault = zeros(numSamples,1,'quaternion');
for i = 1:numSamples

    [accelBody,gyroBody] = IMU(accNED(i,:),angVelNED(i,:),orientationNED(i,:));
```

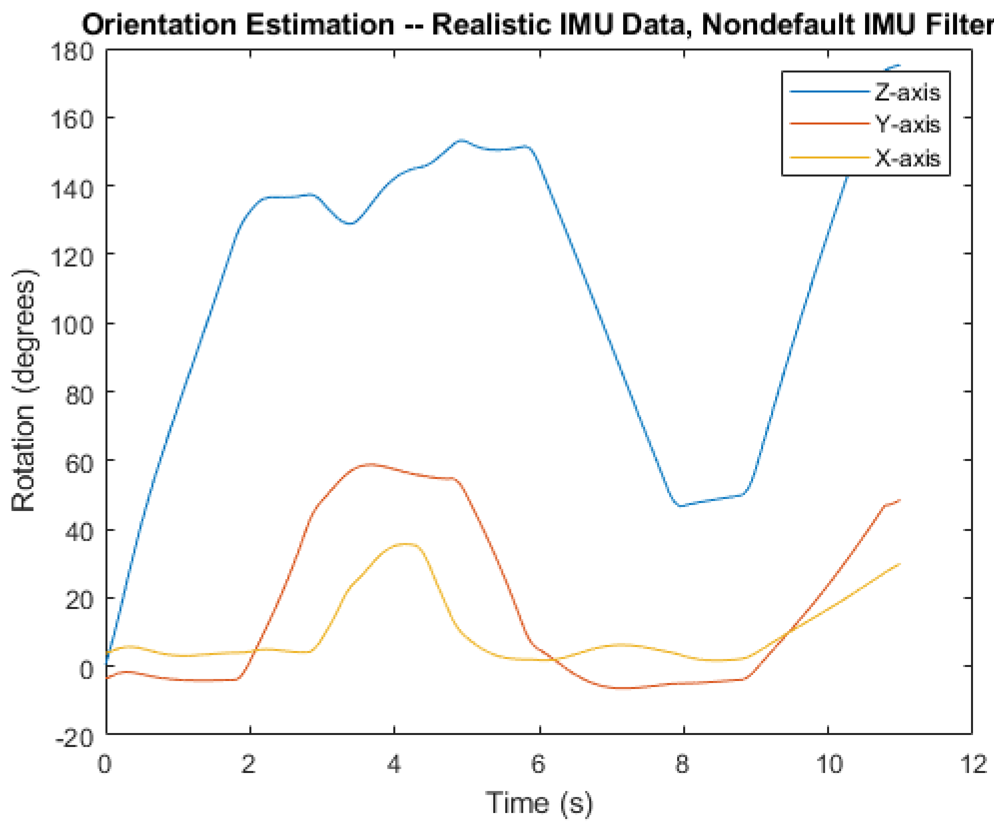
```
    orientationDefault(i) = aFilter(accelBody,gyroBody);

end
release(aFilter)

figure(2)
plot(t,eulerd(orientationDefault,'ZYX','frame'))
xlabel('Time (s)')
ylabel('Rotation (degrees)')
title('Orientation Estimation -- Realistic IMU Data, Default IMU Filter')
legend('Z-axis','Y-axis','X-axis')
```




The ability of the `imufilter` to track the ground-truth data is significantly reduced when modeling a realistic IMU. To improve performance, modify properties of your `imufilter` object. These values were determined empirically. Run the loop again and plot the orientation estimate over time.

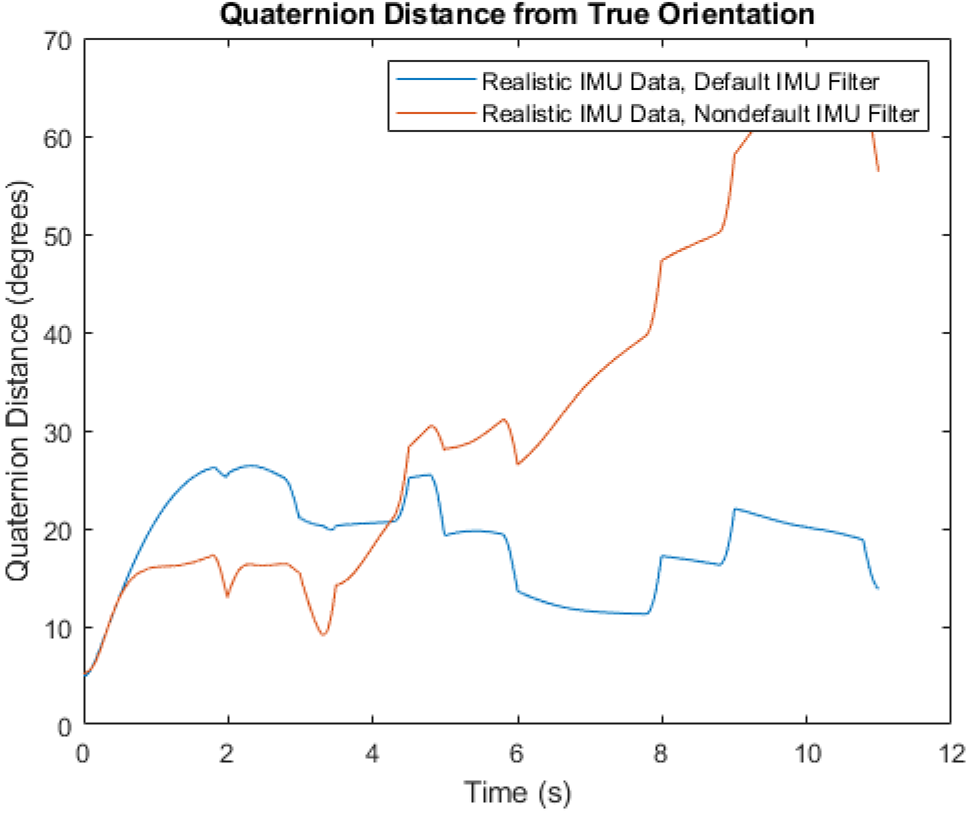
```
aFilter.GyroscopeNoise          = 7.6154e-7;
aFilter.AccelerometerNoise      = 0.0015398;
aFilter.GyroscopeDriftNoise     = 3.0462e-12;
aFilter.LinearAccelerationNoise = 0.00096236;
aFilter.InitialProcessNoise     = aFilter.InitialProcessNoise*10;

orientationNondefault = zeros(numSamples,1,'quaternion');
for i = 1:numSamples
    [accelBody,gyroBody] = IMU(accNED(i,:),angVelNED(i,:),orientationNED(i,:));

    orientationNondefault(i) = aFilter(accelBody,gyroBody);
```

```
end
release(aFilter)

figure(3)
plot(t,eulerd(orientationNondefault,'ZYX','frame'))
xlabel('Time (s)')
ylabel('Rotation (degrees)')
title('Orientation Estimation -- Realistic IMU Data, Nondefault IMU Filter')
legend('Z-axis','Y-axis','X-axis')
```




To quantify the improved performance of the modified `imufilter`, plot the quaternion distance between the ground-truth motion and the orientation as returned by the `imufilter` with default and nondefault properties.

```
qDistDefault = rad2deg(dist(orientationNED,orientationDefault));
qDistNondefault = rad2deg(dist(orientationNED,orientationNondefault));

figure(4)
plot(t,[qDistDefault,qDistNondefault])
title('Quaternion Distance from True Orientation')
legend('Realistic IMU Data, Default IMU Filter', ...
       'Realistic IMU Data, Nondefault IMU Filter')
xlabel('Time (s)')
ylabel('Quaternion Distance (degrees)')
```




## Algorithms

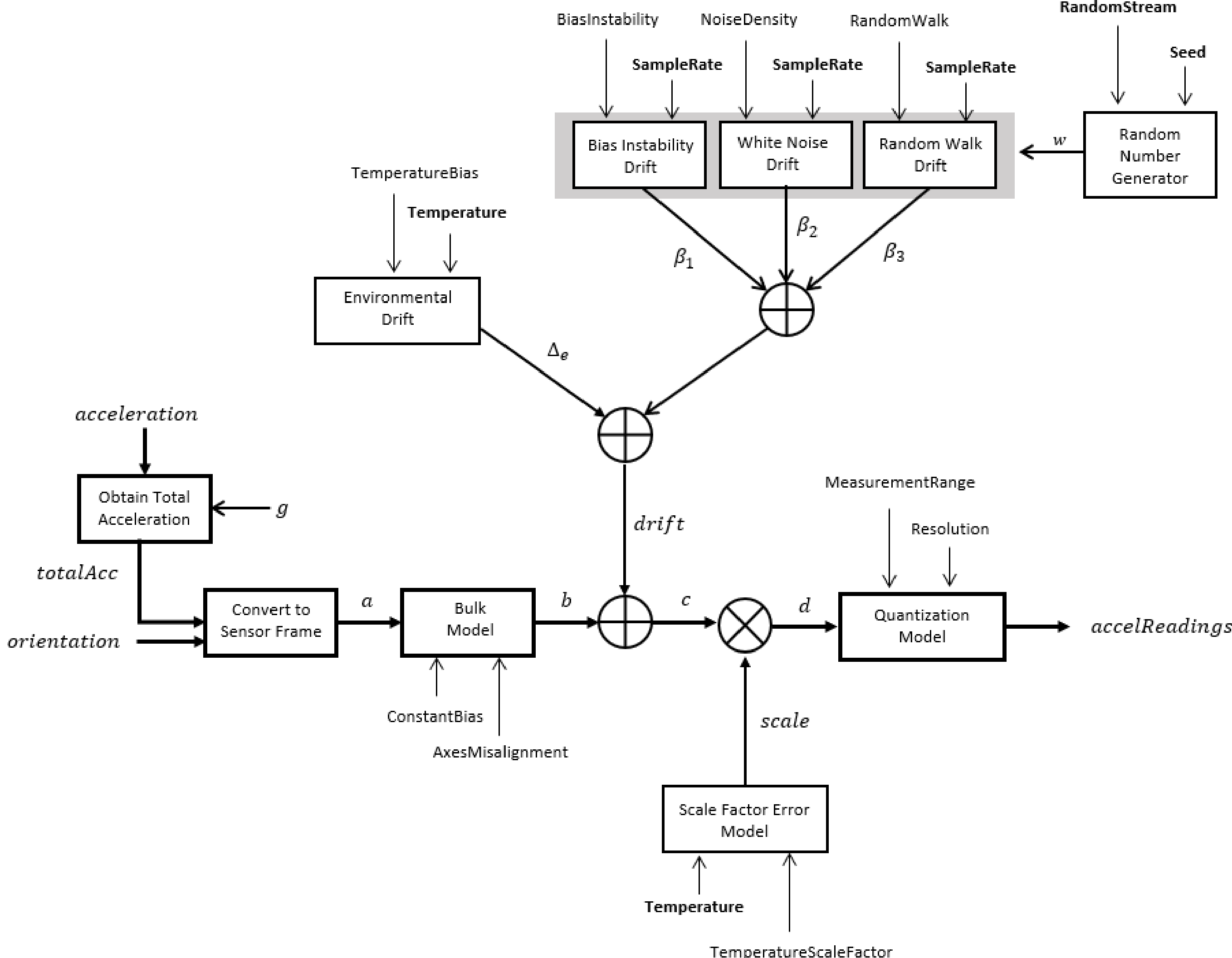
---

**Tip** In the following algorithm description, variables in italic fonts are inputs or outputs of the `imuSensor` object. Variables in bold fonts are properties of the `imuSensor`. Variables in normal fonts are properties of the `accelparams`, `gyroparams`, or `magparams` object.

---

### Accelerometer

The following algorithm description assumes an NED navigation frame. The accelerometer model uses the ground-truth orientation and acceleration inputs and the `imuSensor` and `accelparams` properties to model accelerometer readings.




**Obtain Total Acceleration**

To obtain the total acceleration (*totalAcc*), the acceleration is preprocessed by negating and adding the gravity constant vector ($g$= [0; 0; 9.8] m/s$^2$ assuming an NED frame) as:

$$totalAcc = -acceleration + g$$

The `acceleration` term is negated to obtain zero total acceleration readings when the accelerometer is in a free fall. The `acceleration` term is also known as the specific force.

**Convert to Sensor Frame**

Then the total acceleration is converted from the local navigation frame to the sensor frame using:

$$a = (orientation)(totalAcc)^T$$

If the orientation is input in quaternion form, it is converted to a rotation matrix before processing.

#### Bulk Model

The ground-truth acceleration in the sensor frame, $a$, passes through the bulk model, which adds axes misalignment and bias:

$$b = \left( \begin{bmatrix} 1 & \frac{\alpha_2}{100} & \frac{\alpha_3}{100} \\ \frac{\alpha_1}{100} & 1 & \frac{\alpha_3}{100} \\ \frac{\alpha_1}{100} & \frac{\alpha_2}{100} & 1 \end{bmatrix} \left(a^T\right) \right)^T + \text{ConstantBias}$$

where ConstantBias is a property of `accelparams`, and $\alpha_1$, $\alpha_2$, and $\alpha_3$ are given by the first, second, and third elements of the AxesMisalignment property of `accelparams`.

#### Bias Instability Drift

The bias instability drift is modeled as white noise biased and then filtered:

$$\beta_1(k) = \frac{1}{2}\beta_1(k-1) + (\text{BiasInstability})w(k)$$

where $k$ is the discrete time step index, BiasInstability is a property of `accelparams`, $w$ is white noise that follows a normal distribution of mean 0 and variance of 1. The discrete time step size is the reciprocal of the SampleRate property.

#### White Noise Drift

White noise drift is modeled by multiplying elements of the white noise random stream by the standard deviation:

$$\beta_2 = (w)\left(\sqrt{\frac{\text{SampleRate}}{2}}\right)(\text{NoiseDensity})$$

where $w$ is white noise that follows a normal distribution of mean 0 and variance of 1, SampleRate is an `imuSensor` property, and NoiseDensity is an `accelparams` property.

#### Random Walk Drift

The random walk drift is modeled by biasing elements of the white noise random stream and then filtering:

$$\beta_2(k) = \beta_2(k-1) + w(k)\left(\frac{\text{RandomWalk}}{\sqrt{\frac{\text{SampleRate}}{2}}}\right)$$

where $k$ is the discrete time step index, RandomWalk is a property of `accelparams`, SampleRate is a property of `imuSensor`, $w$ is white noise that follows a normal distribution of mean 0 and variance of 1. The discrete time step size is the reciprocal of the SampleRate property.

#### Environmental Drift Noise

The environmental drift noise is modeled by multiplying the temperature difference from a standard with the temperature bias:

$$\Delta_e = (\text{Temperature} - 25)(\text{TemperatureBias})$$

where Temperature is a property of `imuSensor`, and TemperatureBias is a property of `accelparams`. The constant 25 corresponds to a standard temperature.

#### Scale Factor Error Model

The temperature scale factor error is modeled as:

$$scaleFactorError = 1 + \left(\frac{\text{Temperature} - 25}{100}\right)(\text{TemperatureScaleFactor})$$

where Temperature is a property of `imuSensor`, and TemperatureScaleFactor is a property of `accelparams`. The constant 25 corresponds to a standard temperature.

#### Quantization Model

The quantization is modeled by first saturating the continuous signal model:

$$e = \begin{cases} \text{MeasurementRange} & \text{if} \quad d > \text{MeasurementRange} \\ -\text{MeasurementRange} & \text{if} \quad -d > \text{MeasurementRange} \\ d & \text{else} \end{cases}$$

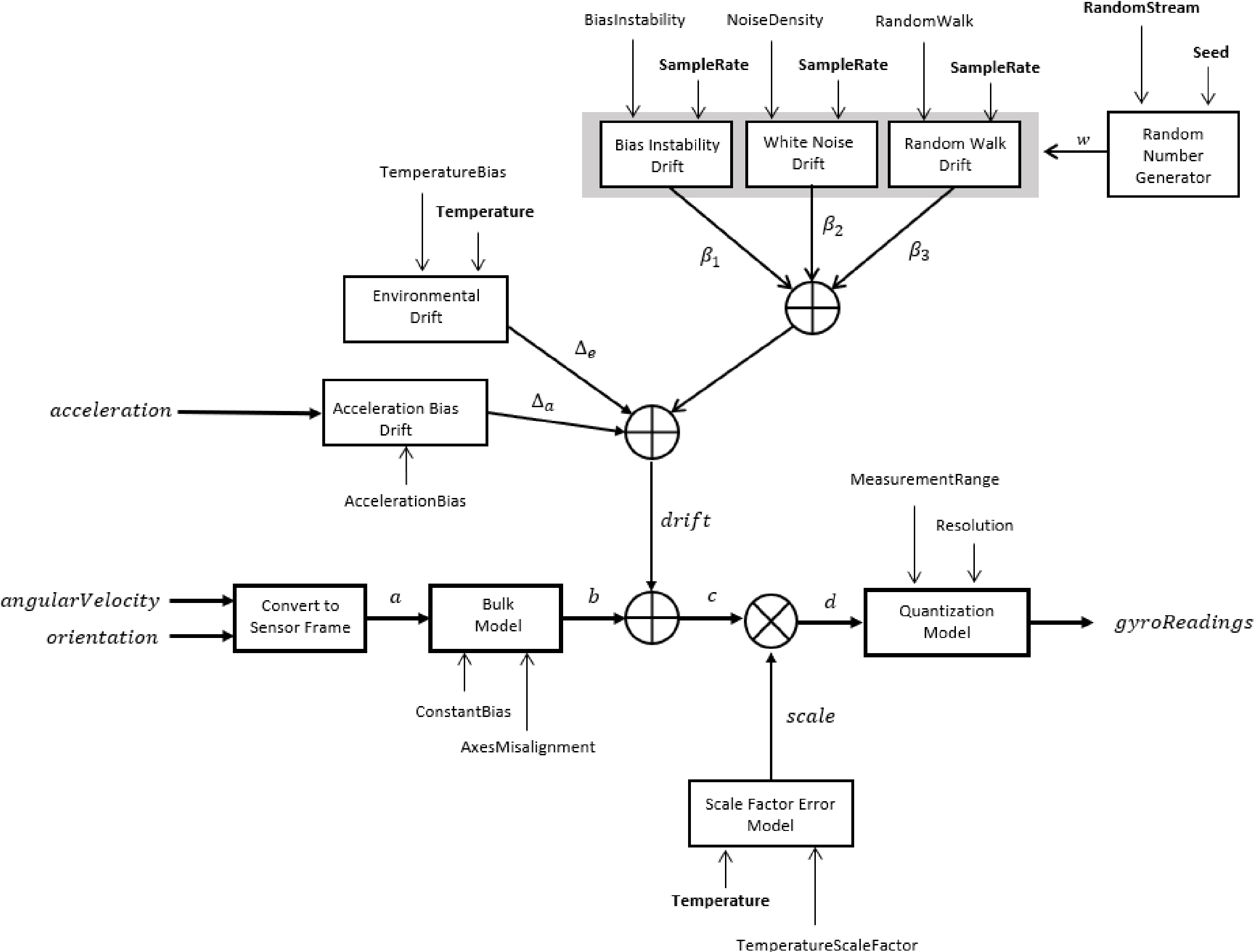
and then setting the resolution:

$$accelReadings = (\text{Resolution})\left(\text{round}\left(\frac{e}{\text{Resolution}}\right)\right)$$

where MeasurementRange is a property of `accelparams`.

### Gyroscope

The following algorithm description assumes an NED navigation frame. The gyroscope model uses the ground-truth orientation, acceleration, and angular velocity inputs, and the `imuSensor` and `gyroparams` properties to model accelerometer readings.




**Convert to Sensor Frame**

The ground-truth angular velocity is converted from the local frame to the sensor frame using the ground-truth orientation:

$$a = (orientation)(angularVelocity)^T$$

If the orientation is input in quaternion form, it is converted to a rotation matrix before processing.

**Bulk Model**

The ground-truth angular velocity in the sensor frame, $a$, passes through the bulk model, which adds axes misalignment and bias:

$$b = \left( \begin{bmatrix} 1 & \frac{\alpha_2}{100} & \frac{\alpha_3}{100} \\ \frac{\alpha_1}{100} & 1 & \frac{\alpha_3}{100} \\ \frac{\alpha_1}{100} & \frac{\alpha_2}{100} & 1 \end{bmatrix} \left(a^T\right) \right)^T + \text{ConstantBias}$$

where ConstantBias is a property of `gyroparams`, and $\alpha_1$, $\alpha_2$, and $\alpha_3$ are given by the first, second, and third elements of the AxesMisalignment property of `gyroparams`.

#### Bias Instability Drift

The bias instability drift is modeled as white noise biased and then filtered:

$$\beta_1(k) = \frac{1}{2}\beta_1(k-1) + (\text{BiasInstability})w(k)$$

where $k$ is the discrete time step index, BiasInstability is a property of `gyroparams`, $w$ is white noise that follows a normal distribution of mean 0 and variance of 1. The discrete time step size is the reciprocal of the SampleRate property.

#### White Noise Drift

White noise drift is modeled by multiplying elements of the white noise random stream by the standard deviation:

$$\beta_2 = (w)\left(\sqrt{\frac{\text{SampleRate}}{2}}\right)(\text{NoiseDensity})$$

where $w$ is white noise that follows a normal distribution of mean 0 and variance of 1, SampleRate is an `imuSensor` property, and NoiseDensity is an `gyroparams` property.

#### Random Walk Drift

The random walk drift is modeled by biasing elements of the white noise random stream and then filtering:

$$\beta_2(k) = \beta_2(k-1) + w(k)\left(\frac{\text{RandomWalk}}{\sqrt{\frac{\text{SampleRate}}{2}}}\right)$$

where $k$ is the discrete time step index, RandomWalk is a property of `gyroparams`, SampleRate is a property of `imuSensor`, and $w$ is white noise that follows a normal distribution of mean 0 and variance of 1. The discrete time step size is the reciprocal of the SampleRate property.

#### Environmental Drift Noise

The environmental drift noise is modeled by multiplying the temperature difference from a standard with the temperature bias:

$$\Delta_e = (\text{Temperature} - 25)(\text{TemperatureBias})$$

where Temperature is a property of `imuSensor`, and TemperatureBias is a property of `gyroparams`. The constant 25 corresponds to a standard temperature.

#### Acceleration Bias Drift

The acceleration bias drift is modeled by multiplying the acceleration input and acceleration bias:

$$\Delta_a = \mathit{acceleration} * \text{AccelerationBias}$$

where AccelerationBias is a property of `gyroparams`.

#### Scale Factor Error Model

The temperature scale factor error is modeled as:

$$scaleFactorError = 1 + \left(\frac{\text{Temperature} - 25}{100}\right)(\text{TemperatureScaleFactor})$$

where Temperature is a property of `imuSensor`, and TemperatureScaleFactor is a property of `gyroparams`. The constant 25 corresponds to a standard temperature.

#### Quantization Model

The quantization is modeled by first saturating the continuous signal model:

$$e = \begin{cases} \text{MeasurementRange} & \text{if} \quad d > \text{MeasurementRange} \\ -\text{MeasurementRange} & \text{if} \quad -d > \text{MeasurementRange} \\ d & \text{else} \end{cases}$$

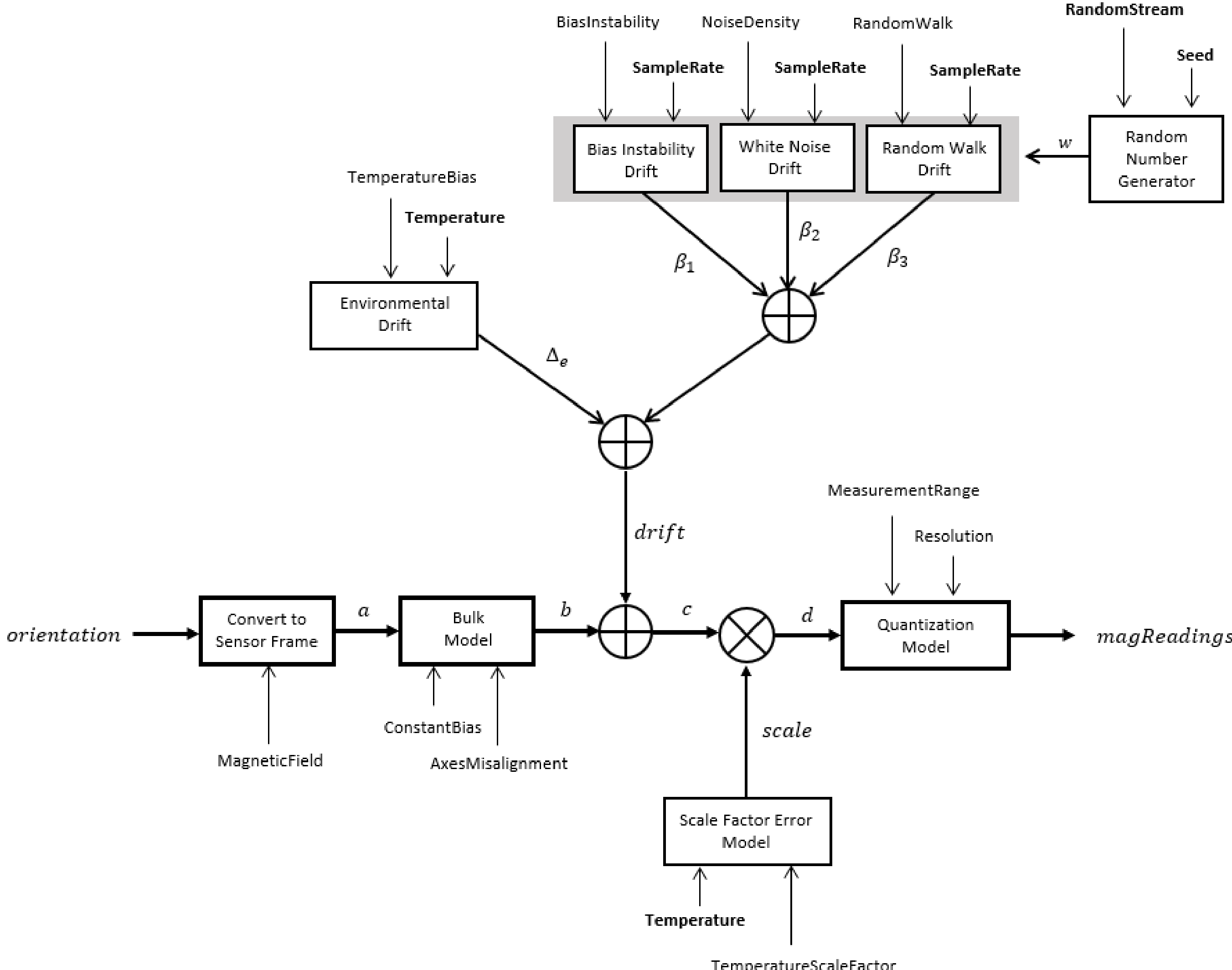
and then setting the resolution:

$$gyroReadings = (\text{Resolution})\left(\text{round}\left(\frac{e}{\text{Resolution}}\right)\right)$$

where MeasurementRange is a property of `gyroparams`.

### Magnetometer

The following algorithm description assumes an NED navigation frame. The magnetometer model uses the ground-truth orientation and acceleration inputs, and the `imuSensor` and `magparams` properties to model magnetometer readings.




**Convert to Sensor Frame**

The ground-truth acceleration is converted from the local frame to the sensor frame using the ground-truth orientation:

$$a = (orientation)(totalAcc)^T$$

If the orientation is input in quaternion form, it is converted to a rotation matrix before processing.

**Bulk Model**

The ground-truth acceleration in the sensor frame, *a*, passes through the bulk model, which adds axes misalignment and bias:

$$b = \left( \begin{bmatrix} 1 & \frac{\alpha_2}{100} & \frac{\alpha_3}{100} \\ \frac{\alpha_1}{100} & 1 & \frac{\alpha_3}{100} \\ \frac{\alpha_1}{100} & \frac{\alpha_2}{100} & 1 \end{bmatrix} \left(a^T\right) \right)^T + \text{ConstantBias}$$

where ConstantBias is a property of `magparams`, and $\alpha_1$, $\alpha_2$, and $\alpha_3$ are given by the first, second, and third elements of the AxesMisalignment property of `magparams`.

**Bias Instability Drift**

The bias instability drift is modeled as white noise biased and then filtered:

$$\beta_1(k) = \frac{1}{2}\beta_1(k-1) + (\text{BiasInstability})w(k)$$

where $k$ is the discrete time step index, BiasInstability is a property of `magparams`, $w$ is white noise that follows a normal distribution of mean 0 and variance of 1. The discrete time step size is the reciprocal of the SampleRate property.

**White Noise Drift**

White noise drift is modeled by multiplying elements of the white noise random stream by the standard deviation:

$$\beta_2 = (w)\left(\sqrt{\frac{\text{SampleRate}}{2}}\right)(\text{NoiseDensity})$$

where $w$ is white noise that follows a normal distribution of mean 0 and variance of 1, SampleRate is an `imuSensor` property, and NoiseDensity is an `magparams` property.

**Random Walk Drift**

The random walk drift is modeled by biasing elements of the white noise random stream and then filtering:

$$\beta_2(k) = \beta_2(k-1) + w(k)\left(\frac{\text{RandomWalk}}{\sqrt{\frac{\text{SampleRate}}{2}}}\right)$$

where $k$ is the discrete time step index, RandomWalk is a property of `magparams`, SampleRate is a property of `imuSensor`, $w$ is white noise that follows a normal distribution of mean 0 and variance of 1. The discrete time step size is the reciprocal of the SampleRate property.

**Environmental Drift Noise**

The environmental drift noise is modeled by multiplying the temperature difference from a standard with the temperature bias:

$$\Delta_e = (\text{Temperature} - 25)(\text{TemperatureBias})$$

where Temperature is a property of `imuSensor`, and TemperatureBias is a property of `magparams`. The constant 25 corresponds to a standard temperature.

#### Scale Factor Error Model

The temperature scale factor error is modeled as:

$$scaleFactorError = 1 + \left(\frac{\text{Temperature} - 25}{100}\right)(\text{TemperatureScaleFactor})$$

where Temperature is a property of `imuSensor`, and TemperatureScaleFactor is a property of `magparams`. The constant 25 corresponds to a standard temperature.

#### Quantization Model

The quantization is modeled by first saturating the continuous signal model:

$$e = \begin{cases} \text{MeasurementRange} & \text{if} \quad d > \text{MeasurementRange} \\ -\text{MeasurementRange} & \text{if} \quad -d > \text{MeasurementRange} \\ d & \text{else} \end{cases}$$

and then setting the resolution:

$$magReadings = (\text{Resolution})\left(\text{round}\left(\frac{e}{\text{Resolution}}\right)\right)$$

where MeasurementRange is a property of `magparams`.

# Version History

**Introduced in R2019b**

## Extended Capabilities

#### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

The object functions, `perturbations` and `perturb`, do not support code generation.

Usage notes and limitations:

See “System Objects in MATLAB Code Generation” (MATLAB Coder).

## See Also

#### Classes

`accelparams` | `gyroparams` | `magparams`

#### Objects

`gpsSensor`

# insSensor

Inertial navigation system and GNSS/GPS simulation model

## Description

The `insSensor` System object models a device that fuses measurements from an inertial navigation system (INS) and global navigation satellite system (GNSS) such as a GPS, and outputs the fused measurements.

To output fused INS and GNSS measurements:

1. Create the `insSensor` object and set its properties.
2. Call the object with arguments, as if it were a function.

To learn more about how System objects work, see What Are System Objects?

# Creation

## Syntax

```
INS = insSensor
INS = insSensor(Name,Value)
```

### Description

`INS = insSensor` returns a System object, `INS`, that models a device that outputs measurements from an INS and GNSS.

`INS = insSensor(Name,Value)` sets properties on page 2-555 using one or more name-value pairs. Unspecified properties have default values. Enclose each property name in quotes.

## Properties

Unless otherwise indicated, properties are *nontunable*, which means you cannot change their values after calling the object. Objects lock when you call them, and the `release` function unlocks them.

If a property is *tunable*, you can change its value at any time.

For more information on changing property values, see System Design in MATLAB Using System Objects.

**`MountingLocation` — Location of sensor on platform (m)**
`[0 0 0]` (default) | three-element real-valued vector of form [*x y z*]

Location of the sensor on the platform, in meters, specified as a three-element real-valued vector of the form [*x y z*]. The vector defines the offset of the sensor origin from the origin of the platform.

**Tunable:** Yes

Data Types: `single` | `double`

**`RollAccuracy` — Accuracy of roll measurement (deg)**
`0.2` (default) | nonnegative real scalar

Accuracy of the roll measurement of the sensor body, in degrees, specified as a nonnegative real scalar.

Roll is the rotation around the *x*-axis of the sensor body. Roll noise is modeled as a white noise process. `RollAccuracy` sets the standard deviation of the roll measurement noise.

**Tunable:** Yes

Data Types: `single` | `double`

**`PitchAccuracy` — Accuracy of pitch measurement (deg)**
`0.2` (default) | nonnegative real scalar

Accuracy of the pitch measurement of the sensor body, in degrees, specified as a nonnegative real scalar.

Pitch is the rotation around the *y*-axis of the sensor body. Pitch noise is modeled as a white noise process. `PitchAccuracy` defines the standard deviation of the pitch measurement noise.

**Tunable:** Yes

Data Types: `single` | `double`

**`YawAccuracy` — Accuracy of yaw measurement (deg)**
`1` (default) | nonnegative real scalar

Accuracy of the yaw measurement of the sensor body, in degrees, specified as a nonnegative real scalar.

Yaw is the rotation around the *z*-axis of the sensor body. Yaw noise is modeled as a white noise process. `YawAccuracy` defines the standard deviation of the yaw measurement noise.

**Tunable:** Yes

Data Types: `single` | `double`

**`PositionAccuracy` — Accuracy of position measurement (m)**
`[1 1 1]` (default) | nonnegative real scalar | three-element real-valued vector

Accuracy of the position measurement of the sensor body, in meters, specified as a nonnegative real scalar or a three-element real-valued vector. The elements of the vector set the accuracy of the *x*-, *y*-, and *z*-position measurements, respectively. If you specify `PositionAccuracy` as a scalar value, then the object sets the accuracy of all three positions to this value.

Position noise is modeled as a white noise process. `PositionAccuracy` defines the standard deviation of the position measurement noise.

**Tunable:** Yes

Data Types: `single` | `double`

**`VelocityAccuracy` — Accuracy of velocity measurement (m/s)**
`0.05` (default) | nonnegative real scalar

Accuracy of the velocity measurement of the sensor body, in meters per second, specified as a nonnegative real scalar.

Velocity noise is modeled as a white noise process. `VelocityAccuracy` defines the standard deviation of the velocity measurement noise.

**Tunable:** Yes

Data Types: `single` | `double`

#### `AccelerationAccuracy` — Accuracy of acceleration measurement ($m/s^2$)

`0` (default) | nonnegative real scalar

Accuracy of the acceleration measurement of the sensor body, in meters per second, specified as a nonnegative real scalar.

Acceleration noise is modeled as a white noise process. `AccelerationAccuracy` defines the standard deviation of the acceleration measurement noise.

**Tunable:** Yes

Data Types: `single` | `double`

#### `AngularVelocityAccuracy` — Accuracy of angular velocity measurement (deg/s)

`0` (default) | nonnegative real scalar

Accuracy of the angular velocity measurement of the sensor body, in meters per second, specified as a nonnegative real scalar.

Angular velocity is modeled as a white noise process. `AngularVelocityAccuracy` defines the standard deviation of the acceleration measurement noise.

**Tunable:** Yes

Data Types: `single` | `double`

#### `TimeInput` — Enable input of simulation time

`false` or `0` (default) | `true` or `1`

Enable input of simulation time, specified as a logical `0` (`false`) or `1` (`true`). Set this property to `true` to input the simulation time by using the `simTime` argument.

**Tunable:** No

Data Types: `logical`

#### `HasGNSSFix` — Enable GNSS fix

`true` or `1` (default) | `false` or `0`

Enable GNSS fix, specified as a logical `1` (`true`) or `0` (`false`). Set this property to `false` to simulate the loss of a GNSS receiver fix. When a GNSS receiver fix is lost, position measurements drift at a rate specified by the `PositionErrorFactor` property.

**Tunable:** Yes

##### Dependencies

To enable this property, set `TimeInput` to `true`.

Data Types: logical

**PositionErrorFactor — Position error factor without GNSS fix**
[0 0 0] (default) | nonnegative scalar | 1-by-3 vector of scalars

Position error factor without GNSS fix, specified as a scalar or a 1-by-3 vector of scalars.

When the HasGNSSFix property is set to false, the position error grows at a quadratic rate due to constant bias in the accelerometer. The position error for a position component $E(t)$ can be expressed as $E(t) = 1/2\alpha t^2$, where $\alpha$ is the position error factor for the corresponding component and $t$ is the time since the GNSS fix is lost. While running, the object computes $t$ based on the simTime input. The computed $E(t)$ values for the $x$, $y$, and $z$ components are added to the corresponding position components of the gTruth input.

**Tunable:** Yes

**Dependencies**

To enable this property, set TimeInput to true and HasGNSSFix to false.

Data Types: single | double

**RandomStream — Random number source**
'Global stream' (default) | 'mt19937ar with seed'

Random number source, specified as one of these options:

- 'Global stream' –– Generate random numbers using the current global random number stream.
- 'mt19937ar with seed' –– Generate random numbers using the mt19937ar algorithm, with the seed specified by the Seed property.

Data Types: char | string

**Seed — Initial seed**
67 (default) | nonnegative integer

Initial seed of the mt19937ar random number generator algorithm, specified as a nonnegative integer.

**Dependencies**

To enable this property, set RandomStream to 'mt19937ar with seed'.

Data Types: single | double | int8 | int16 | int32 | int64 | uint8 | uint16 | uint32 | uint64

## Usage

## Syntax

```
measurement = INS(gTruth)
measurement = INS(gTruth,simTime)
```

**Description**

`measurement = INS(gTruth)` models the data received from an INS sensor reading and GNSS sensor reading. The output measurement is based on the inertial ground-truth state of the sensor body, `gTruth`.

`measurement = INS(gTruth,simTime)` additionally specifies the time of simulation, `simTime`. To enable this syntax, set the `TimeInput` property to `true`.

**Input Arguments**

**`gTruth` — Inertial ground-truth state of sensor body**
structure

Inertial ground-truth state of sensor body, in local Cartesian coordinates, specified as a structure containing these fields:

| Field | Description |
| --- | --- |
| `'Position'` | Position, in meters, specified as a real, finite *N*-by-3 matrix of [*x y z*] vectors. *N* is the number of samples in the current frame. |
| `'Velocity'` | Velocity (*v*), in meters per second, specified as a real, finite *N*-by-3 matrix of [$v_x$ $v_y$ $v_z$] vector. *N* is the number of samples in the current frame. |
| `'Orientation'` | Orientation with respect to the local Cartesian coordinate system, specified as one of these options:<br>• *N*-element column vector of `quaternion` objects<br>• 3-by-3-by-*N* array of rotation matrices<br>• *N*-by-3 matrix of [$x_{roll}$ $y_{pitch}$ $z_{yaw}$] angles in degrees<br>Each quaternion or rotation matrix is a frame rotation from the local Cartesian coordinate system to the current sensor body coordinate system. *N* is the number of samples in the current frame. |
| `'Acceleration'` | Acceleration (*a*), in meters per second squared, specified as a real, finite *N*-by-3 matrix of [$a_x$ $a_y$ $a_z$] vectors. *N* is the number of samples in the current frame. |
| `'AngularVelocity'` | Angular velocity ($\omega$), in degrees per second squared, specified as a real, finite *N*-by-3 matrix of [$\omega_x$ $\omega_y$ $\omega_z$] vectors. *N* is the number of samples in the current frame. |

The field values must be of type `double` or `single`.

The `Position`, `Velocity`, and `Orientation` fields are required. The other fields are optional.

Example: `struct('Position',[0 0 0],'Velocity',[0 0 0],'Orientation',quaternion([1 0 0 0]))`

**`simTime` — Simulation time**
nonnegative real scalar

Simulation time, in seconds, specified as a nonnegative real scalar.

Data Types: `single` | `double`

### Output Arguments

**`measurement` — Measurement of sensor body motion**
structure

Measurement of the sensor body motion, in local Cartesian coordinates, returned as a structure containing these fields:

| Field | Description |
|---|---|
| `'Position'` | Position, in meters, specified as a real, finite *N*-by-3 matrix of [*x y z*] vectors. *N* is the number of samples in the current frame. |
| `'Velocity'` | Velocity (*v*), in meters per second, specified as a real, finite *N*-by-3 matrix of [$v_x$ $v_y$ $v_z$] vector. *N* is the number of samples in the current frame. |
| `'Orientation'` | Orientation with respect to the local Cartesian coordinate system, specified as one of these options:<br>• *N*-element column vector of `quaternion` objects<br>• 3-by-3-by-*N* array of rotation matrices<br>• *N*-by-3 matrix of [$x_{roll}$ $y_{pitch}$ $z_{yaw}$] angles in degrees<br><br>Each quaternion or rotation matrix is a frame rotation from the local Cartesian coordinate system to the current sensor body coordinate system. *N* is the number of samples in the current frame. |
| `'Acceleration'` | Acceleration (*a*), in meters per second squared, specified as a real, finite *N*-by-3 matrix of [$a_x$ $a_y$ $a_z$] vectors. *N* is the number of samples in the current frame. |
| `'AngularVelocity'` | Angular velocity (*ω*), in degrees per second squared, specified as a real, finite *N*-by-3 matrix of [$\omega_x$ $\omega_y$ $\omega_z$] vectors. *N* is the number of samples in the current frame. |

The returned field values are of type `double` or `single` and are of the same type as the corresponding field values in the `gTruth` input.

## Object Functions

To use an object function, specify the System object as the first input argument. For example, to release system resources of a System object named `obj`, use this syntax:

```
release(obj)
```

### Specific to `insSensor`

| | |
|---|---|
| perturbations | Perturbation defined on object |
| perturb | Apply perturbations to object |

### Common to All System Objects

| | |
|---|---|
| step | Run System object algorithm |
| clone | Create duplicate System object |
| isLocked | Determine if System object is in use |
| reset | Reset internal states of System object |
| release | Release resources and allow changes to System object property values and input characteristics |

## Examples

#### Generate INS Measurements from Stationary Input

Create a motion structure that defines a stationary position at the local north-east-down (NED) origin. Because the platform is stationary, you need to define only a single sample. Assume the ground-truth motion is sampled for 10 seconds with a 100 Hz sample rate. Create a default `insSensor` System object™. Preallocate variables to hold output from the `insSensor` object.

```
Fs = 100;
duration = 10;
numSamples = Fs*duration;

motion = struct( ...
    'Position',zeros(1,3), ...
    'Velocity',zeros(1,3), ...
    'Orientation',ones(1,1,'quaternion'));

INS = insSensor;

positionMeasurements = zeros(numSamples,3);
velocityMeasurements = zeros(numSamples,3);
orientationMeasurements = zeros(numSamples,1,'quaternion');
```

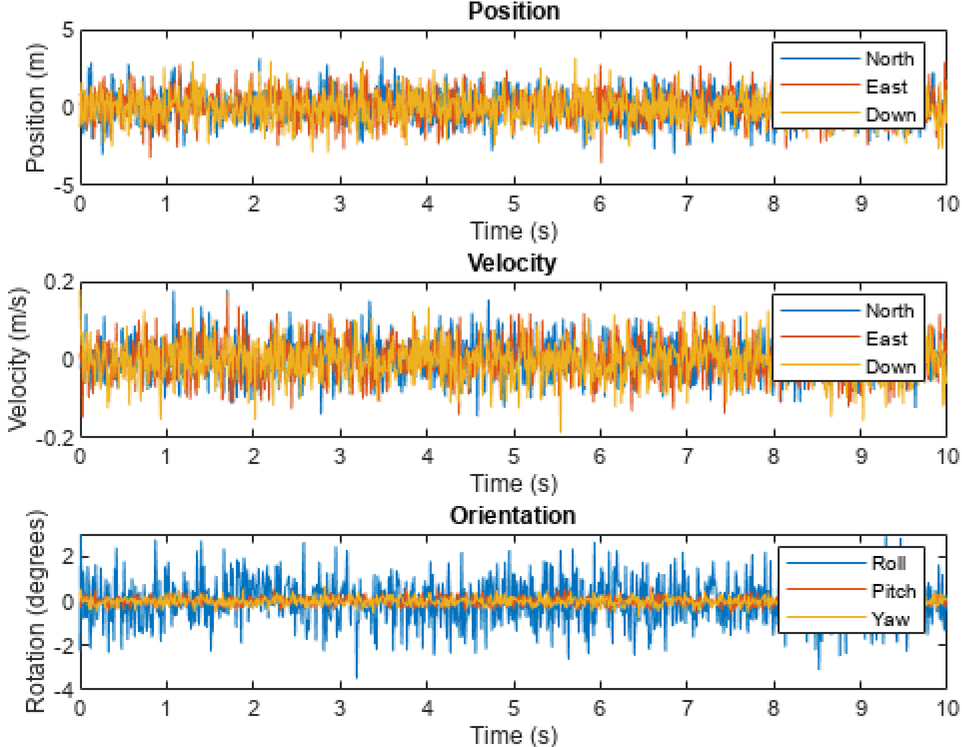
In a loop, call `INS` with the stationary motion structure to return the position, velocity, and orientation measurements in the local NED coordinate system. Log the position, velocity, and orientation measurements.

```
for i = 1:numSamples

    measurements = INS(motion);

    positionMeasurements(i,:) = measurements.Position;
    velocityMeasurements(i,:) = measurements.Velocity;
```

```
    orientationMeasurements(i) = measurements.Orientation;
end
```

Convert the orientation from quaternions to Euler angles for visualization purposes. Plot the position, velocity, and orientation measurements over time.

```
orientationMeasurements = eulerd(orientationMeasurements,'ZYX','frame');

t = (0:(numSamples-1))/Fs;

subplot(3,1,1)
plot(t,positionMeasurements)
title('Position')
xlabel('Time (s)')
ylabel('Position (m)')
legend('North','East','Down')

subplot(3,1,2)
plot(t,velocityMeasurements)
title('Velocity')
xlabel('Time (s)')
ylabel('Velocity (m/s)')
legend('North','East','Down')

subplot(3,1,3)
plot(t,orientationMeasurements)
title('Orientation')
xlabel('Time (s)')
ylabel('Rotation (degrees)')
legend('Roll', 'Pitch', 'Yaw')
```




#### Generate INS Measurements for a Turning Platform

Generate INS measurements using the `insSensor` System object™. Use `waypointTrajectory` to generate the ground-truth path.

Specify a ground-truth orientation that begins with the sensor body *x*-axis aligned with North and ends with the sensor body *x*-axis aligned with East. Specify waypoints for an arc trajectory and a time-of-arrival vector for the corresponding waypoints. Use a 100 Hz sample rate. Create a `waypointTrajectory` System object with the waypoint constraints, and set `SamplesPerFrame` so that the entire trajectory is output with one call.

```
eulerAngles = [0,0,0; ...
               0,0,0; ...
               90,0,0; ...
               90,0,0];
orientation = quaternion(eulerAngles,'eulerd','ZYX','frame');

r = 20;
waypoints = [0,0,0; ...
             100,0,0; ...
             100+r,r,0; ...
             100+r,100+r,0];

toa = [0,10,10+(2*pi*r/4),20+(2*pi*r/4)];
```

```
Fs = 100;
numSamples = floor(Fs*toa(end));

path = waypointTrajectory('Waypoints',waypoints, ...
    'TimeOfArrival',toa, ...
    'Orientation',orientation, ...
    'SampleRate',Fs, ...
    'SamplesPerFrame',numSamples);
```

Create an `insSensor` System object to model receiving INS data. Set the `PositionAccuracy` to `0.1`.

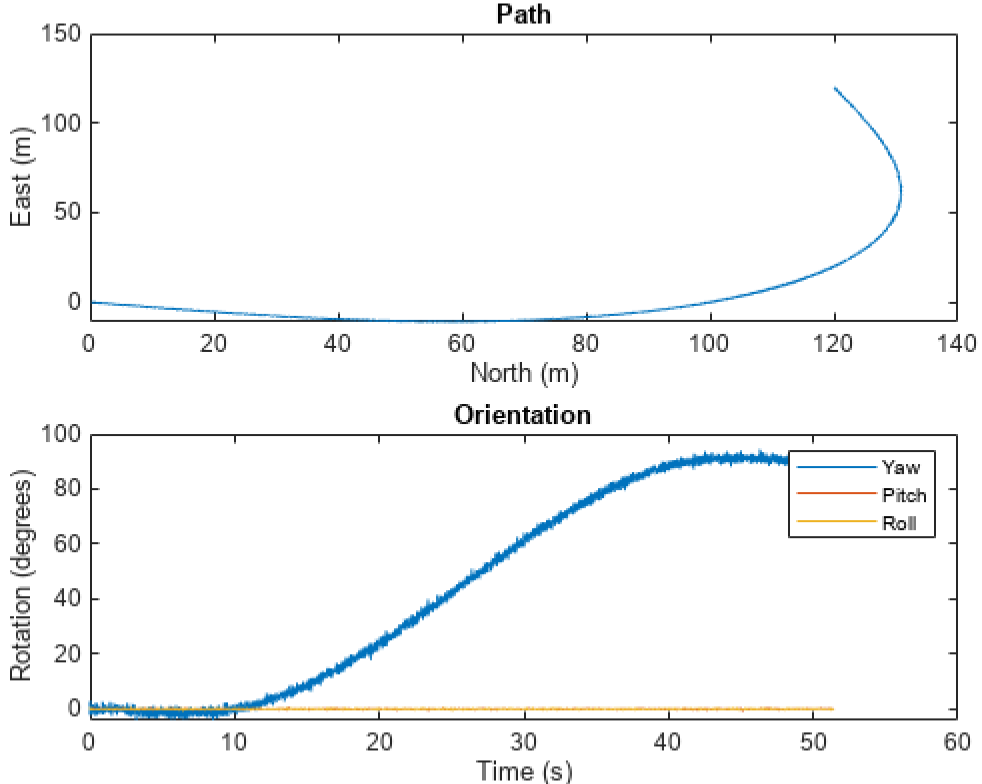
```
ins = insSensor('PositionAccuracy',0.1);
```

Call the waypoint trajectory object, `path`, to generate the ground-truth motion. Call the INS simulator, `ins`, with the ground-truth motion to generate INS measurements.

```
[motion.Position,motion.Orientation,motion.Velocity] = path();
insMeas = ins(motion);
```

Convert the orientation returned by `ins` to Euler angles in degrees for visualization purposes. Plot the full path and orientation over time.

```
orientationMeasurementEuler = eulerd(insMeas.Orientation,'ZYX','frame');

subplot(2,1,1)
plot(insMeas.Position(:,1),insMeas.Position(:,2));
title('Path')
xlabel('North (m)')
ylabel('East (m)')

subplot(2,1,2)
t = (0:(numSamples-1)).'/Fs;
plot(t,orientationMeasurementEuler(:,1), ...
     t,orientationMeasurementEuler(:,2), ...
     t,orientationMeasurementEuler(:,3));
title('Orientation')
legend('Yaw','Pitch','Roll')
xlabel('Time (s)')
ylabel('Rotation (degrees)')
```




## Version History

**Introduced in R2020b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

The object functions, `perturbations` and `perturb`, do not support code generation.

Usage notes and limitations:

See "System Objects in MATLAB Code Generation" (MATLAB Coder).

## See Also

### Objects

`imuSensor` | `gpsSensor`

### Objects

### Topics

"Model IMU, GPS, and INS/GPS"

"Simulate Inertial Sensor Readings from a Driving Scenario"

# loadparams

Load sensor parameters from JSON file

## Syntax

```
loadparams(sensor,file,PN)
```

## Description

`loadparams(sensor,file,PN)` configures the `imuSensor` object, `sensor`, to match the parameters in the `PN` part of a JSON file, `File`.

## Examples

### Load Pre-defined Parameters in `imuSensor`

Create an `imuSensor` system object.

```
s = imuSensor;
```

Load a JSON file.

```
fn = fullfile(matlabroot,'toolbox','shared',...
    'positioning','positioningdata','generic.json');
```

Here is a screen shot of the JSON file with some parts collapsed.

```
{
    "GenericLowCost9Axis":
    {
        "Accelerometer":
        {
            "MeasurementRange": 19.6133,
            "Resolution": 0.0023928,
            "ConstantBias": [0.19,0.19,0.19],
            "AxesMisalignment": [0,0,0],
            "NoiseDensity": [0.0012356,0.0012356,0.0012356],
            "BiasInstability": [0,0,0],
            "RandomWalk": [0,0,0],
            "TemperatureBias": [0,0,0],
            "TemperatureScaleFactor": [0,0,0]
        },
        "Gyroscope":
        {⟺},
        "Magnetometer":
        {⟺}
    },
    "GenericLowCost6Axis":
    {⟺}
}
```

Configure the object as a 6-axis sensor.

```
loadparams(s,fn,'GenericLowCost6Axis')
s
```

```
s = 
  imuSensor with properties:

          IMUType: 'accel-gyro'
       SampleRate: 100
      Temperature: 25
    Accelerometer: [1x1 accelparams]
        Gyroscope: [1x1 gyroparams]
     RandomStream: 'Global stream'
```

Configure the object as a 9-axis sensor.

```
loadparams(s,fn,'GenericLowCost9Axis')
s
```

```
s = 
  imuSensor with properties:

          IMUType: 'accel-gyro-mag'
       SampleRate: 100
      Temperature: 25
    MagneticField: [27.5550 -2.4169 -16.0849]
    Accelerometer: [1x1 accelparams]
        Gyroscope: [1x1 gyroparams]
     Magnetometer: [1x1 magparams]
     RandomStream: 'Global stream'
```

## Input Arguments

**`sensor` — IMU sensor**
`imuSensor` object

IMU sensor, specified as an `imuSensor` system object.

**`file` — JSON file**
`.json` file

JavaScript Object Notation (JSON) format file, specified as a `.json` file.

**PN — Part name**
`string`

Part name in a JSON file, specified as a string.

# Version History

**Introduced in R2020a**

## See Also

`imuSensor`

# kinematicTrajectory

Rate-driven trajectory generator

## Description

The `kinematicTrajectory` System object generates trajectories using specified acceleration and angular velocity.

To generate a trajectory from rates:

1. Create the `kinematicTrajectory` object and set its properties.
2. Call the object with arguments, as if it were a function.

To learn more about how System objects work, see What Are System Objects?

# Creation

## Syntax

```
trajectory = kinematicTrajectory
trajectory = kinematicTrajectory(Name,Value)
```

### Description

`trajectory = kinematicTrajectory` returns a System object, `trajectory`, that generates a trajectory based on acceleration and angular velocity.

`trajectory = kinematicTrajectory(Name,Value)` sets each property `Name` to the specified `Value`. Unspecified properties have default values.

Example: `trajectory = kinematicTrajectory('SampleRate',200,'Position',[0,1,10])` creates a kinematic trajectory System object, `trajectory`, with a sample rate of 200 Hz and the initial position set to [0,1,10].

## Properties

If a property is *tunable*, you can change its value at any time.

**`SampleRate` — Sample rate of trajectory (Hz)**
`100` (default) | positive scalar

Sample rate of trajectory in Hz, specified as a positive scalar.

**Tunable:** Yes

Data Types: `single` | `double`

**`Position` — Position state in local navigation coordinate system (m)**
`[0 0 0]` (default) | 3-element row vector

Position state in the local navigation coordinate system in meters, specified as a three-element row vector.

**Tunable:** Yes

Data Types: single | double

**Velocity — Velocity state in local navigation coordinate system (m/s)**
[0 0 0] (default) | 3-element row vector

Velocity state in the local navigation coordinate system in m/s, specified as a three-element row vector.

**Tunable:** Yes

Data Types: single | double

**Orientation — Orientation state in local navigation coordinate system**
quaternion(1,0,0,0) (default) | scalar quaternion | 3-by-3 real matrix

Orientation state in the local navigation coordinate system, specified as a scalar quaternion or 3-by-3 real matrix. The orientation is a frame rotation from the local navigation coordinate system to the current body frame.

**Tunable:** Yes

Data Types: quaternion | single | double

**AccelerationSource — Source of acceleration state**
'Input' (default) | 'Property'

Source of acceleration state, specified as 'Input' or 'Property'.

- 'Input' –– specify acceleration state as an input argument to the kinematic trajectory object
- 'Property' –– specify acceleration state by setting the Acceleration property

**Tunable:** No

Data Types: char | string

**Acceleration — Acceleration state (m/s$^2$)**
[0 0 0] (default) | three-element row vector

Acceleration state in m/s$^2$, specified as a three-element row vector.

**Tunable:** Yes

**Dependencies**

To enable this property, set AccelerationSource to 'Property'.

Data Types: single | double

**AngularVelocitySource — Source of angular velocity state**
'Input' (default) | 'Property'

Source of angular velocity state, specified as 'Input' or 'Property'.

- 'Input' –– specify angular velocity state as an input argument to the kinematic trajectory object
- 'Property' –– specify angular velocity state by setting the AngularVelocity property

**Tunable:** No

Data Types: char | string

#### AngularVelocity — Angular velocity state (rad/s)
[0 0 0] (default) | three-element row vector

Angular velocity state in rad/s, specified as a three-element row vector.

**Tunable:** Yes

##### Dependencies

To enable this property, set AngularVelocitySource to 'Property'.

Data Types: single | double

#### SamplesPerFrame — Number of samples per output frame
1 (default) | positive integer

Number of samples per output frame, specified as a positive integer.

**Tunable:** No

##### Dependencies

To enable this property, set AngularVelocitySource to 'Property' and AccelerationSource to 'Property'.

Data Types: single | double

## Usage

## Syntax

```
[position,orientation,velocity,acceleration,angularVelocity] = trajectory(
bodyAcceleration,bodyAngularVelocity)
[position,orientation,velocity,acceleration,angularVelocity] = trajectory(
bodyAngularVelocity)
[position,orientation,velocity,acceleration,angularVelocity] = trajectory(
bodyAcceleration)
[position,orientation,velocity,acceleration,angularVelocity] = trajectory()
```

### Description

[position,orientation,velocity,acceleration,angularVelocity] = trajectory(
bodyAcceleration,bodyAngularVelocity) outputs the trajectory state and then updates the trajectory state based on bodyAcceleration and bodyAngularVelocity.

This syntax is only valid if AngularVelocitySource is set to 'Input' and AccelerationSource is set to 'Input'.

`[position,orientation,velocity,acceleration,angularVelocity] = trajectory(bodyAngularVelocity)` outputs the trajectory state and then updates the trajectory state based on `bodyAngularVelocity`.

This syntax is only valid if `AngularVelocitySource` is set to `'Input'` and `AccelerationSource` is set to `'Property'`.

`[position,orientation,velocity,acceleration,angularVelocity] = trajectory(bodyAcceleration)` outputs the trajectory state and then updates the trajectory state based on `bodyAcceleration`.

This syntax is only valid if `AngularVelocitySource` is set to `'Property'` and `AccelerationSource` is set to `'Input'`.

`[position,orientation,velocity,acceleration,angularVelocity] = trajectory()` outputs the trajectory state and then updates the trajectory state.

This syntax is only valid if `AngularVelocitySource` is set to `'Property'` and `AccelerationSource` is set to `'Property'`.

### Input Arguments

#### `bodyAcceleration` — Acceleration in body coordinate system (m/s$^2$)

*N*-by-3 matrix

Acceleration in the body coordinate system in meters per second squared, specified as an *N*-by-3 matrix.

*N* is the number of samples in the current frame.

#### `bodyAngularVelocity` — Angular velocity in body coordinate system (rad/s)

*N*-by-3 matrix

Angular velocity in the body coordinate system in radians per second, specified as an *N*-by-3 matrix.

*N* is the number of samples in the current frame.

### Output Arguments

#### `position` — Position in local navigation coordinate system (m)

*N*-by-3 matrix

Position in the local navigation coordinate system in meters, returned as an *N*-by-3 matrix.

*N* is the number of samples in the current frame.

Data Types: `single` | `double`

#### `orientation` — Orientation in local navigation coordinate system

*N*-element quaternion column vector | 3-by-3-by-*N* real array

Orientation in the local navigation coordinate system, returned as an *N*-by-1 quaternion column vector or a 3-by-3-by-*N* real array. Each quaternion or 3-by-3 rotation matrix is a frame rotation from the local navigation coordinate system to the current body coordinate system.

*N* is the number of samples in the current frame.

Data Types: `single` | `double`

**`velocity` — Velocity in local navigation coordinate system (m/s)**
*N*-by-3 matrix

Velocity in the local navigation coordinate system in meters per second, returned as an *N*-by-3 matrix.

*N* is the number of samples in the current frame.

Data Types: `single` | `double`

**`acceleration` — Acceleration in local navigation coordinate system (m/s$^2$)**
*N*-by-3 matrix

Acceleration in the local navigation coordinate system in meters per second squared, returned as an *N*-by-3 matrix.

*N* is the number of samples in the current frame.

Data Types: `single` | `double`

**`angularVelocity` — Angular velocity in local navigation coordinate system (rad/s)**
*N*-by-3 matrix

Angular velocity in the local navigation coordinate system in radians per second, returned as an *N*-by-3 matrix.

*N* is the number of samples in the current frame.

Data Types: `single` | `double`

## Object Functions

### Specific to `kinematicTrajectory`

| | |
|---|---|
| perturbations | Perturbation defined on object |
| perturb | Apply perturbations to object |

### Common to All System Objects

| | |
|---|---|
| step | Run System object algorithm |

## Examples

#### Create Default `kinematicTrajectory`

Create a default `kinematicTrajectory` System object™ and explore the relationship between input, properties, and the generated trajectories.

```
trajectory = kinematicTrajectory
```

```
trajectory = 
  kinematicTrajectory with properties:

               SampleRate: 100
```

```
              Position: [0 0 0]
           Orientation: [1x1 quaternion]
              Velocity: [0 0 0]
    AccelerationSource: 'Input'
 AngularVelocitySource: 'Input'
```

By default, the `kinematicTrajectory` object has an initial position of [0 0 0] and an initial velocity of [0 0 0]. Orientation is described by a quaternion one (1 + 0i + 0j + 0k).

The `kinematicTrajectory` object maintains a visible and writable state in the properties `Position`, `Velocity`, and `Orientation`. When you call the object, the state is output and then updated.

For example, call the object by specifying an acceleration and angular velocity relative to the body coordinate system.

```
bodyAcceleration = [5,5,0];
bodyAngularVelocity = [0,0,1];
[position,orientation,velocity,acceleration,angularVelocity] = trajectory(bodyAcceleration,bodyAn
```

```
position = 1×3

     0     0     0


orientation = quaternion
     1 + 0i + 0j + 0k


velocity = 1×3

     0     0     0


acceleration = 1×3

     5     5     0


angularVelocity = 1×3

     0     0     1
```

The position, orientation, and velocity output from the `trajectory` object correspond to the state reported by the properties before calling the object. The `trajectory` state is updated after being called and is observable from the properties:

```
trajectory
```

```
trajectory = 
  kinematicTrajectory with properties:

            SampleRate: 100
              Position: [2.5000e-04 2.5000e-04 0]
           Orientation: [1x1 quaternion]
              Velocity: [0.0500 0.0500 0]
    AccelerationSource: 'Input'
```

```
    AngularVelocitySource: 'Input'
```

The `acceleration` and `angularVelocity` output from the `trajectory` object correspond to the `bodyAcceleration` and `bodyAngularVelocity`, except that they are returned in the navigation coordinate system. Use the `orientation` output to rotate `acceleration` and `angularVelocity` to the body coordinate system and verify they are approximately equivalent to `bodyAcceleration` and `bodyAngularVelocity`.

```
rotatedAcceleration = rotatepoint(orientation,acceleration)
```

```
rotatedAcceleration = 1×3

     5     5     0
```

```
rotatedAngularVelocity = rotatepoint(orientation,angularVelocity)
```

```
rotatedAngularVelocity = 1×3

     0     0     1
```

The `kinematicTrajectory` System object™ enables you to modify the trajectory state through the properties. Set the position to [0,0,0] and then call the object with a specified acceleration and angular velocity in the body coordinate system. For illustrative purposes, clone the `trajectory` object before modifying the `Position` property. Call both objects and observe that the positions diverge.

```
trajectoryClone = clone(trajectory);
trajectory.Position = [0,0,0];
```

```
position = trajectory(bodyAcceleration,bodyAngularVelocity)
```

```
position = 1×3

     0     0     0
```

```
clonePosition = trajectoryClone(bodyAcceleration,bodyAngularVelocity)
```

```
clonePosition = 1×3
10^-3 ×

    0.2500    0.2500         0
```

### Create Oscillating Trajectory

This example shows how to create a trajectory oscillating along the North axis of a local NED coordinate system using the `kinematicTrajectory` System object™.

Create a default `kinematicTrajectory` object. The default initial orientation is aligned with the local NED coordinate system.

```
traj = kinematicTrajectory
```

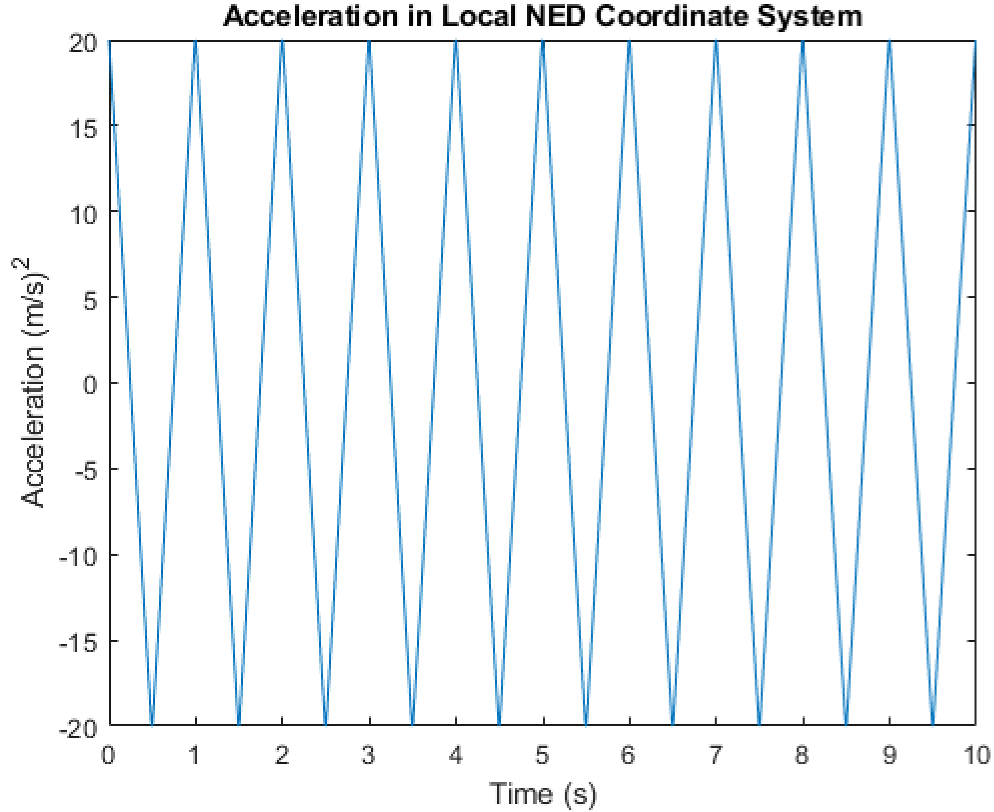
```
traj = 

  kinematicTrajectory with properties:

               SampleRate: 100
                 Position: [0 0 0]
              Orientation: [1x1 quaternion]
                 Velocity: [0 0 0]
       AccelerationSource: 'Input'
    AngularVelocitySource: 'Input'
```

Define a trajectory for a duration of 10 seconds consisting of rotation around the East axis (pitch) and an oscillation along North axis of the local NED coordinate system. Use the default `kinematicTrajectory` sample rate.

```
fs = traj.SampleRate;
duration = 10;

numSamples = duration*fs;

cyclesPerSecond = 1;
samplesPerCycle = fs/cyclesPerSecond;
numCycles = ceil(numSamples/samplesPerCycle);
maxAccel = 20;

triangle = [linspace(maxAccel,1/fs-maxAccel,samplesPerCycle/2), ...
    linspace(-maxAccel,maxAccel-(1/fs),samplesPerCycle/2)]';
oscillation = repmat(triangle,numCycles,1);
oscillation = oscillation(1:numSamples);

accNED = [zeros(numSamples,2),oscillation];

angVelNED = zeros(numSamples,3);
angVelNED(:,2) = 2*pi;
```

Plot the acceleration control signal.

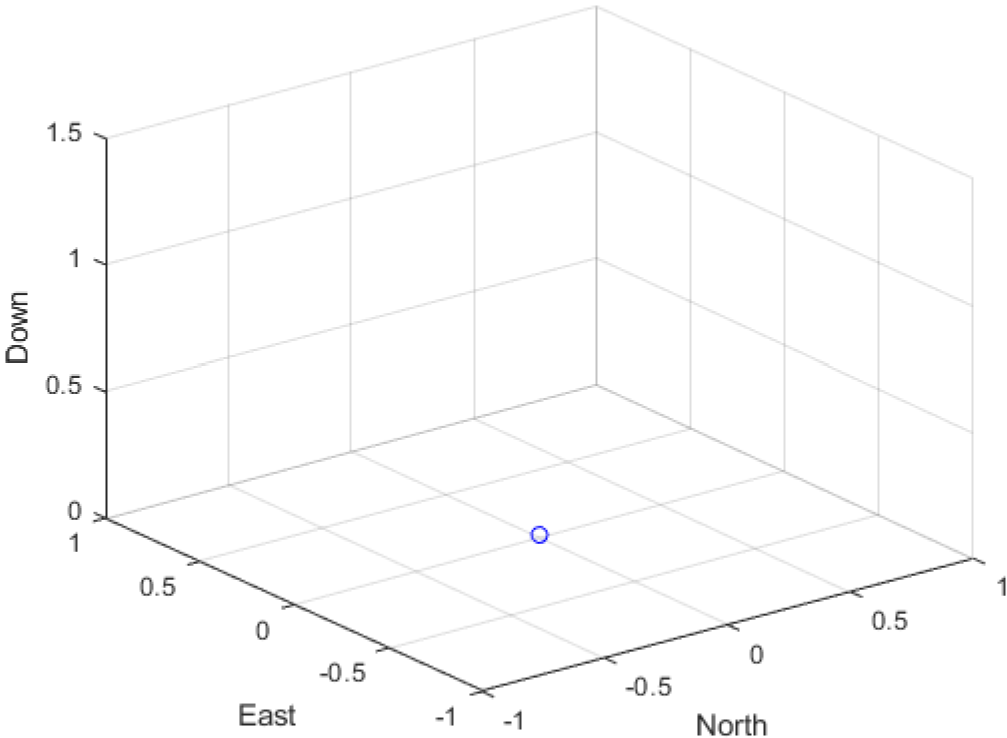
```
timeVector = 0:1/fs:(duration-1/fs);

figure(1)
plot(timeVector,oscillation)
xlabel('Time (s)')
ylabel('Acceleration (m/s)^2')
title('Acceleration in Local NED Coordinate System')
```

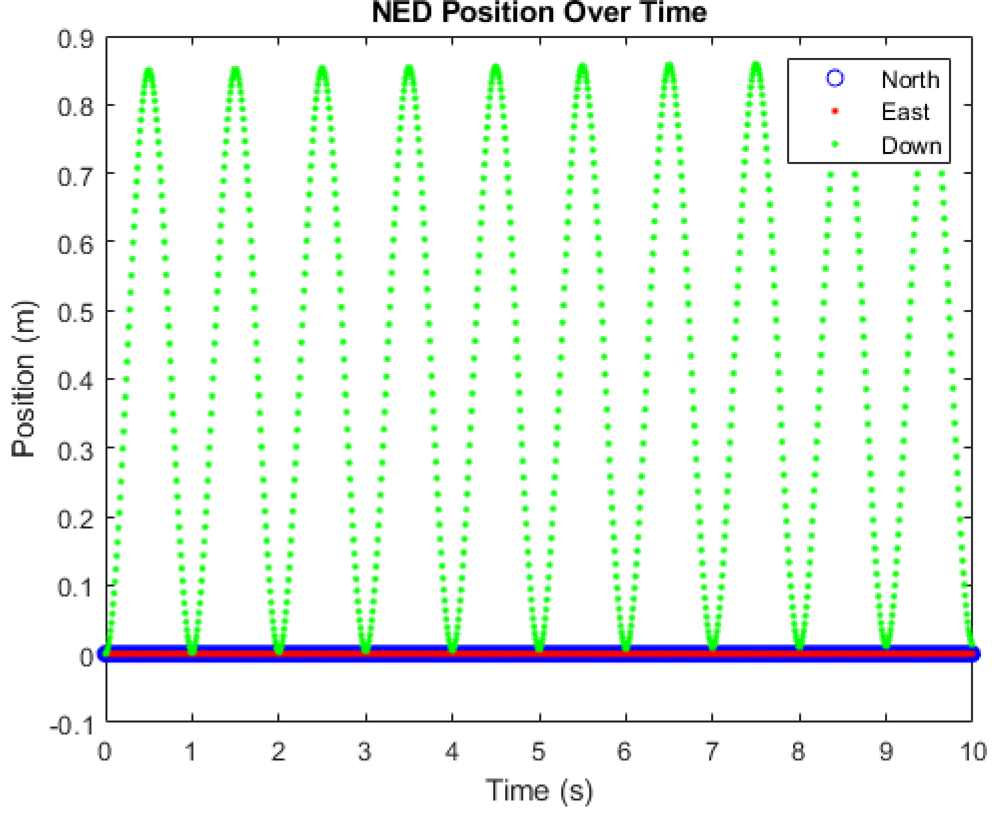



Generate the trajectory sample-by-sample in a loop. The `kinematicTrajectory` System object assumes the acceleration and angular velocity inputs are in the local sensor body coordinate system. Rotate the acceleration and angular velocity control signals from the NED coordinate system to the sensor body coordinate system using `rotateframe` and the `Orientation` state. Update a 3-D plot of the position at each time. Add `pause` to mimic real-time processing. Once the loop is complete, plot the position over time. Rotating the `accNED` and `angVelNED` control signals to the local body coordinate system assures the motion stays along the Down axis.

```
figure(2)
plotHandle = plot3(traj.Position(1),traj.Position(2),traj.Position(3),'bo');
grid on
xlabel('North')
ylabel('East')
zlabel('Down')
axis([-1 1 -1 1 0 1.5])
hold on

q = ones(numSamples,1,'quaternion');
for ii = 1:numSamples
     accBody = rotateframe(traj.Orientation,accNED(ii,:));
     angVelBody = rotateframe(traj.Orientation,angVelNED(ii,:));

    [pos(ii,:),q(ii),vel,ac] = traj(accBody,angVelBody);

    set(plotHandle,'XData',pos(ii,1),'YData',pos(ii,2),'ZData',pos(ii,3))

    pause(1/fs)
```

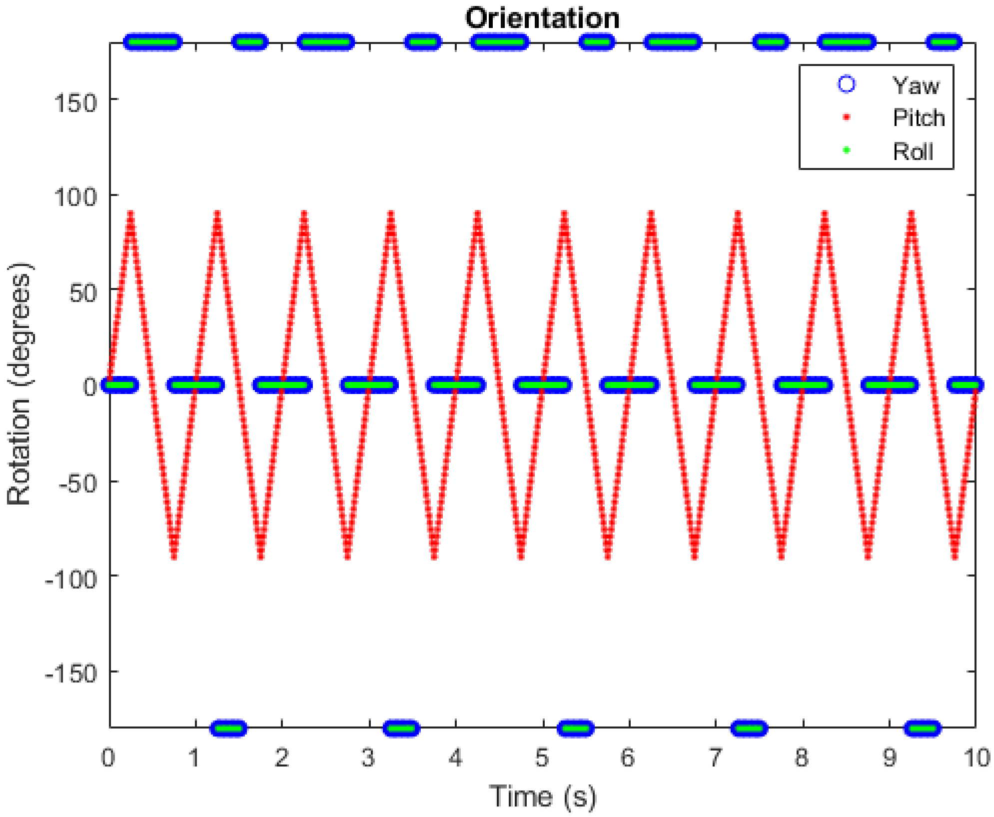
```
end

figure(3)
plot(timeVector,pos(:,1),'bo',...
     timeVector,pos(:,2),'r.',...
     timeVector,pos(:,3),'g.')
xlabel('Time (s)')
ylabel('Position (m)')
title('NED Position Over Time')
legend('North','East','Down')
```






Convert the recorded orientation to Euler angles and plot. Although the orientation of the platform changed over time, the acceleration always acted along the North axis.

```
figure(4)
eulerAngles = eulerd(q,'ZYX','frame');
plot(timeVector,eulerAngles(:,1),'bo',...
     timeVector,eulerAngles(:,2),'r.',...
     timeVector,eulerAngles(:,3),'g.')
axis([0,duration,-180,180])
legend('Yaw','Pitch','Roll')
xlabel('Time (s)')
ylabel('Rotation (degrees)')
title('Orientation')
```




#### Generate a Coil Trajectory

This example shows how to generate a coil trajectory using the `kinematicTrajectory` System object™.

Create a circular trajectory for a 1000 second duration and a sample rate of 10 Hz. Set the radius of the circle to 5000 meters and the speed to 80 meters per second. Set the climb rate to 100 meters per second and the pitch to 15 degrees. Specify the initial orientation as pointed in the direction of motion.

```
duration = 1000; % seconds
fs = 10;         % Hz
N = duration*fs; % number of samples

radius = 5000;   % meters
speed = 80;      % meters per second
climbRate = 50;  % meters per second
initialYaw = 90; % degrees
pitch = 15;      % degrees

initPos = [radius, 0, 0];
initVel = [0, speed, climbRate];
initOrientation = quaternion([initialYaw,pitch,0],'eulerd','zyx','frame');

trajectory = kinematicTrajectory('SampleRate',fs, ...
```

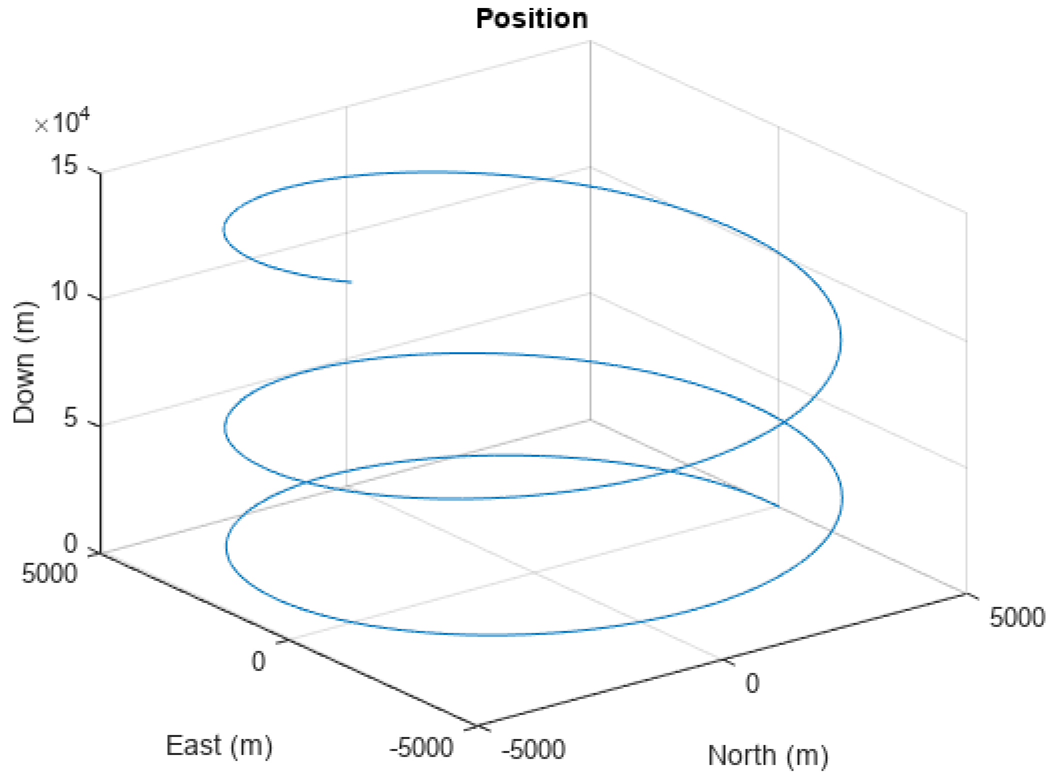
```
    'Velocity',initVel, ...
    'Position',initPos, ...
    'Orientation',initOrientation);
```

Specify a constant acceleration and angular velocity in the body coordinate system. Rotate the body frame to account for the pitch.

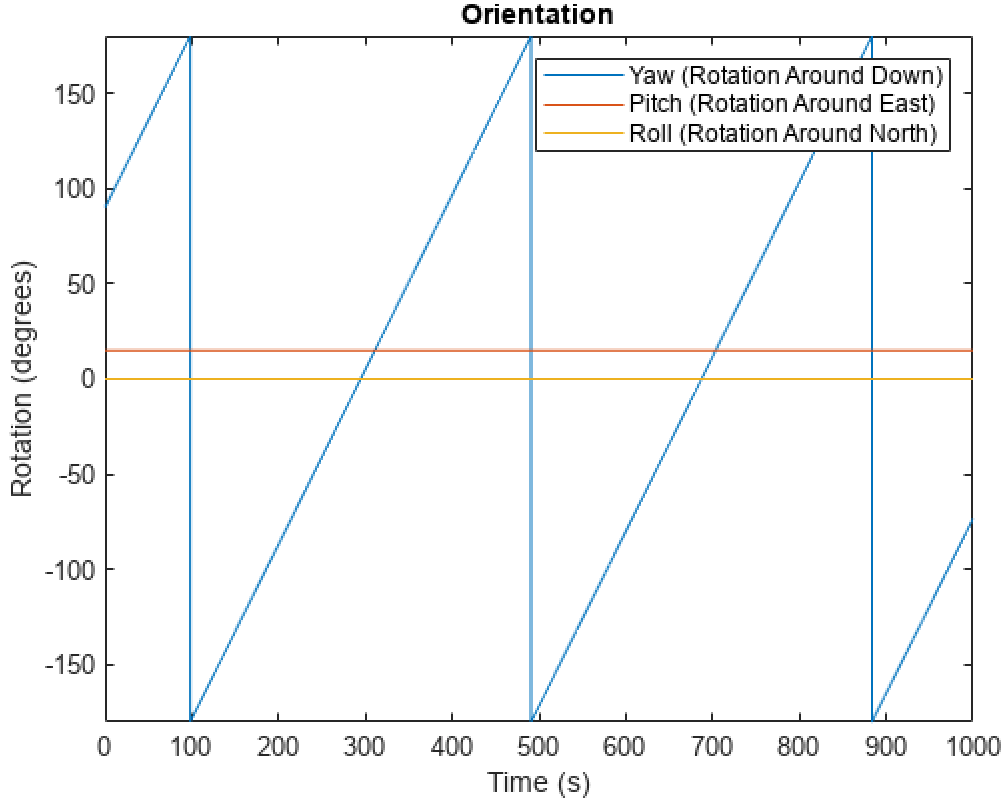
```
accBody = zeros(N,3);
accBody(:,2) = speed^2/radius;
accBody(:,3) = 0.2;

angVelBody = zeros(N,3);
angVelBody(:,3) = speed/radius;

pitchRotation = quaternion([0,pitch,0],'eulerd','zyx','frame');
angVelBody = rotateframe(pitchRotation,angVelBody);
accBody = rotateframe(pitchRotation,accBody);
```

Call `trajectory` with the specified acceleration and angular velocity in the body coordinate system. Plot the position, orientation, and speed over time.

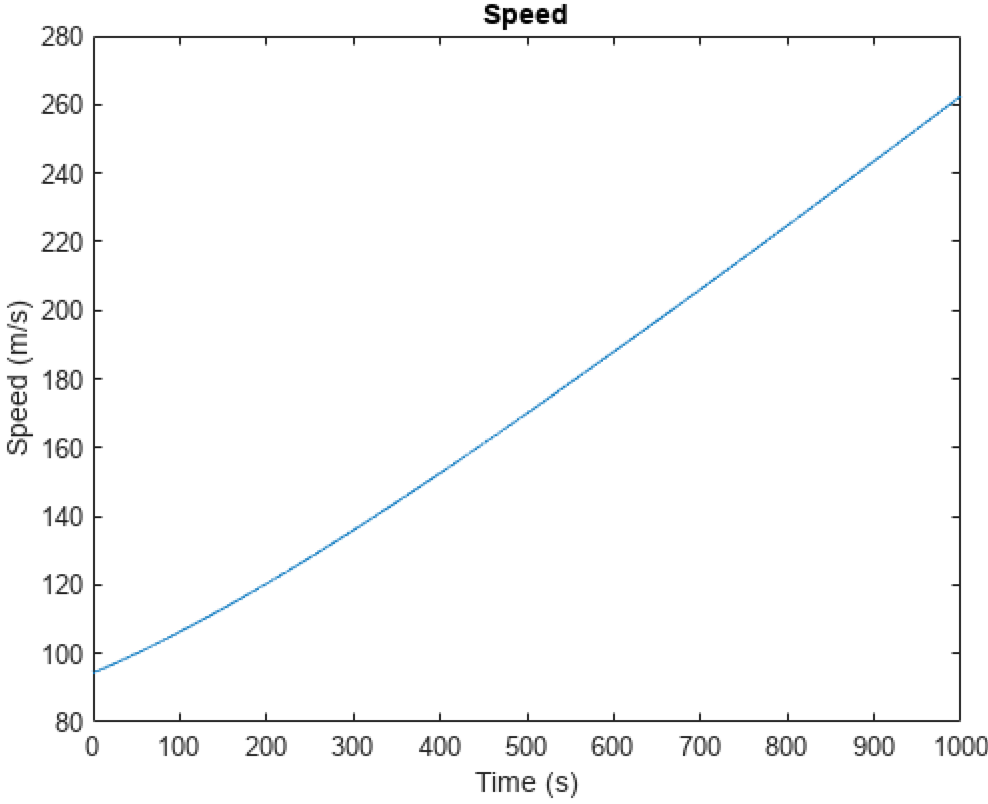
```
[position, orientation, velocity] = trajectory(accBody,angVelBody);

eulerAngles = eulerd(orientation,'ZYX','frame');
speed = sqrt(sum(velocity.^2,2));

timeVector = (0:(N-1))/fs;

figure(1)
plot3(position(:,1),position(:,2),position(:,3))
xlabel('North (m)')
ylabel('East (m)')
zlabel('Down (m)')
title('Position')
grid on
```




```
figure(2)
plot(timeVector,eulerAngles(:,1),...
     timeVector,eulerAngles(:,2),...
     timeVector,eulerAngles(:,3))
axis([0,duration,-180,180])
legend('Yaw (Rotation Around Down)','Pitch (Rotation Around East)','Roll (Rotation Around North)
xlabel('Time (s)')
ylabel('Rotation (degrees)')
title('Orientation')
```




```
figure(3)
plot(timeVector,speed)
xlabel('Time (s)')
ylabel('Speed (m/s)')
title('Speed')
```




**Generate Spiraling Circular Trajectory with No Inputs**

Define a constant angular velocity and constant acceleration that describe a spiraling circular trajectory.

```
Fs = 100;
r = 10;
speed = 2.5;
initialYaw = 90;

initPos = [r 0 0];
initVel = [0 speed 0];
initOrient = quaternion([initialYaw 0 0], 'eulerd', 'ZYX', 'frame');

accBody = [0 speed^2/r 0.01];
angVelBody = [0 0 speed/r];
```

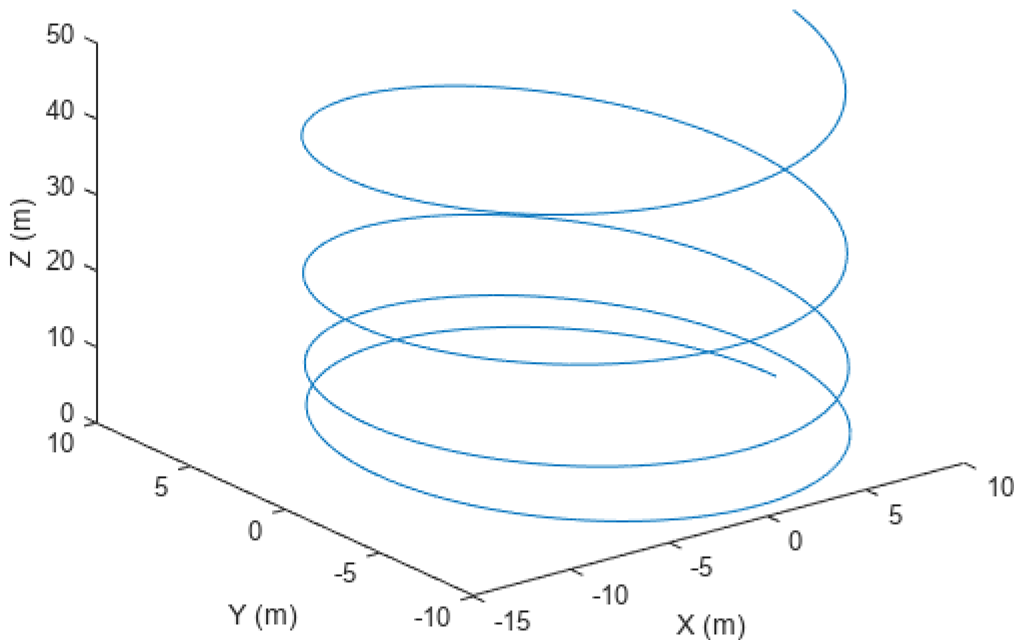
Create a kinematic trajectory object.

```
traj = kinematicTrajectory('SampleRate',Fs, ...
    'Position',initPos, ...
    'Velocity',initVel, ...
    'Orientation',initOrient, ...
    'AccelerationSource','Property', ...
    'Acceleration',accBody, ...
```

```
    'AngularVelocitySource','Property', ...
    'AngularVelocity',angVelBody);
```

Call the kinematic trajectory object in a loop and log the position output. Plot the position over time.

```
N = 10000;
pos = zeros(N, 3);
for i = 1:N
    pos(i,:) = traj();
end

plot3(pos(:,1), pos(:,2), pos(:,3))
title('Position')
xlabel('X (m)')
ylabel('Y (m)')
zlabel('Z (m)')
```




# Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

The object functions, `perturbations` and `perturb`, do not support code generation.

Usage notes and limitations:

"System Objects in MATLAB Code Generation" (MATLAB Coder)

## See Also

`waypointTrajectory`

# lidarScan

Create object for storing 2-D lidar scan

## Description

A `lidarScan` object contains data for a single 2-D lidar (light detection and ranging) scan. The lidar scan is a laser scan for a 2-D plane with distances (`Ranges`) measured from the sensor to obstacles in the environment at specific angles (`Angles`). Use this laser scan object as an input to other robotics algorithms such as `matchScans`, `controllerVFH`, or `monteCarloLocalization`.

## Creation

### Syntax

```
scan = lidarScan(ranges,angles)
scan = lidarScan(cart)
```

#### Description

`scan = lidarScan(ranges,angles)` creates a `lidarScan` object from the `ranges` and `angles`, that represent the data collected from a lidar sensor. The `ranges` and `angles` inputs are vectors of the same length and are set directly to the `Ranges` and `Angles` properties.

`scan = lidarScan(cart)` creates a `lidarScan` object using the input Cartesian coordinates as an *n*-by-2 matrix. The `Cartesian` property is set directly from this input.

`scan = lidarScan(scanMsg)` creates a `lidarScan` object from a `LaserScan` ROS message object.

### Properties

**Ranges — Range readings from lidar in meters**
vector

Range readings from lidar, specified as a vector in meters. This vector is the same length as `Angles`, and the vector elements are measured in meters.

Data Types: `single` | `double`

**`Angles` — Angle of readings from lidar in radians**
vector

Angle of range readings from lidar, specified as a vector. This vector is the same length as `Ranges`, and the vector elements are measured in radians. Angles are measured counter-clockwise around the positive *z*-axis.

Data Types: `single` | `double`

**`Cartesian` — Cartesian coordinates of lidar readings in meters**
`[x y]` matrix

Cartesian coordinates of lidar readings, returned as an `[x y]` matrix. In the lidar coordinate frame, positive *x* is forward and positive *y* is to the left.

Data Types: `single` | `double`

**`Count` — Number of lidar readings**
scalar

Number of lidar readings, returned as a scalar. This scalar is also equal to the length of the `Ranges` and `Angles` vectors or the number of rows in `Cartesian`.

Data Types: `double`

## Object Functions

| | |
|---|---|
| plot | Display laser or lidar scan readings |
| removeInvalidData | Remove invalid range and angle data |
| transformScan | Transform laser scan based on relative pose |

## Examples

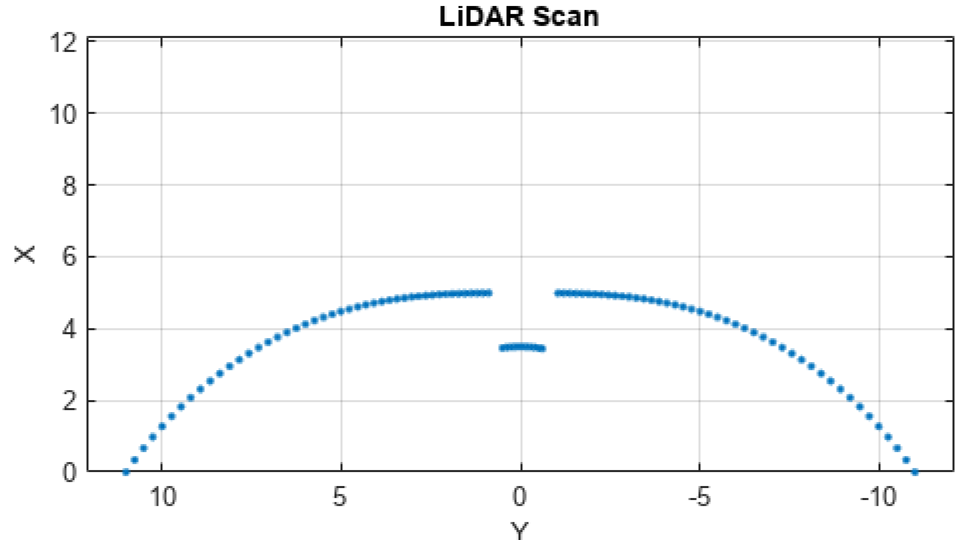
### Plot Lidar Scan and Remove Invalid Points

Specify lidar data as vectors of ranges and angles. These values include readings outside of the sensors range.

```
x = linspace(-2,2);
ranges = abs((1.5).*x.^2 + 5);
ranges(45:55) = 3.5;
angles = linspace(-pi/2,pi/2,numel(ranges));
```

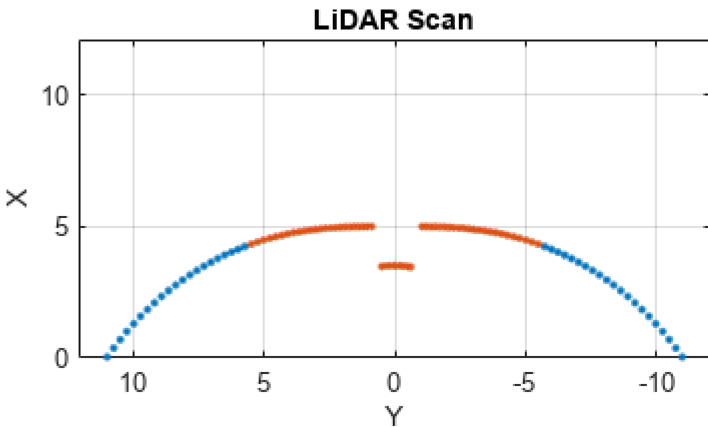
Create a lidar scan by specifying the ranges and angles. Plot all points of the lidar scan.

```
scan = lidarScan(ranges,angles);
plot(scan)
```




Remove invalid points based on a specified minimum and maximum range.

```
minRange = 0.1;
maxRange = 7;
scan2 = removeInvalidData(scan,'RangeLimits',[minRange maxRange]);
hold on
plot(scan2)
legend('All Points','Valid Points')
```




#### Transform Laser Scans

Create a `lidarScan` object. Specify the ranges and angles as vectors.

```
refRanges = 5*ones(1,300);
refAngles = linspace(-pi/2,pi/2,300);
refScan = lidarScan(refRanges,refAngles);
```

Translate the laser scan by an `[x y]` offset of `(0.5,0.2)`.

```
transformedScan = transformScan(refScan,[0.5 0.2 0]);
```

Rotate the laser scan by 20 degrees.

```
rotateScan = transformScan(refScan,[0,0,deg2rad(20)]);
```

#### Match Lidar Scans

Create a reference lidar scan using `lidarScan` (Robotics System Toolbox). Specify ranges and angles as vectors.

```
refRanges = 5*ones(1,300);
refAngles = linspace(-pi/2,pi/2,300);
refScan = lidarScan(refRanges,refAngles);
```

Using the `transformScan` (Robotics System Toolbox) function, generate a second lidar scan at an `x,y` offset of `(0.5,0.2)`.

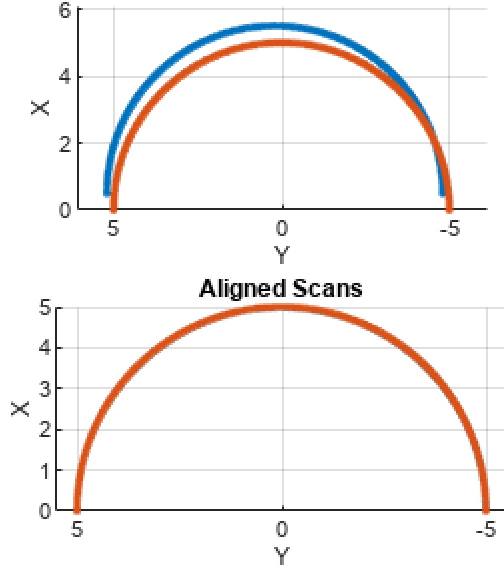
```
currScan = transformScan(refScan,[0.5 0.2 0]);
```

Match the reference scan and the second scan to estimate the pose difference between them.

```
pose = matchScans(currScan,refScan);
```

Use the `transformScan` function to align the scans by transforming the second scan into the frame of the first scan using the relative pose difference. Plot both the original scans and the aligned scans.

```
currScan2 = transformScan(currScan,pose);

subplot(2,1,1);
hold on
plot(currScan)
plot(refScan)
title('Original Scans')
hold off

subplot(2,1,2);
hold on
plot(currScan2)
plot(refScan)
title('Aligned Scans')
xlim([0 5])
hold off
```




## Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation
Generate C and C++ code using MATLAB® Coder™.

Usage notes and limitations:

Lidar scans require a limited size in code generation. The lidar scans are limited to 4000 points (range and angles) as a maximum.

## See Also
`matchScans` | `transformScan` | `controllerVFH` | `monteCarloLocalization`

# plot

Display laser or lidar scan readings

## Syntax

```
plot(scanObj)
plot( ___ ,Name,Value)
linehandle = plot( ___ )
```

## Description

`plot(scanObj)` plots the lidar scan readings specified in `scanObj`.

`plot( ___ ,Name,Value)` provides additional options specified by one or more `Name,Value` pair arguments.

`linehandle = plot( ___ )` returns a column vector of line series handles, using any of the arguments from previous syntaxes. Use `linehandle` to modify properties of the line series after it is created.

## Examples

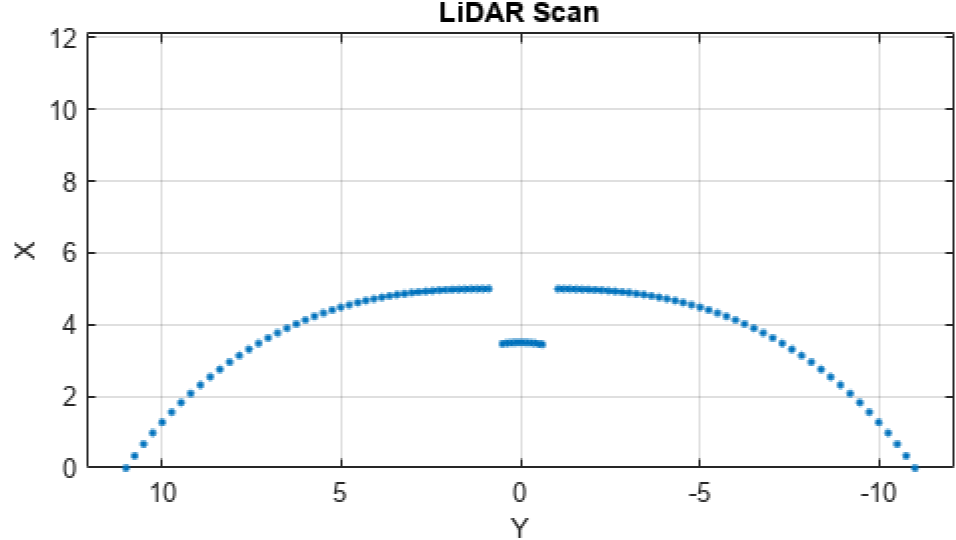
### Plot Lidar Scan and Remove Invalid Points

Specify lidar data as vectors of ranges and angles. These values include readings outside of the sensors range.

```
x = linspace(-2,2);
ranges = abs((1.5).*x.^2 + 5);
ranges(45:55) = 3.5;
angles = linspace(-pi/2,pi/2,numel(ranges));
```

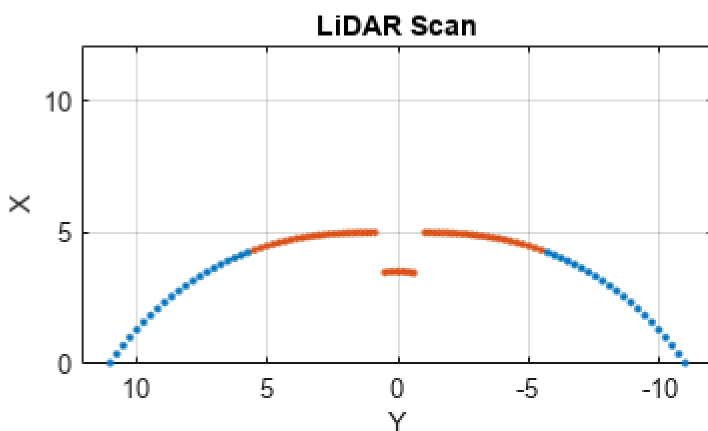
Create a lidar scan by specifying the ranges and angles. Plot all points of the lidar scan.

```
scan = lidarScan(ranges,angles);
plot(scan)
```




Remove invalid points based on a specified minimum and maximum range.

```
minRange = 0.1;
maxRange = 7;
scan2 = removeInvalidData(scan,'RangeLimits',[minRange maxRange]);
hold on
plot(scan2)
legend('All Points','Valid Points')
```




## Input Arguments

**`scanObj` — Lidar scan readings**
`lidarScan` object

Lidar scan readings, specified as a `lidarScan` object.

### Name-Value Pair Arguments

Specify optional pairs of arguments as `Name1=Value1,...,NameN=ValueN`, where `Name` is the argument name and `Value` is the corresponding value. Name-value arguments must appear after other arguments, but the order of the pairs does not matter.

*Before R2021a, use commas to separate each name and value, and enclose* `Name` *in quotes.*

Example: `"MaximumRange",5`

**`Parent` — Parent of axes**
axes object

Parent of axes, specified as the comma-separated pair consisting of `"Parent"` and an axes object in which the laser scan is drawn. By default, the laser scan is plotted in the currently active axes.

**`MaximumRange` — Range of laser scan**
`scan.RangeMax` (default) | scalar

Range of laser scan, specified as the comma-separated pair consisting of "MaximumRange" and a scalar. When you specify this name-value pair argument, the minimum and maximum *x*-axis and the maximum *y*-axis limits are set based on specified value. The minimum *y*-axis limit is automatically determined by the opening angle of the laser scanner.

This name-value pair only works when you input scanMsg as the laser scan.

## Outputs

**linehandle — One or more chart line objects**
scalar | vector

One or more chart line objects, returned as a scalar or a vector. These are unique identifiers, which you can use to query and modify properties of a specific chart line.

# Version History

**Introduced in R2015a**

## See Also

matchScans | transformScan | controllerVFH | monteCarloLocalization

**Topics**

"Estimate Robot Pose with Scan Matching"

# lidarSLAM

Perform localization and mapping using lidar scans

## Description

The `lidarSLAM` class performs simultaneous localization and mapping (SLAM) for lidar scan sensor inputs. The SLAM algorithm takes in lidar scans and attaches them to a node in an underlying pose graph. The algorithm then correlates the scans using scan matching. It also searches for loop closures, where scans overlap previously mapped regions, and optimizes the node poses in the pose graph.

## Creation

### Syntax

```
slamObj = lidarSLAM
slamObj = lidarSLAM(mapResolution,maxLidarRange)
slamObj = lidarSLAM(mapResolution,maxLidarRange,maxNumScans)
```

#### Description

`slamObj = lidarSLAM` creates a lidar SLAM object. The default occupancy map size is 20 cells per meter. The maximum range for each lidar scan is 8 meters.

`slamObj = lidarSLAM(mapResolution,maxLidarRange)` creates a lidar SLAM object and sets the `MapResolution` and `MaxLidarRange` properties based on the inputs.

`slamObj = lidarSLAM(mapResolution,maxLidarRange,maxNumScans)` specifies the upper bound on the number of accepted scans allowed when generating code. `maxNumScans` is a positive integer. This scan limit is only required when generating code.

## Properties

**PoseGraph — Underlying pose graph that connects scans**
`poseGraph` object

Underlying pose graph that connects scans, specified as a `poseGraph` object. Adding scans to `lidarSLAM` updates this pose graph. When loop closures are found, the pose graph is optimized using `OptimizationFcn`.

**MapResolution — Resolution of occupancy grid map**
`20` cells per meter (default) | positive integer

Resolution of the occupancy grid map, specified as a positive integer in cells per meter. Specify the map resolution on construction.

**MaxLidarRange — Maximum range of lidar sensor**
`8` meters (default) | positive scalar

Maximum range of the lidar sensor, specified as a positive scalar in meters. Specify the maximum range on construction.

**`OptimizationFcn` — Pose graph optimization function**
`optimizePoseGraph` (default) | function handle

Pose graph optimization function, specified as a function handle. By default, the algorithm calls the `optimizePoseGraph` function. To specify your own optimization method, the class requires the function signature to be:

```
[updatedPose,stat] = myOptimizationFcn(poseGraph)
```

`poseGraph` is a `poseGraph` object. `updatedPose` is an *n*-by-3 vector of `[x y theta]` poses listed in sequential node ID order. `stat` is a structure containing a `ResidualError` field as a positive scalar. Use the `stat` structure to include other information relevant to your optimization.

**`LoopClosureThreshold` — Threshold for accepting loop closures**
`100` (default) | positive scalar

Threshold on the score from the scan matching algorithm for accepting loop closures, specified as a positive scalar. Higher thresholds correspond to a better match, but scores vary based on sensor data.

**`LoopClosureSearchRadius` — Search radius for loop closure detection**
`8` meters (default) | positive scalar

Search radius for loop closure detection, specified as a positive scalar. Increasing this radius affects performance by increasing search time. Tune this distance based on your environment and the expected vehicle trajectory.

**`LoopClosureMaxAttempts` — Number of attempts at finding loop closures**
`1` (default) | positive integer

Number of attempts at finding looping closures, specified as a positive integer. Increasing the number of attempts affects performance by increasing search time.

**`LoopClosureAutoRollback` — Allow automatic rollback of added loop closures**
`true` (default) | `false`

Allow automatic rollback of added loop closures, specified as `true` or `false`. The SLAM object tracks the residual error returned by the `OptimizationFcn`. If it detects a sudden change in the residual error and this property is `true`, it rejects (rolls back) the loop closure.

**`OptimizationInterval` — Number of loop closures accepted to trigger optimization**
`1` (default) | positive integer

Number of loop closures accepted to trigger optimization, specified as a positive integer. By default, the `PoseGraph` is optimized every time `lidarSLAM` adds a loop closure.

**`MovementThreshold` — Minimum change in pose required to process scans**
`[0 0]` (default) | `[translation rotation]`

Minimum change in pose required to process scans, specified as a `[translation rotation]` vector. A relative pose change for a newly added scan is calculated as `[x y theta]`. If the translation in *xy*-position or rotation of `theta` exceeds these thresholds, the `lidarSLAM` object accepts the scan and adds a pose is added to the `PoseGraph`.

**`ScanRegistrationMethod` — Scan registration method**
`'BranchAndBound'` (default) | `'PhaseCorrelation'`

Scan registration method, specified as a character vector.

---
**Note** Image Processing Toolbox™ is required for using Phase Correlation method.

---

**`TranslationSearchRange` — Incremental match translational search range**
`[maxLidarRange/2 maxLidarRange/2]` (default) | two-element vector of the form `[x y]`

Incremental match translational search range, specified as a two-element vector of the form `[x y]` in meters. This property is only applicable when the `ScanRegistrationMethod` property is set to `'BranchAndBound'`.

These values define the search window around the initial translation estimate specified in the `relPoseEst` argument of the `addScan` function. Set the value of this property to the maximum expected translation between consecutive accepted scans.

This property is similar to the `'TranslationSearchRange'` name-value pair argument in `matchScansGrid` function.

**`RotationSearchRange` — Incremental match rotational search range**
`pi/2` (default) | positive scalar

Incremental match rotational search range, specified as positive scalar in radians. This property is only applicable when the `ScanRegistrationMethod` property is set to `'BranchAndBound'`.

This values define the search window around the initial rotation estimate specified in the `relPoseEst` argument of the `addScan` function. Set the value of this property to the maximum expected rotation between consecutive accepted scans.

This property is similar to the `'RotationSearchRange'` name-value pair argument in `matchScansGrid` function.

## Object Functions

| | |
|---|---|
| addScan | Add scan to lidar SLAM map |
| copy | Copy lidar SLAM object |
| removeLoopClosures | Remove loop closures from pose graph |
| scansAndPoses | Extract scans and corresponding poses |
| show | Plot scans and robot poses |

## Examples

### Perform SLAM Using Lidar Scans

Use a `lidarSLAM` object to iteratively add and compare lidar scans and build an optimized pose graph of the robot trajectory. To get an occupancy map from the associated poses and scans, use the `buildMap` function.

### Load Data and Set Up SLAM Algorithm

Load a cell array of `lidarScan` objects. The lidar scans were collected in a parking garage on a Husky® robot from ClearPath Robotics®. Typically, lidar scans are taken at a high frequency and each scan is not needed for SLAM. Therefore, down sample the scans by selecting only every 40th scan.

```
load garage_fl1_southend.mat scans
scans = scans(1:40:end);
```

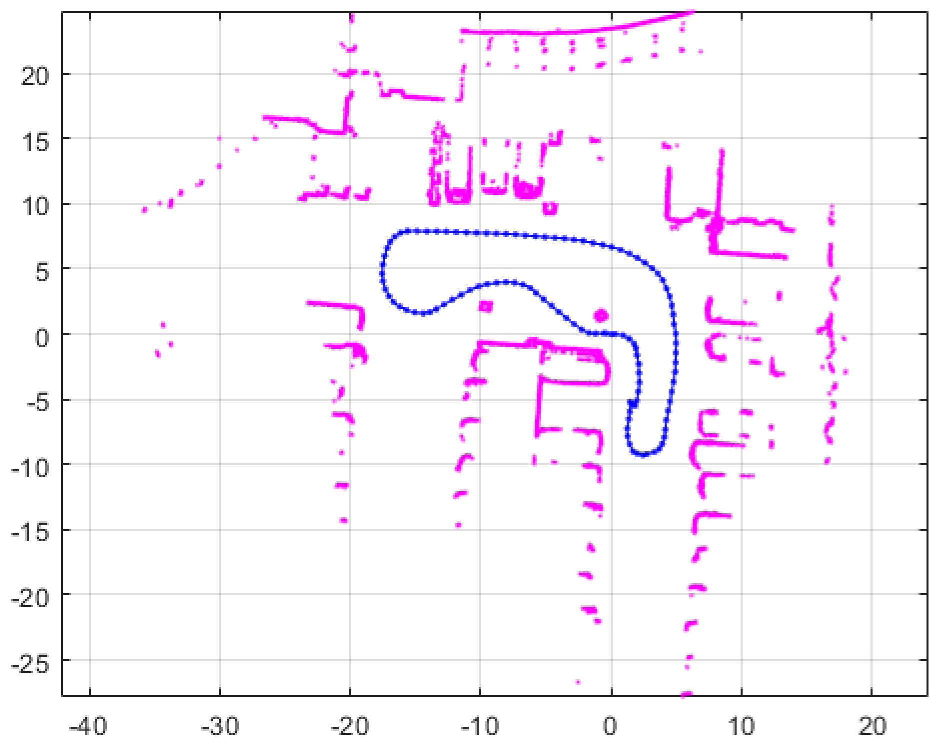
To set up the SLAM algorithm, specify the lidar range, map resolution, loop closure threshold, and search radius. Tune these parameters for your specific robot and environment. Create the `lidarSLAM` object with these parameters.

```
maxRange = 19.2; % meters
resolution = 10; % cells per meter

slamObj = lidarSLAM(resolution,maxRange);
slamObj.LoopClosureThreshold = 360;
slamObj.LoopClosureSearchRadius = 8;
```

### Add Scans Iteratively

Using a `for` loop, add scans to the SLAM object. The object uses scan matching to compare each added scan to previously added ones. To improve the map, the object optimizes the pose graph whenever it detects a loop closure. Every 10 scans, display the stored poses and scans.

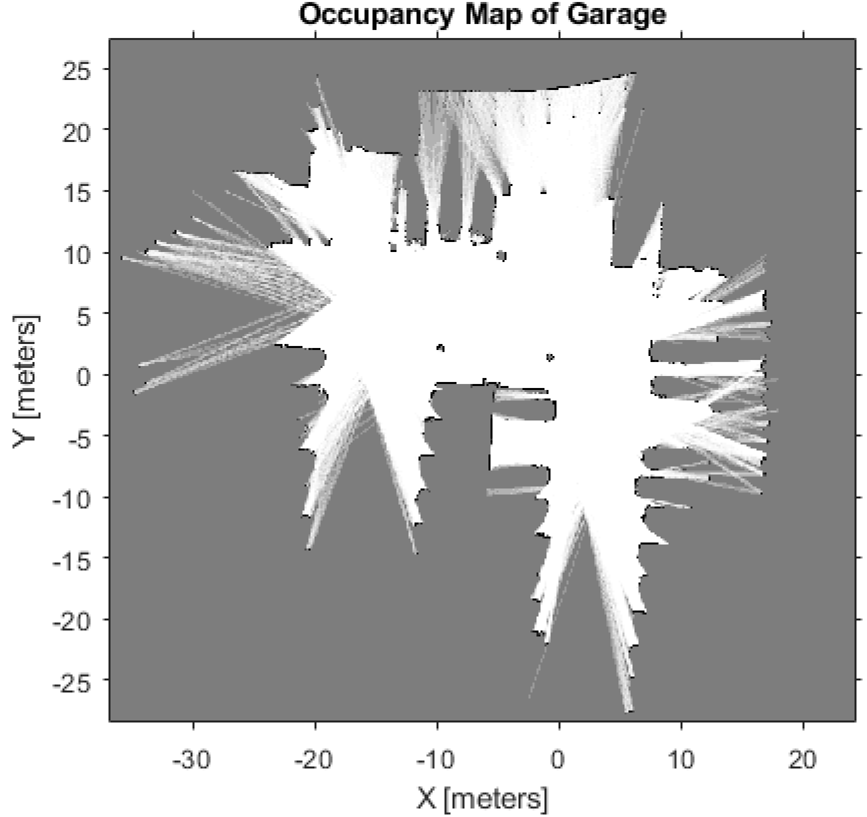
```
for i = 1:numel(scans)

    addScan(slamObj,scans{i});

    if rem(i,10) == 0
        show(slamObj);
    end
end
```




### View Occupancy Map

After adding all the scans to the SLAM object, build an `occupancyMap` map by calling `buildMap` with the scans and poses. Use the same map resolution and max range you used with the SLAM object.

```
[scansSLAM,poses] = scansAndPoses(slamObj);
occMap = buildMap(scansSLAM,poses,resolution,maxRange);
figure
show(occMap)
title('Occupancy Map of Garage')
```




## More About

### SLAM

Simultaneous localization and mapping (SLAM) is a general concept for algorithms correlating different sensor readings to build a map of a vehicle environment and track pose estimates. Different algorithms use different types of sensors and methods for correlating data.

The `lidarSLAM` algorithm uses lidar scans and odometry information as sensor inputs. The lidar scans map the environment and are correlated between each other to build an underlying pose graph of the vehicle trajectory. Odometry information is an optional input that gives an initial pose estimate for the scans to aid in the correlation. Scan matching algorithms correlate scans to previously added scans to estimate the relative pose between them and add them to an underlying pose graph.

The pose graph contains nodes connected by edges that represent the relative poses of the vehicle. Edges specify constraints on the node as an information matrix. To correct for drifting pose estimates, the algorithm optimizes over the whole pose graph whenever it detects loop closures.

The algorithm assumes that data comes from a vehicle navigating an environment and incrementally getting laser scans along its path. Therefore, scans are first compared to the most recent scan to identify relative poses and are added to the pose graph incrementally. However, the algorithm also searches for loop closures, which identify when the vehicle scans an area that was previously visited.

When working with SLAM algorithms, the environment and vehicle sensors affect the performance and data correlation quality. Tune your parameters properly for your expected environment or dataset.

# Version History

**Introduced in R2019b**

## References

[1] Hess, Wolfgang, Damon Kohler, Holger Rapp, and Daniel Andor. "Real-Time Loop Closure in 2D LIDAR SLAM." *2016 IEEE International Conference on Robotics and Automation (ICRA)*. 2016.

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

Use this syntax when constructing `lidarSLAM` objects for code generation:

`slamObj= lidarSLAM(mapResolution,maxLidarRange,maxNumScans)` specifies the upper bound on the number of accepted scans allowed when generating code. `maxNumScans` is a positive integer. This scan limit is only required when generating code.

## See Also

`poseGraph` | `optimizePoseGraph`

### Topics

"Implement Simultaneous Localization And Mapping (SLAM) with Lidar Scans"
"Implement Online Simultaneous Localization And Mapping (SLAM) with Lidar Scans"

# addScan

Add scan to lidar SLAM map

## Syntax

```
addScan(slamObj,currScan)
addScan(slamObj,currScan,relPoseEst)
[isAccepted,loopClosureInfo,optimInfo] = addScan( ___ )
```

## Description

`addScan(slamObj,currScan)` adds a lidar scan, `currScan`, to the lidar SLAM object, `slamObj`. The function uses scan matching to correlate this scan to the most recent one, then adds it to the pose graph defined in `slamObj`. If the scan is accepted, `addScan` detects loop closures and optimizes based on settings in `slamObj`.

`addScan(slamObj,currScan,relPoseEst)` also specifies a relative pose to the latest lidar scan pose in `slamObj`. This relative pose improves the scan matching.

**Note** The `relPoseEst` input is ignored when the `ScanRegistrationMethod` property of `lidarSLAM` object is set to `'PhaseCorrelation'`.

`[isAccepted,loopClosureInfo,optimInfo] = addScan( ___ )` outputs detailed information about adding the scan to the SLAM object. `isAccepted` indicates if the scan is added or rejected. `loopClosureInfo` and `optimInfo` indicate if a loop closure is detected or the pose graph is optimized.

## Examples

### Perform SLAM Using Lidar Scans

Use a `lidarSLAM` object to iteratively add and compare lidar scans and build an optimized pose graph of the robot trajectory. To get an occupancy map from the associated poses and scans, use the `buildMap` function.

#### Load Data and Set Up SLAM Algorithm

Load a cell array of `lidarScan` objects. The lidar scans were collected in a parking garage on a Husky® robot from ClearPath Robotics®. Typically, lidar scans are taken at a high frequency and each scan is not needed for SLAM. Therefore, down sample the scans by selecting only every 40th scan.

```
load garage_fl1_southend.mat scans
scans = scans(1:40:end);
```

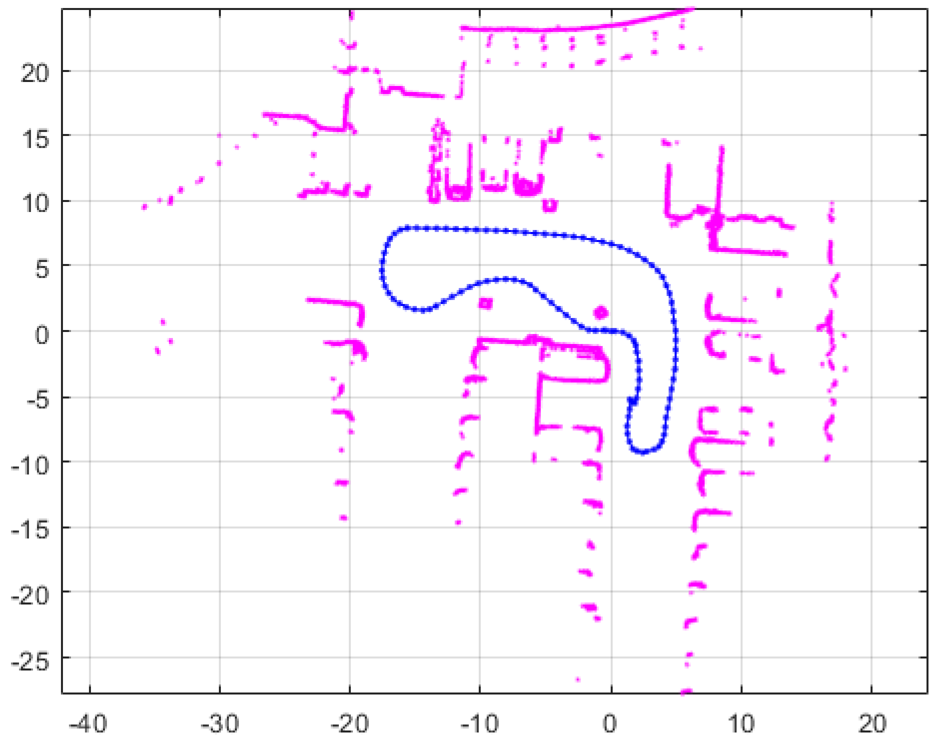
To set up the SLAM algorithm, specify the lidar range, map resolution, loop closure threshold, and search radius. Tune these parameters for your specific robot and environment. Create the `lidarSLAM` object with these parameters.

```
maxRange = 19.2; % meters
resolution = 10; % cells per meter

slamObj = lidarSLAM(resolution,maxRange);
slamObj.LoopClosureThreshold = 360;
slamObj.LoopClosureSearchRadius = 8;
```

#### Add Scans Iteratively

Using a `for` loop, add scans to the SLAM object. The object uses scan matching to compare each added scan to previously added ones. To improve the map, the object optimizes the pose graph whenever it detects a loop closure. Every 10 scans, display the stored poses and scans.

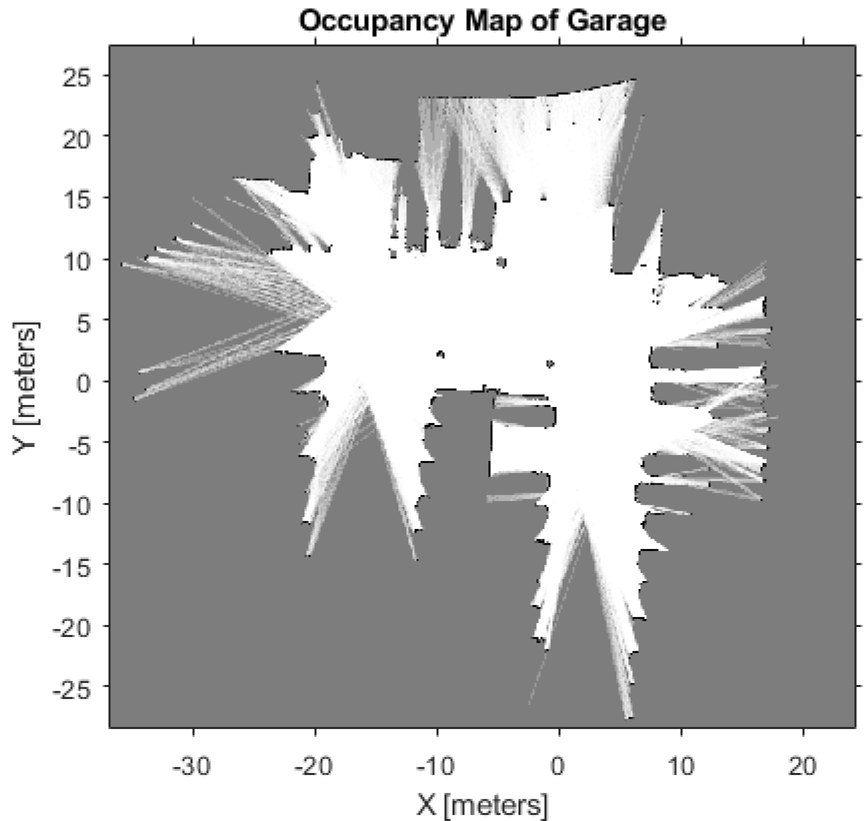
```
for i = 1:numel(scans)

    addScan(slamObj,scans{i});

    if rem(i,10) == 0
        show(slamObj);
    end
end
```




#### View Occupancy Map

After adding all the scans to the SLAM object, build an `occupancyMap` map by calling `buildMap` with the scans and poses. Use the same map resolution and max range you used with the SLAM object.

```
[scansSLAM,poses] = scansAndPoses(slamObj);
occMap = buildMap(scansSLAM,poses,resolution,maxRange);
figure
show(occMap)
title('Occupancy Map of Garage')
```




## Input Arguments

**slamObj — Lidar SLAM object**
lidarSLAM object

Lidar SLAM object, specified as a lidarSLAM object. The object contains the SLAM algorithm parameters, sensor data, and underlying pose graph used to build the map.

**currScan — Lidar scan reading**
lidarScan object

Lidar scan reading, specified as a lidarScan object. This scan is correlated to the most recent scan in slamObj using scan matching.

**relPoseEst — Relative pose estimate of scan**
[x y theta] vector

Relative pose estimate of scan, specified as an [x y theta] vector. This relative pose improves scan matching.

## Output Arguments

**`isAccepted` — Indicates if scan is accepted**
`true` | `false`

Indicates if scan is accepted, returned as `true` or `false`. If the relative pose between scans is below the `MovementThreshold` property of `slamObj`, the scan is rejected. By default, all scans are accepted.

**`loopClosureInfo` — Loop closure details**
structure

Loop closure details, returned as a structure with these fields:

- `EdgeIDs` –– IDs of newly connected edges in the pose graph, returned as a vector.
- `Edges` –– Newly added loop closure edges, returned as an *n*-by-2 matrix of node IDs that each edge connects.
- `Scores` –– Scores of newly connected edges in the pose graph returned from scan matching, returned as a vector.

---

**Note** If the `LoopClosureAutoRollback` property is set to `true` in `slamObj`, loop closure edges can be removed from the pose graph. This property rejects loops closures if the residual error changes drastically after optimization. Therefore, some of the edge IDs listed in this structure may not exist in the actual pose graph.

---

**`optimInfo` — Pose graph optimization details**
structure

Pose graph optimization details, returned as a structure with these fields:

- `IsPerformed` –– Boolean indicating if optimization is performed when adding this scan. Optimization performance depends on the `OptimizationInterval` property in `slamObj`.
- `IsAccepted` –– Boolean indicating if optimization was accepted based on `ResidualError`.
- `ResidualError` –– Error associated with optimization, returned as a scalar.
- `LoopClosureRemoved` –– List of IDs of loop closure edges removed during optimization, returned as a vector.

# Version History

**Introduced in R2019b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

Use this syntax when constructing `lidarSLAM` objects for code generation:

`slamObj= lidarSLAM(mapResolution,maxLidarRange,maxNumScans)` specifies the upper bound on the number of accepted scans allowed when generating code. `maxNumScans` is a positive integer. This scan limit is only required when generating code.

## See Also

`poseGraph` | `optimizePoseGraph`

### Topics

"Implement Simultaneous Localization And Mapping (SLAM) with Lidar Scans"
"Implement Online Simultaneous Localization And Mapping (SLAM) with Lidar Scans"

# copy

Copy lidar SLAM object

## Syntax

```
newSlamObj = copy(slamObj)
```

## Description

`newSlamObj = copy(slamObj)` creates a deep copy of `slamObj` with the same properties. Any changes made to `newSlamObj` are not reflected in `slamObj`.

## Examples

### Create Copy of Lidar SLAM

Create a `lidarSLAM` object.

```
slamObj = lidarSLAM
```

```
slamObj = 
  lidarSLAM with properties:

                 PoseGraph: [1x1 poseGraph]
             MapResolution: 20
             MaxLidarRange: 8
           OptimizationFcn: @optimizePoseGraph
      LoopClosureThreshold: 100
   LoopClosureSearchRadius: 8
    LoopClosureMaxAttempts: 1
   LoopClosureAutoRollback: 1
      OptimizationInterval: 1
         MovementThreshold: [0 0]
    ScanRegistrationMethod: 'BranchAndBound'
    TranslationSearchRange: [4 4]
       RotationSearchRange: 1.5708
```

Create a copy of the lidar SLAM object.

```
slamObjNew = copy(slamObj)
```

```
slamObjNew = 
  lidarSLAM with properties:

                 PoseGraph: [1x1 poseGraph]
             MapResolution: 20
             MaxLidarRange: 8
           OptimizationFcn: @optimizePoseGraph
      LoopClosureThreshold: 100
   LoopClosureSearchRadius: 8
```

```
     LoopClosureMaxAttempts: 1
    LoopClosureAutoRollback: 1
       OptimizationInterval: 1
          MovementThreshold: [0 0]
     ScanRegistrationMethod: 'BranchAndBound'
     TranslationSearchRange: [4 4]
        RotationSearchRange: 1.5708
```

#### Remove Loop Closures from Pose Graph in Lidar SLAM Object

Load laser scan data from a file.

```
load("offlineSlamData.mat");
```

To set up the SLAM algorithm:

1. Specify the lidar range, map resolution, loop closure threshold, and search radius.
2. Tune these parameters for your specific robot and environment.
3. Create the `lidarSLAM` object with these parameters.

```
maxLidarRange = 8;
mapResolution = 20;
slamObj = lidarSLAM(mapResolution,maxLidarRange);
slamObj.LoopClosureThreshold = 210;
slamObj.LoopClosureSearchRadius = 8;
```

Add scans iteratively to the SLAM object.

```
for i = 1:numel(scans)
    addScan(slamObj,scans{i});
end
```

Create a copy of the SLAM object. Display the underlying pose graph of the SLAM object.

```
slamObj2 = copy(slamObj);
slamObj2.PoseGraph
```

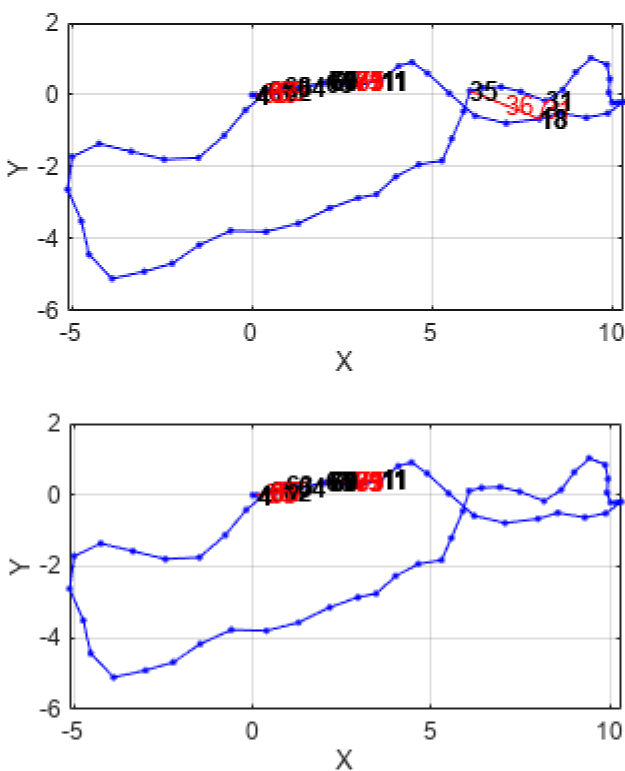
```
ans = 
  poseGraph with properties:

               NumNodes: 71
               NumEdges: 83
    NumLoopClosureEdges: 13
     LoopClosureEdgeIDs: [31 36 63 65 67 69 71 73 75 77 79 81 83]
        LandmarkNodeIDs: [1x0 double]
```

Remove the first two loop closures by specifying their edge IDs.

```
lcEdgeIDs = slamObj2.PoseGraph.LoopClosureEdgeIDs(1:2);
removeLoopClosures(slamObj2,lcEdgeIDs)
```

Plot the pose graphs of the SLAM object before and after removing the loop closures.

```
subplot(2,1,1)
show(slamObj.PoseGraph);
subplot(2,1,2)
show(slamObj2.PoseGraph);
```




## Input Arguments

**slamObj — Lidar SLAM object**
lidarSLAM object

Lidar SLAM object, specified as a lidarSLAM object. The object contains the SLAM algorithm parameters, sensor data, and underlying pose graph used to build the map.

## Output Arguments

**newSlamObj — Lidar SLAM object**
lidarSLAM object

Lidar SLAM object, returned as a lidarSLAM object.

# Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

Use this syntax when constructing `lidarSLAM` objects for code generation:

`slamObj= lidarSLAM(mapResolution,maxLidarRange,maxNumScans)` specifies the upper bound on the number of accepted scans allowed when generating code. `maxNumScans` is a positive integer. This scan limit is only required when generating code.

## See Also

`poseGraph` | `optimizePoseGraph`

### Topics

"Implement Simultaneous Localization And Mapping (SLAM) with Lidar Scans"
"Implement Online Simultaneous Localization And Mapping (SLAM) with Lidar Scans"

# removeLoopClosures

Remove loop closures from pose graph

## Syntax

```
removeLoopClosures(slamObj)
removeLoopClosures(slamObj,lcEdgeIDs)
```

## Description

`removeLoopClosures(slamObj)` removes all loop closures from the underlying pose graph in `slamObj`.

`removeLoopClosures(slamObj,lcEdgeIDs)` removes the loop closure edges with the specified IDs from the underlying pose graph in `slamObj`.

## Examples

### Remove Loop Closures from Pose Graph in Lidar SLAM Object

Load laser scan data from a file.

```
load("offlineSlamData.mat");
```

To set up the SLAM algorithm:

1. Specify the lidar range, map resolution, loop closure threshold, and search radius.
2. Tune these parameters for your specific robot and environment.
3. Create the `lidarSLAM` object with these parameters.

```
maxLidarRange = 8;
mapResolution = 20;
slamObj = lidarSLAM(mapResolution,maxLidarRange);
slamObj.LoopClosureThreshold = 210;
slamObj.LoopClosureSearchRadius = 8;
```

Add scans iteratively to the SLAM object.

```
for i = 1:numel(scans)
    addScan(slamObj,scans{i});
end
```

Create a copy of the SLAM object. Display the underlying pose graph of the SLAM object.

```
slamObj2 = copy(slamObj);
slamObj2.PoseGraph
```

```
ans = 
  poseGraph with properties:
```

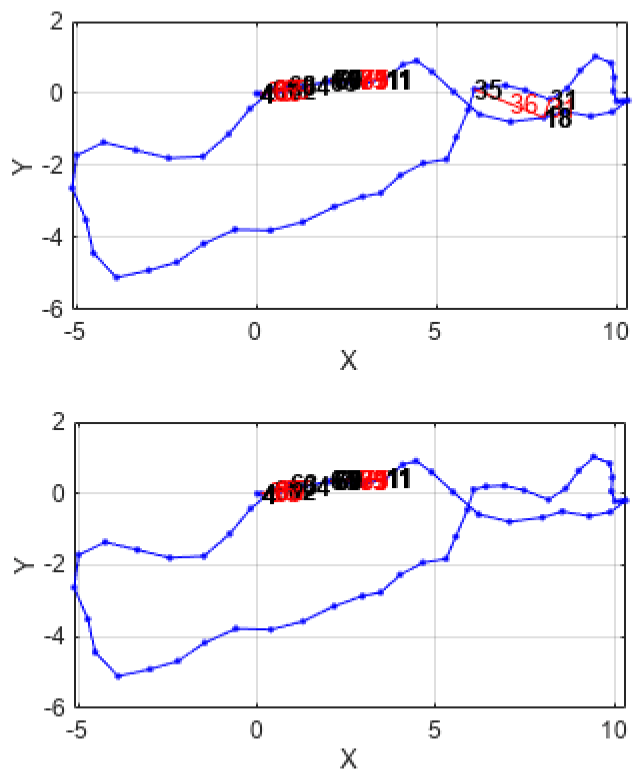
```
             NumNodes: 71
             NumEdges: 83
    NumLoopClosureEdges: 13
     LoopClosureEdgeIDs: [31 36 63 65 67 69 71 73 75 77 79 81 83]
        LandmarkNodeIDs: [1x0 double]
```

Remove the first two loop closures by specifying their edge IDs.

```
lcEdgeIDs = slamObj2.PoseGraph.LoopClosureEdgeIDs(1:2);
removeLoopClosures(slamObj2,lcEdgeIDs)
```

Plot the pose graphs of the SLAM object before and after removing the loop closures.

```
subplot(2,1,1)
show(slamObj.PoseGraph);
subplot(2,1,2)
show(slamObj2.PoseGraph);
```




## Input Arguments

**slamObj — Lidar SLAM object**
`lidarSLAM` object

Lidar SLAM object, specified as a `lidarSLAM` object. The object contains the SLAM algorithm parameters, sensor data, and underlying pose graph used to build the map

**`lcEdgeIDs` — Loop closure edge IDs**
vector of positive integers

Loop closure edge IDs, specified as a vector of positive integers. To find specific edge IDs, use `findEdgeID` on the underlying `poseGraph` object defined in `slamObj`.

# Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

Use this syntax when constructing `lidarSLAM` objects for code generation:

`slamObj= lidarSLAM(mapResolution,maxLidarRange,maxNumScans)` specifies the upper bound on the number of accepted scans allowed when generating code. `maxNumScans` is a positive integer. This scan limit is only required when generating code.

## See Also

`poseGraph` | `optimizePoseGraph`

### Topics

“Implement Simultaneous Localization And Mapping (SLAM) with Lidar Scans”
“Implement Online Simultaneous Localization And Mapping (SLAM) with Lidar Scans”

# scansAndPoses

Extract scans and corresponding poses

## Syntax

```
[scans,poses] = scansAndPoses(slamObj)
[scans,poses] = scansAndPoses(slamObj,nodeIDs)
```

## Description

`[scans,poses] = scansAndPoses(slamObj)` returns the scans used by the `lidarSLAM` object as `lidarScan` objects, along with their associated `[x y theta]` poses from the underlying pose graph of `slamObj`.

`[scans,poses] = scansAndPoses(slamObj,nodeIDs)` returns the scans and poses for the specific node IDs. To get the node IDs, see the underlying `poseGraph` object in `slamObj` for the node IDs.

## Examples

#### Perform SLAM Using Lidar Scans

Use a `lidarSLAM` object to iteratively add and compare lidar scans and build an optimized pose graph of the robot trajectory. To get an occupancy map from the associated poses and scans, use the `buildMap` function.

#### Load Data and Set Up SLAM Algorithm

Load a cell array of `lidarScan` objects. The lidar scans were collected in a parking garage on a Husky® robot from ClearPath Robotics®. Typically, lidar scans are taken at a high frequency and each scan is not needed for SLAM. Therefore, down sample the scans by selecting only every 40th scan.

```
load garage_fl1_southend.mat scans
scans = scans(1:40:end);
```

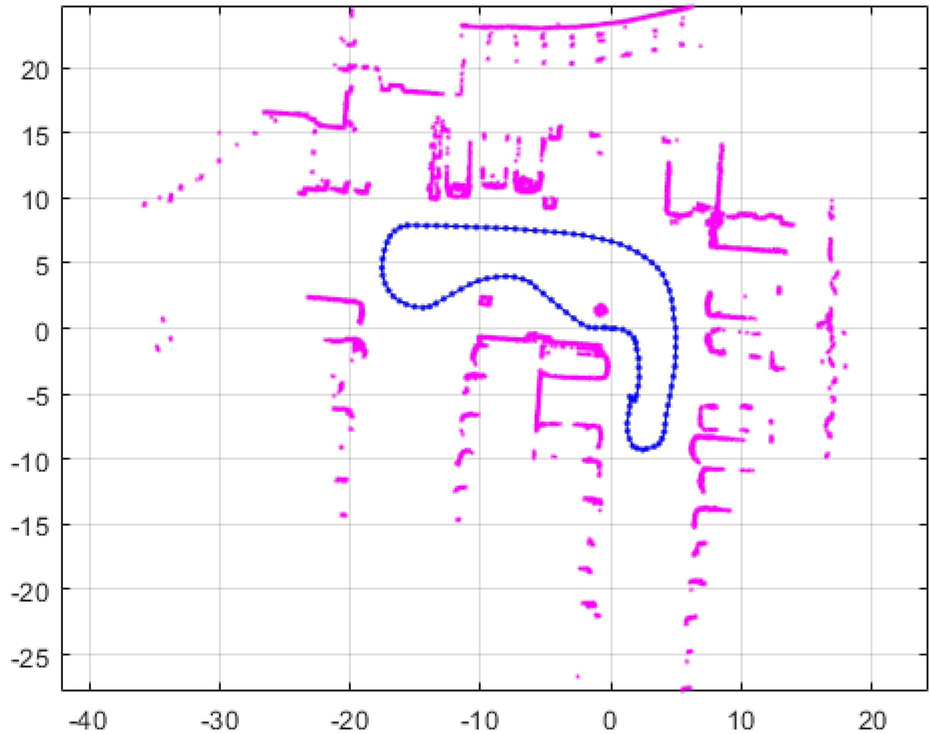
To set up the SLAM algorithm, specify the lidar range, map resolution, loop closure threshold, and search radius. Tune these parameters for your specific robot and environment. Create the `lidarSLAM` object with these parameters.

```
maxRange = 19.2; % meters
resolution = 10; % cells per meter

slamObj = lidarSLAM(resolution,maxRange);
slamObj.LoopClosureThreshold = 360;
slamObj.LoopClosureSearchRadius = 8;
```

### Add Scans Iteratively

Using a `for` loop, add scans to the SLAM object. The object uses scan matching to compare each added scan to previously added ones. To improve the map, the object optimizes the pose graph whenever it detects a loop closure. Every 10 scans, display the stored poses and scans.

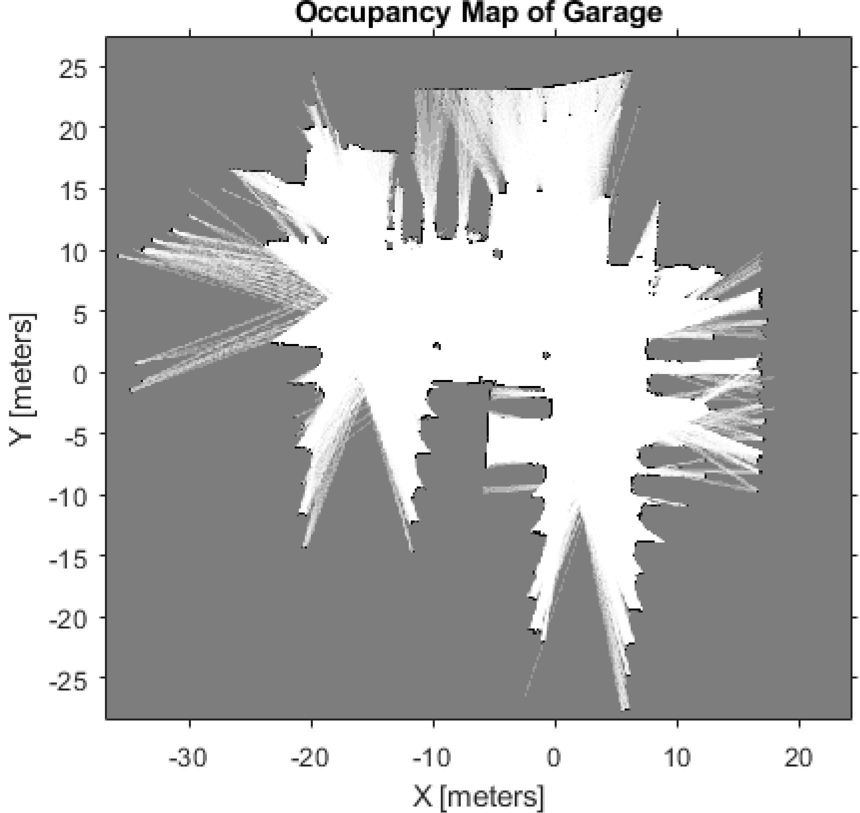
```
for i = 1:numel(scans)

    addScan(slamObj,scans{i});

    if rem(i,10) == 0
        show(slamObj);
    end
end
```




### View Occupancy Map

After adding all the scans to the SLAM object, build an `occupancyMap` map by calling `buildMap` with the scans and poses. Use the same map resolution and max range you used with the SLAM object.

```
[scansSLAM,poses] = scansAndPoses(slamObj);
occMap = buildMap(scansSLAM,poses,resolution,maxRange);
figure
show(occMap)
title('Occupancy Map of Garage')
```




## Input Arguments

**slamObj — Lidar SLAM object**
lidarSLAM object

Lidar SLAM object, specified as a `lidarSLAM` object. The object contains the SLAM algorithm parameters, sensor data, and underlying pose graph used to build the map.

**nodeIDs — Node IDs from pose graph**
positive integer

Node IDs from pose graph, specified as a positive integer. Nodes are added to the pose graph with sequential ID numbers. To get the node IDs, see the underlying `poseGraph` object in `slamObj` for the node IDs.

## Output Arguments

**scans — Lidar scan readings**
lidarScan object

Lidar scan readings, returned as a `lidarScan` object.

**poses — Pose for each scan**
*n*-by-3 matrix | [x y theta] vectors

Pose for each scan, returned as an *n*-by-3 matrix of `[x y theta]` vectors. Each row is a pose that corresponds to a scan in `scans`.

## Version History

**Introduced in R2019b**

### Extended Capabilities

#### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

Use this syntax when constructing `lidarSLAM` objects for code generation:

`slamObj= lidarSLAM(mapResolution,maxLidarRange,maxNumScans)` specifies the upper bound on the number of accepted scans allowed when generating code. `maxNumScans` is a positive integer. This scan limit is only required when generating code.

## See Also

`poseGraph` | `optimizePoseGraph`

#### Topics

"Implement Simultaneous Localization And Mapping (SLAM) with Lidar Scans"
"Implement Online Simultaneous Localization And Mapping (SLAM) with Lidar Scans"

# show

Plot scans and robot poses

## Syntax

```
show(slamObj)
show(slamObj,Name,Value)
axes = show(___)
```

## Description

`show(slamObj)` plots all the scans added to the `input lidarSLAM` object overlaid with the lidar poses in its underlying pose graph.

`show(slamObj,Name,Value)` specifies options using `Name,Value` pair arguments. For example, `"Poses","off"` turns off display of the underlying pose graph in `slamObj`.

`axes = show(___)` returns the axes handle that the lidar SLAM data is plotted to using any of the previous syntaxes.

## Examples

### Perform SLAM Using Lidar Scans

Use a `lidarSLAM` object to iteratively add and compare lidar scans and build an optimized pose graph of the robot trajectory. To get an occupancy map from the associated poses and scans, use the `buildMap` function.

#### Load Data and Set Up SLAM Algorithm

Load a cell array of `lidarScan` objects. The lidar scans were collected in a parking garage on a Husky® robot from ClearPath Robotics®. Typically, lidar scans are taken at a high frequency and each scan is not needed for SLAM. Therefore, down sample the scans by selecting only every 40th scan.

```
load garage_fl1_southend.mat scans
scans = scans(1:40:end);
```

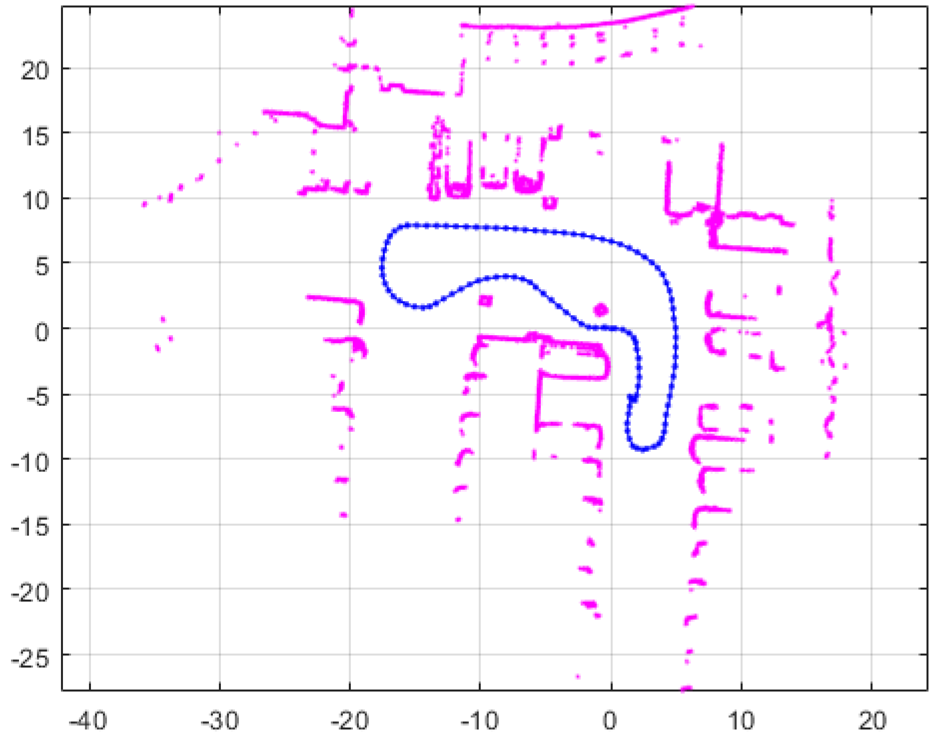
To set up the SLAM algorithm, specify the lidar range, map resolution, loop closure threshold, and search radius. Tune these parameters for your specific robot and environment. Create the `lidarSLAM` object with these parameters.

```
maxRange = 19.2; % meters
resolution = 10; % cells per meter

slamObj = lidarSLAM(resolution,maxRange);
slamObj.LoopClosureThreshold = 360;
slamObj.LoopClosureSearchRadius = 8;
```

### Add Scans Iteratively

Using a `for` loop, add scans to the SLAM object. The object uses scan matching to compare each added scan to previously added ones. To improve the map, the object optimizes the pose graph whenever it detects a loop closure. Every 10 scans, display the stored poses and scans.

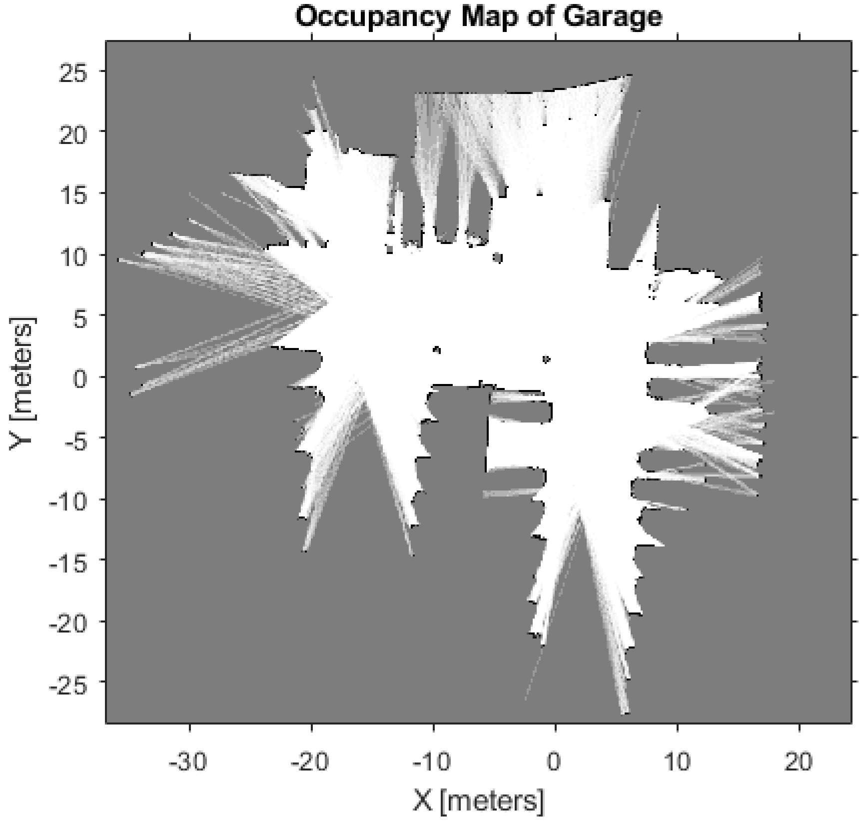
```
for i = 1:numel(scans)

    addScan(slamObj,scans{i});

    if rem(i,10) == 0
        show(slamObj);
    end
end
```




### View Occupancy Map

After adding all the scans to the SLAM object, build an `occupancyMap` map by calling `buildMap` with the scans and poses. Use the same map resolution and max range you used with the SLAM object.

```
[scansSLAM,poses] = scansAndPoses(slamObj);
occMap = buildMap(scansSLAM,poses,resolution,maxRange);
figure
show(occMap)
title('Occupancy Map of Garage')
```




## Input Arguments

**slamObj — Lidar SLAM object**
lidarSLAM object

Lidar SLAM object, specified as a lidarSLAM object. The object contains the SLAM algorithm parameters, sensor data, and underlying pose graph used to build the map.

### Name-Value Pair Arguments

Specify optional pairs of arguments as Name1=Value1,...,NameN=ValueN, where Name is the argument name and Value is the corresponding value. Name-value arguments must appear after other arguments, but the order of the pairs does not matter.

*Before R2021a, use commas to separate each name and value, and enclose* Name *in quotes.*

Example: "Poses","off"

**Parent — Axes used to plot pose graph**
Axes object | UIAxes object

Axes used to plot the pose graph, specified as the comma-separated pair consisting of "Parent" and either an Axes or UIAxes object. See axes or uiaxes.

**Poses — Display lidar poses**
"on" (default) | "off"

Display lidar poses, specified as the comma-separated pair consisting of `"Poses"` and `"on"` or `"off"`.

### Output Arguments

**axes — Axes used to plot the map**
`Axes` object | `UIAxes` object

Axes used to plot the map, returned as either an `Axes` or `UIAxes` object. See `axes` or `uiaxes`.

## Version History

**Introduced in R2019b**

### See Also

`poseGraph` | `optimizePoseGraph`

**Topics**

"Implement Simultaneous Localization And Mapping (SLAM) with Lidar Scans"
"Implement Online Simultaneous Localization And Mapping (SLAM) with Lidar Scans"

# likelihoodFieldSensorModel

Create a likelihood field range sensor model

## Description

The `likelihoodFieldSensor` object creates a likelihood field sensor model object for range sensors. This object contains specific sensor model parameters. You can use this object to specify the model parameters in a `monteCarloLocalization` object.

## Creation

### Syntax

`lf = likelihoodFieldSensorModel`

#### Description

`lf = likelihoodFieldSensorModel` creates a likelihood field sensor model object for range sensors.

### Properties

**`Map` — Occupancy grid representing the map**
`binaryOccupancyMap` object (default)

Occupancy grid representing the map, specified as a `binaryOccupancyMap` object. This object represents the environment of the vehicle as a grid with binary values indicating obstacles as `true` (`1`) and free locations as `false` (`0`).

**`SensorPose` — Pose of the range sensor relative to the vehicle**
[0 0 0] (default) | three-element vector

Pose of the range sensor relative to the coordinate frame of the vehicle, specified as a three-element vector, `[x y theta]`.

**`SensorLimits` — Minimum and maximum range of sensor**
[0 12] (default) | two-element vector

Minimum and maximum range of sensor, specified as a two-element vector in meters.

**`NumBeams` — Number of beams used for likelihood computation**
60 (default) | scalar

Number of beams used for likelihood computation, specified as a scalar. The computation efficiency can be improved by specifying a smaller number of beams than the actual number available from the sensor.

**MeasurementNoise — Standard deviation for measurement noise**
0.2 (default) | scalar

Standard deviation for measurement noise, specified as a scalar.

**RandomMeasurementWeight — Weight for probability of random measurement**
0.05 (default) | scalar

Weight for probability of random measurement, specified as a scalar. This scalar is the probability that the measurement is not accurate due to random interference.

**ExpectedMeasurementWeight — Weight for probability of expected measurement**
0.95 (default) | scalar

Weight for probability of expected measurement, specified as a scalar. The weight is the probability of getting a correct range measurement within the noise limits specified in MeasurementNoise property.

**MaxLikelihoodDistance — Maximum distance to find nearest obstacles**
2.0 (default) | scalar

Maximum distance to find nearest obstacles, specified as a scalar in meters.

## Limitations

If you change your sensor model after using it with the monteCarloLocalization object, call release on that object beforehand. For example:

```
mcl = monteCarloLocalization;
[isUpdated,pose,covariance] = mcl(ranges,angles);
release(mcl)
mcl.SensorModel.NumBeams = 120;
```

# Version History

**Introduced in R2019b**

## See Also

monteCarloLocalization | odometryMotionModel

**Topics**

“Localize TurtleBot Using Monte Carlo Localization Algorithm”
“Monte Carlo Localization Algorithm”

# magparams

Magnetometer sensor parameters

## Description

The `magparams` class creates a magnetometer sensor parameters object. You can use this object to model a magnetometer when simulating an IMU with `imuSensor`. See the “Algorithms” on page 2-545 section of `imuSensor` for details of `magparams` modeling.

## Creation

### Syntax

```
params = magarams
params = magparams(Name,Value)
```

#### Description

`params = magarams` returns an ideal magnetometer sensor parameters object with default values.

`params = magparams(Name,Value)` configures `magparams` object properties using one or more `Name,Value` pair arguments. `Name` is a property name and `Value` is the corresponding value. `Name` must appear inside single quotes (`''`). You can specify several name-value pair arguments in any order as `Name1,Value1,...,NameN,ValueN`. Any unspecified properties take default values.

### Properties

**`MeasurementRange` — Maximum sensor reading (μT)**
`Inf` (default) | real positive scalar

Maximum sensor reading in μT, specified as a real positive scalar.

Data Types: `single` | `double`

**`Resolution` — Resolution of sensor measurements (μT/LSB)**
`0` (default) | real nonnegative scalar

Resolution of sensor measurements in μT/LSB, specified as a real nonnegative scalar. Here, LSB is the acronym for least significant bit.

Data Types: `single` | `double`

**`ConstantBias` — Constant sensor offset bias (μT)**
`[0 0 0]` (default) | real scalar | real 3-element row vector

Constant sensor offset bias in μT, specified as a real scalar or 3-element row vector. Any scalar input is converted into a real 3-element row vector where each element has the input scalar value.

Data Types: `single` | `double`

**AxesMisalignment — Sensor axes skew (%)**
`diag([100 100 100])` (default) | scalar in the range [0,100] | 3-element row vector in the range [0,100] | 3-by-3 matrix in the range [0,100]

Sensor axes skew in percentage, specified as a scalar, a 3-element row vector, or a 3-by-3 matrix with values ranging from `0` to `100`. The diagonal elements of the matrix account for the misalignment effects for each axes. The off-diagonal elements account for the cross-axes misalignment effects. The measured state $v_{measure}$ is obtained from the true state $v_{true}$ via the misalignment matrix as:

$$v_{measure} = \frac{1}{100} M v_{true} = \frac{1}{100} \begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{bmatrix} v_{true}$$

- If you specify the property as a scalar, then all the off-diagonal elements of the matrix take the value of the specified scalar and all the diagonal elements are 100.
- If you specify the property as a vector [$a$ $b$ $c$], then $m_{21} = m_{31} = a$, $m_{12} = m_{32} = b$, and $m_{13} = m_{23} = c$. All the diagonal elements are 100.

Data Types: `single` | `double`

**NoiseDensity — Power spectral density of sensor noise (μT/√Hz)**
`[0 0 0]` (default) | real scalar | real 3-element row vector

Power spectral density of sensor noise in μT/√Hz, specified as a real scalar or 3-element row vector. Any scalar input is converted into a real 3-element row vector where each element has the input scalar value.

Data Types: `single` | `double`

**BiasInstability — Instability of the bias offset (μT)**
`[0 0 0]` (default) | real scalar | real 3-element row vector

Instability of the bias offset in μT, specified as a real scalar or 3-element row vector. Any scalar input is converted into a real 3-element row vector where each element has the input scalar value.

Data Types: `single` | `double`

**RandomWalk — Integrated white noise of sensor (μT/√Hz)**
`[0 0 0]` (default) | real scalar | real 3-element row vector

Integrated white noise of sensor in (μT/√Hz), specified as a real scalar or 3-element row vector. Any scalar input is converted into a real 3-element row vector where each element has the input scalar value.

Data Types: `single` | `double`

**TemperatureBias — Sensor bias from temperature (μT/°C)**
`[0 0 0]` (default) | real scalar | real 3-element row vector

Sensor bias from temperature in (μT/℃), specified as a real scalar or 3-element row vector. Any scalar input is converted into a real 3-element row vector where each element has the input scalar value.

Data Types: `single` | `double`

**TemperatureScaleFactor — Scale factor error from temperature (%/°C)**
`[0 0 0]` (default) | real scalar in the range [0,100] | real 3-element row vector in the range [0,100]

Scale factor error from temperature in (%/℃), specified as a real scalar or 3-element row vector with values ranging from 0 to 100. Any scalar input is converted into a real 3-element row vector where each element has the input scalar value.

Data Types: `single` | `double`

## Examples

### Generate Magnetometer Data from Stationary Inputs

Generate magnetometer data for an imuSensor object from stationary inputs.

Generate a magnetometer parameter object with a maximum sensor reading of 1200 μT and a resolution of 0.1 μT/LSB. The constant offset bias is 1 μT. The sensor has a power spectral density of $\left(\frac{[0.6\ 0.6\ 0.9]}{\sqrt{100}}\right)$ μT/$\sqrt{\text{Hz}}$. The bias from temperature is [0.8 0.8 2.4] μT/$^0$C. The scale factor error from temperature is 0.1 %/$^0$C.

```
params = magparams('MeasurementRange',1200,'Resolution',0.1,'ConstantBias',1,'NoiseDensity',[0.6
```

Use a sample rate of 100 Hz spaced out over 1000 samples. Create the imuSensor object using the magnetometer parameter object.

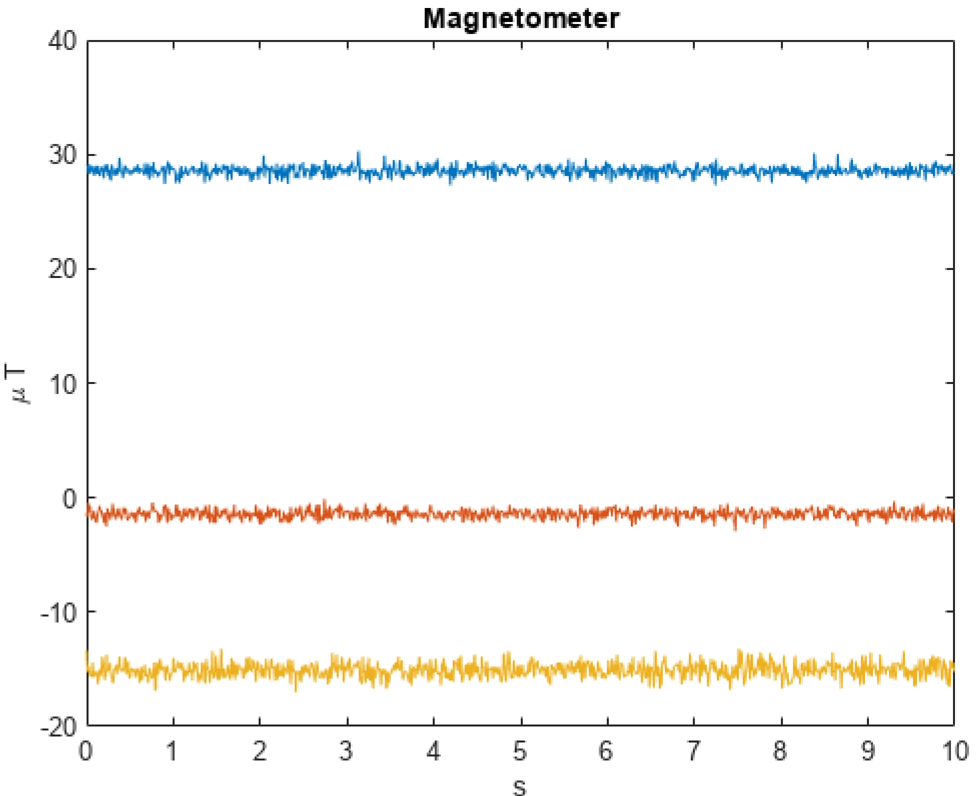
```
Fs = 100;
numSamples = 1000;
t = 0:1/Fs:(numSamples-1)/Fs;

imu = imuSensor('accel-mag','SampleRate', Fs, 'Magnetometer', params);
```

Generate magnetometer data from the imuSensor object.

```
orient = quaternion.ones(numSamples, 1);
acc = zeros(numSamples, 3);
angvel = zeros(numSamples, 3);

[~, magData] = imu(acc, angvel, orient);
```

Plot the resultant magnetometer data.

```
plot(t, magData)
title('Magnetometer')
xlabel('s')
ylabel('\mu T')
```




# Version History

**Introduced in R2018b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`accelparams` | `gyroparams` | `imuSensor`

# mapLayer

Create map layer for *N*-dimensional data

## Description

The `mapLayer` object creates an *N*-dimensional grid map, where the first two dimensions determine the footprint of the map, and all subsequent dimensions dictate the size and layout of the data stored in each cell. For storing scalar binary or probability values for a grid map, use the `binaryOccupancyMap` or `occupancyMap` objects instead.

A map layer stores data for grid cells that represent a discretized region of space. To query and update data using world, local, or grid coordinates, use the `getMapData` and `setMapData` object functions. Each grid cell in the map can store data of any size from a single a value to a multi-dimensional array. For more information, see the DataSize property.

Layer behavior can also be customized by providing function handles during creation using the `GetTransformFcn` and `SetTransformFcn` properties.

## Creation

### Syntax

```
map = mapLayer
map = mapLayer(p)
map = mapLayer(width,height)
map = mapLayer(rows,cols,'grid')
map = mapLayer(width,height,cellDims)
map = mapLayer(rows,cols,cellDims,'grid')
map = mapLayer(sourceMap)
map = mapLayer( ___ ,Name,Value)
```

#### Description

`map = mapLayer` creates an empty map object occupying 10-by-10 meters of space with a resolution of 1 cell per meter.

`map = mapLayer(p)` creates a map from the values in the matrix or matrix array `p`. For 3-D matrix arrays, each cell in the map is filled with the vector of values at each grid location along the third dimension of the array. For an *N*-by-*D* matrix array, each cell contains a matrix (*N*=4) or a matrix array (*N*>4) of data for that grid location.

`map = mapLayer(width,height)` creates a map covering the specified width and height with a resolution of 1 cell per meter.

`map = mapLayer(rows,cols,'grid')` creates a map with a grid size of `rows`,`cols` with a resolution of 1 cell per meter.

`map = mapLayer(width,height,cellDims)` creates the map where the size of the data stored in each cell is defined by the array of integers `cellDims`.

`map = mapLayer(rows,cols,cellDims,'grid')` creates a map with a grid size of `rowscols` where the size of the data stored in each cell is defined by the array of integers `cellDims`.

`map = mapLayer(sourceMap)` creates a new object using the layers copied from another `mapLayer` object.

`map = mapLayer( ___ ,Name,Value)` specifies property values using name-value pairs.

For example, `mapLayer(__,'LocalOriginInWorld',[15 20])` sets the local origin to a specific world location.

## Properties

**`DataSize` — Size of the *N*-dimensional data matrix**
`[10 10]` (default) | vector of integers

Size of the *N*-dimensional data matrix, specified as vector of integers. The first two dimensions define the footprint of the map, and all subsequent dimensions dictate the size and layout of the data stored in each cell. The default value assumes a single value is stored for each cell in a 10-by-10 grid.

If the map stores an *n*-element vector of values in each cell, this property would be `[width height n]`.

If the map stores a 10-by-10 grid with each cell containing a 3-by-3-by-3 matrix array, the data size would be `[10 10 3 3 3]`.

This property is set when you create the object based on the dimensions of the input matrix `p` or the inputs `width`, `height`, and `cellDims`.

After you create the object, this property is read-only.

Data Types: `double`

**`DataType` — Data type of the values stored**
`'double'` (default) | character vector

Data type of the values stored in the map, specified as a character vector.

This property is set based on the data type of the input `p` or the data type of DefaultValue. After you create the object, this property is read-only.

Data Types: `char`

**`DefaultValue` — Default value for unspecified map locations**
`0` (default) | numeric scalar

Default value for unspecified map locations including areas outside the map, specified as a numeric scalar.

If you specify the GetTransformFcn or SetTransformFcn property when creating the object, the default value is updated based on that transformation function. If you create the map with a matrix of values `p`, the transform function modifies the values before storing.

Data Types: `double`

**`GetTransformFcn` — Applies transformations to retrieved values**
function handle

Applies transformations to values retrieved by the `getMapData` function, specified as a function handle.

This function handle is called inside the `getMapData` object function. It can be used to apply a transformation to values retrieved from the map layer. The function definition must have the following format:

```
modifiedValues = getTransformFcnHandle(map,values,varargin)
```

The size of the output `modifiedValues` must match the size of the input `values`. The function provides all map data accessed from the `getMapData` object function to this transform function through the `varargin` inputs.

You can set this property when you create the object. After you create the object, this property is read-only.

Data Types: `function_handle`

**`GridLocationInWorld` — Location of the grid in local coordinates**
`[0 0]` (default) | two-element vector | `[xWorld yWorld]`

Location of the bottom-left corner of the grid in world coordinates, specified as a two-element vector, `[xWorld yWorld]`.

You can set this property when you create the object.

Data Types: `double`

**`GridOriginInLocal` — Location of the grid in local coordinates**
`[0 0]` (default) | two-element vector | `[xLocal yLocal]`

Location of the bottom-left corner of the grid in local coordinates, specified as a two-element vector, `[xLocal yLocal]`.

You can set this property when you create the object.

Data Types: `double`

**`GridSize` — Number of rows and columns in grid**
two-element integer-valued vector

Number of rows and columns in grid, stored as a 1-by-2 real-valued vector representing the number of rows and columns, in that order.

This property is set when you create the object based on the first two dimensions of the input matrix `p`, the inputs `width` and `height`, or the inputs `row` and `col`.

Data Types: `double`

**`LayerName` — Name of layer**
`'mapLayer'` (default) | character vector | string scalar

Name of map layer, specified as a character vector or string scalar.

You can set this property when you create the object. After you create the object, this property is read-only.

Data Types: double

**LocalOriginInWorld — Location of the local frame in world coordinates**
[0 0] (default) | two-element vector | [xWorld yWorld]

Location of the origin of the local frame in world coordinates, specified as a two-element vector, [xLocal yLocal]. Use the move function to shift the local frame as your vehicle moves.

You can set this property when you create the object.

Data Types: double

**Resolution — Grid resolution**
1 (default) | scalar

This property is read-only.

Grid resolution, stored as a scalar in cells per meter representing the number and size of grid locations.

You can set this property when you create the object. After you create the object, this property is read-only.

Data Types: double

**SetTransformFcn — Applies transformations to set values**
function handle

Applies transformations to values set by the setMapData function, specified as a function handle.

This function handle is called inside the setMapData object function. It can be used to apply a transformation to values set in the map layer. The function must have the following syntax:

```
modifiedValues = setTransformFcnHandle(map,values,varargin)
        if numel(varargin) == 0
            return; %
        else
          % Custom Code
        end
end
```

The size of the output, modifiedValues, must match the size of the input, values. The function provides all map data specified in the setMapData object function to this transform function. When creating this object without starting values, the function is called without additional input arguments, so specify an if-statement to return when the number of elements in varagin is zero.

You can set this property when you create the object. After you create the object, this property is read-only.

Data Types: function_handle

**XLocalLimits — Minimum and maximum values of *x*-coordinates in local frame**
two-element vector

This property is read-only.

Minimum and maximum values of *x*-coordinates in local frame, stored as a two-element horizontal vector of the form `[min max]`. Local frame is defined by `LocalOriginInWorld` property.

Data Types: `double`

**`YLocalLimits` — Minimum and maximum values of *y*-coordinates in local frame**
two-element vector

This property is read-only.

Minimum and maximum values of *y*-coordinates in local frame, stored as a two-element horizontal vector of the form `[min max]`. Local frame is defined by `LocalOriginInWorld` property.

Data Types: `double`

**`XWorldLimits` — Minimum and maximum world range values of *x*-coordinates**
two-element vector

This property is read-only.

Minimum and maximum world range values of *x*-coordinates, stored as a 1-by-2 vector representing the minimum and maximum values, in that order.

Data Types: `double`

**`YWorldLimits` — Minimum and maximum world range values of *y*-coordinates**
two-element vector

This property is read-only.

Minimum and maximum world range values of *y*-coordinates, stored as a 1-by-2 vector representing the minimum and maximum values, in that order.

Data Types: `double`

## Object Functions

| | |
|---|---|
| getMapData | Retrieve data from map layer |
| grid2local | Convert grid indices to local coordinates |
| grid2world | Convert grid indices to world coordinates |
| local2grid | Convert local coordinates to grid indices |
| local2world | Convert local coordinates to world coordinates |
| move | Move map in world frame |
| setMapData | Assign data to map layer |
| syncWith | Sync map with overlapping map |
| world2grid | Convert world coordinates to grid indices |
| world2local | Convert world coordinates to local coordinates |

## Examples

### Store and Modify XY Velocities Using A Single Map Layer

Create a map layer that stores two values per grid location as *xy*-velocities.

Create an *m*-by-*n*-by-2 matrix of values. The first element in the third dimension is d*x* and the second is d*y* as velocities.

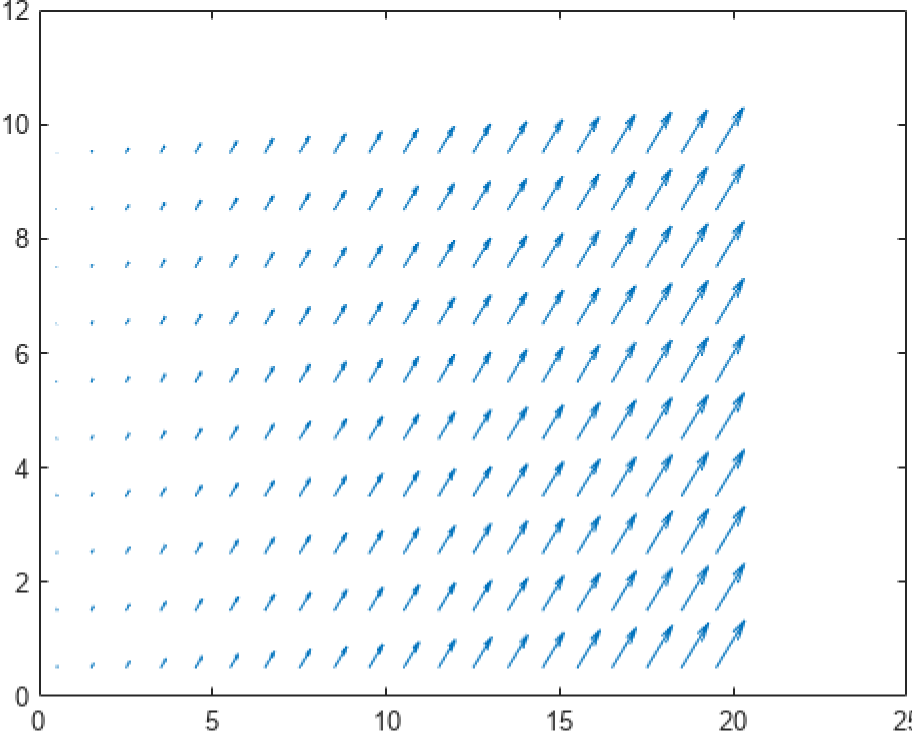
```
dXY = reshape(1:200,10,20);
dXY(:,:,2) = dXY;
```

Create a map layer from the matrix. Specify the resolution and layer name.

```
vLayer = mapLayer(dXY,'Resolution',1,'LayerName','dXY');
```

Get all the map data out as a matrix. Get the xy-locations of the velocity values by creating arrays that cover the minimum and maximum *xy*-world limits and is shifted to the grid-center locations. The *y*-locations are flipped when converting between matrix to world coordinates. Visualize the velocities corresponding to those grid-center locations using the `quiver` function.

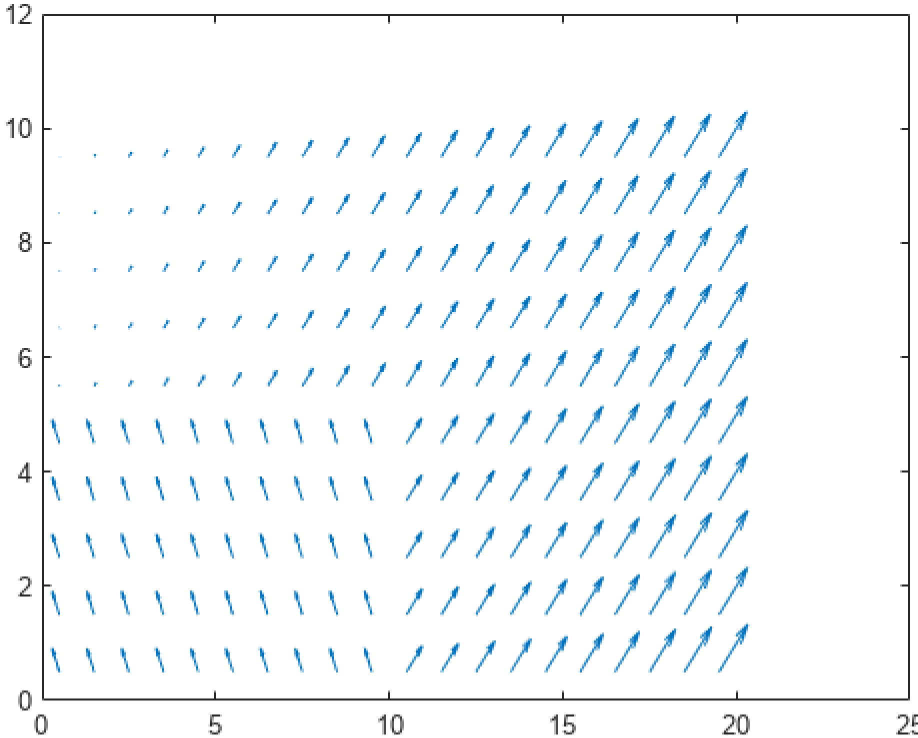
```
v = getMapData(vLayer);

R = 1/(2*vLayer.Resolution);
xLim = vLayer.XWorldLimits;
yLim = vLayer.YWorldLimits;
xLoc = (xLim(1)+R):R*2:(xLim(2)-R);
yLoc = (yLim(2)-R):-R*2:(yLim(1)+R);

quiver(xLoc,yLoc,v(:,:,1),v(:,:,2))
```




Set the bottom-left quadrant to new updated values. Create the values as a matrix and specify the bottom-left corner (0,0) in map coordinates to the `setData` function.

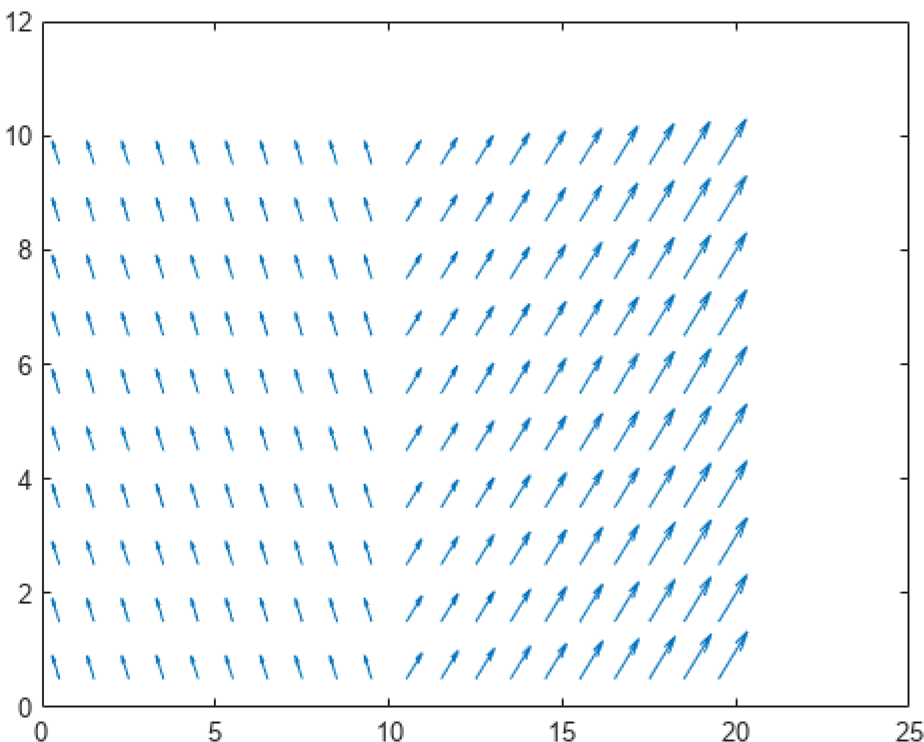
```
updateValues = repmat(reshape([-50,100],[1 1 2]),5,10);

setMapData(vLayer,[0 0],updateValues)
```

```
v = getMapData(vLayer);
quiver(xLoc,yLoc,v(:,:,1),v(:,:,2))
```




Set new values for the top-left quadrant using grid coordinates. For maps, the top-left grid location is (1,1).

```
setMapData(vLayer,[1 1],updateValues,'grid')
v = getMapData(vLayer);
quiver(xLoc,yLoc,v(:,:,1),v(:,:,2))
```




#### Write Custom Transform Functions for Map Layers

The `mapLayer` object enables you to apply custom element-wise transformations when setting and getting data in the map. To transform data you set or get from the map, specify function handles for the `GetTransfomFcn` and `SetTransformFcn` properties. This example shows how to implement a log-odds probabilitistic map layer by creating a lookup table for probability and log-odds values. The transform functions use these lookup tables to convert between these values when setting or getting data.

#### Create Lookup Tables

Generate a full lookup table of values that map the probability values to the minimum and maximum limits of `int16` values.

Create an array of `int16` values from `intmin` to `intmax`. Define the probablilty limits.

```
intType = 'int16';
intLinSpace = intmin(intType):intmax(intType);
numOfPoints = length(intLinSpace);
probLimits = [0.001 .999];
```

The `exampleHelperProbToLogodds` and `examplerHelperLogoddsToProb` functions covert between the log-odds and probability values. Use the helper functions to get the log-odds limits and

generate the array for looking up log-odds values. Create an interpolated grid for the entire lookup table.

```
logOddsLimits = exampleHelperProbToLogodds([0.001 .999]);
logOddsLookup = single(exampleHelperLogoddsToProb(linspace(logOddsLimits(1),logOddsLimits(2),num(
interpTable = griddedInterpolant(logOddsLookup,single(intLinSpace),'nearest');
```

#### Specify Transform Function Handles

The transform function handles utilize example helpers that define how to convert between log-odds integer values and the probability values with an applied saturation limit. The probability saturation limits are `[0.001 .999]` as previously specified. This behavior is similar to the `occupancyMap` object.

```
getXformFcn = @(obj,logodds,varargin)...
    exampleHelperIntLogoddsToProb(logodds,logOddsLookup(:),intLinSpace);

setXformFcn = @(obj,prob,varargin)...
    exampleHelperProbToIntLogodds(prob,interpTable,logOddsLookup(:),intLinSpace,probLimits);
```

#### Create Map Layer

Generate an occupancy map layer object from a matrix of probability values. Specify the get and set transform functions.

```
occupancyLayer = mapLayer(repmat(0.5,10,10),...
                          'LayerName','Occupancy',...
                          'GetTransformFcn',getXformFcn,...
                          'SetTransformFcn',setXformFcn);
```

Notice that when you create the map, the default value is 0.001 instead of 0. This difference is because the `SetTransformFcn` function has been applied to the default value of 0 when you create the object, which saturates the value to 0.001.

```
disp(occupancyLayer.DefaultValue)
```

```
    0.0010
```

#### Get and Set Map Data

The map data matches the matrix you set on creation.

```
extData = getMapData(occupancyLayer)
```

```
extData = 10×10

    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5
    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5
    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5
    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5
    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5
    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5
    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5
    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5
    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5
    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5
```

Set specific map locations to values that are:

- Outside of the probability saturation limits.
- Higher precision than the resolution of the lookup tables.

```
setMapData(occupancyLayer,[0 0],0.00001)
setMapData(occupancyLayer,[5 5],0.25999)
```

For the first location, the probability is bound to the saturation limits.

```
extData = getMapData(occupancyLayer,[0 0])
```

```
extData = 0.0010
```

The second location returns the value closest to the probability value in the lookup table.

```
extData2 = getMapData(occupancyLayer,[5 5])
```

```
extData2 = 0.2600
```

The generated map layer can now be used for updating a probability occupany map that are stored as `int16` values. To combine this map with other layers or map types, see the `multiLayerMap` object.

## Limitations

- `mapLayer` objects can only belong to one `multiLayerMap` object at a time.

# Version History

**Introduced in R2021a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

- The LayerName property must be fixed at compile-time
- The DataType property must be known at compile-time.

As of MATLAB R2022a, default map behavior during code generation has changed, which may result in backwards compatibility issues. Maps such as `mapLayer` now support fixed-size code generation (`DynamicMemoryAllocation="off"`).

1. Maps that are either default-constructed or constructed with compile-time constant size information (or matrices that are of compile-time constant size) produce fixed-size maps.
2. To restore the previous behavior, use the `coder.ignoreConst` function when specifying size inputs, or `coder.varsize` matrix variable name specified as a string scalar or character vector, prior to constructing the map.

## See Also

### Objects

`multiLayerMap` | `occupancyMap3D` | `occupancyMap` | `binaryOccupancyMap`

**Functions**
`getMapData` | `setMapData` | `move` | `syncWith`

**Topics**
"Motion Planning in Urban Environments Using Dynamic Occupancy Grid Map"
"Fuse Multiple Lidar Sensors Using Map Layers"

# getMapData

Retrieve data from map layer

## Syntax

```
mapData = getMapData(map)
mapData = getMapData(map,xy)
mapData = getMapData(map,xy,"local")
mapData = getMapData(map,ij,"grid")
[mapData,inBounds] = getMapData( ___ )

mapData = getMapData(map,bottomLeft,mapSize)
mapData = getMapData(map,bottomLeft,mapSize,"local")
mapData = getMapData(map,topLeft,gridSize,"grid")
```

## Description

`mapData = getMapData(map)` returns a matrix of values that contains all the data for the given map layer `map`.

`mapData = getMapData(map,xy)` returns an array of values for the given *xy*-locations in world coordinates.

`mapData = getMapData(map,xy,"local")` returns an array of values for the given *xy*-locations in local coordinates.

`mapData = getMapData(map,ij,"grid")` returns an array of values for the given *ij*-locations in grid coordinates. Each row of `ij` refers to a grid cell index `[i j]`

`[mapData,inBounds] = getMapData( ___ )` also returns a vector of logical values indicating whether the corresponding input location `xy` or `ij` is valid using the previous syntaxes.

`mapData = getMapData(map,bottomLeft,mapSize)` returns a matrix of values in a subregion of the map layer, `map`. The subregion starts in the bottom-left *xy*-position `bottomLeft` in world coordinates with a given map size `mapSize` specified as `[width height]` in meters.

`mapData = getMapData(map,bottomLeft,mapSize,"local")` specifies the bottom-left corner of the subregion in local coordinates.

`mapData = getMapData(map,topLeft,gridSize,"grid")` specifies the top-left corner of the sub region in grid coordinates. The subregion size, `gridSize` is also given in grid coordinates as `[rows cols]`.

## Examples

### Store and Modify XY Velocities Using A Single Map Layer

Create a map layer that stores two values per grid location as *xy*-velocities.

Create an *m*-by-*n*-by-2 matrix of values. The first element in the third dimension is d*x* and the second is d*y* as velocities.

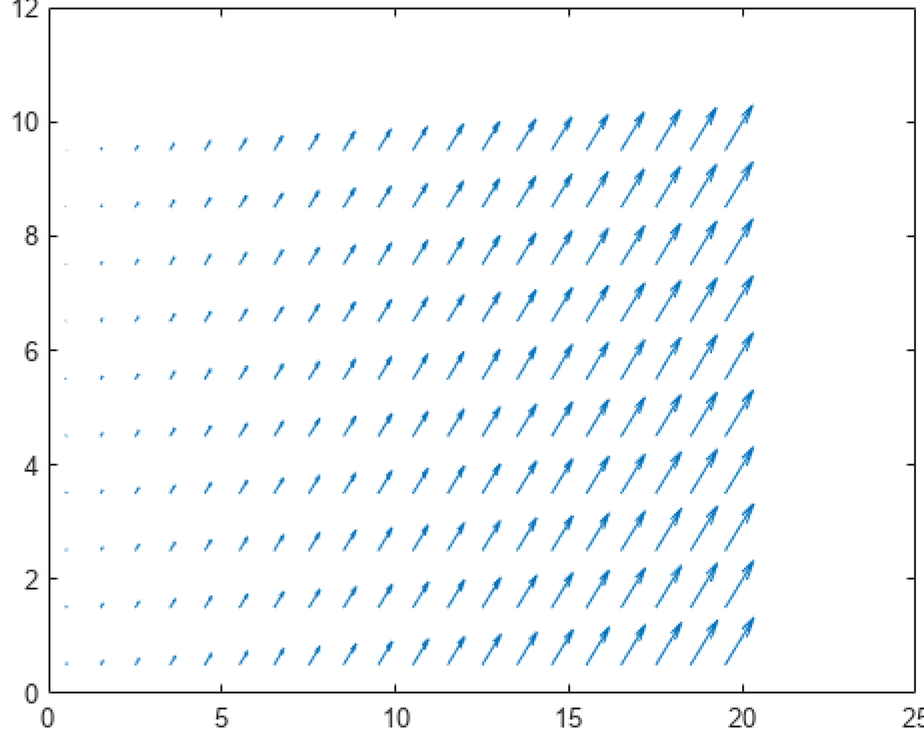
```
dXY = reshape(1:200,10,20);
dXY(:,:,2) = dXY;
```

Create a map layer from the matrix. Specify the resolution and layer name.

```
vLayer = mapLayer(dXY,'Resolution',1,'LayerName','dXY');
```

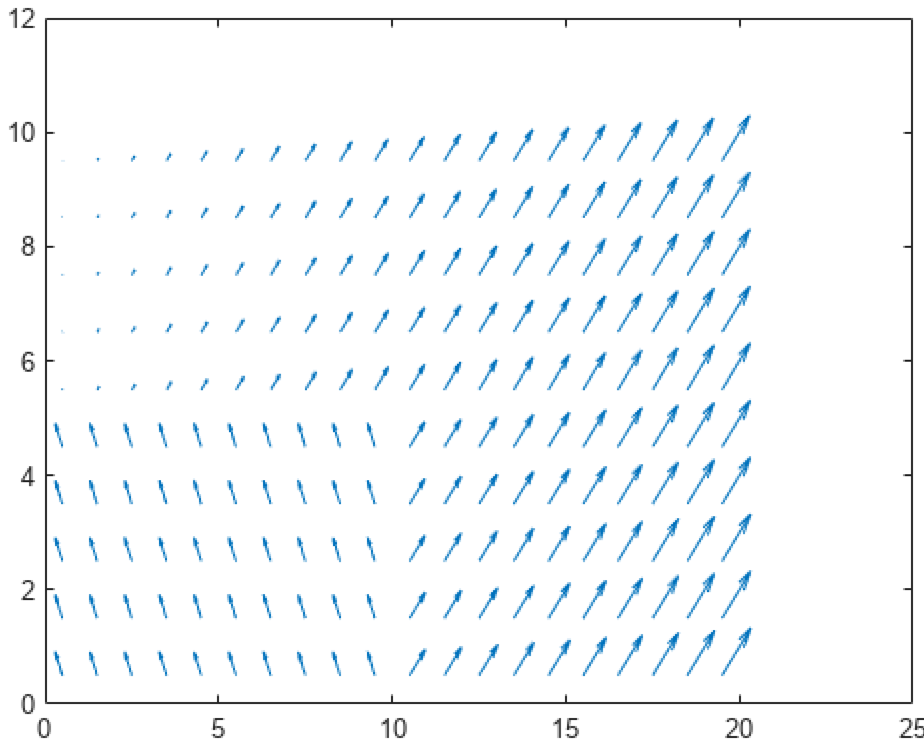
Get all the map data out as a matrix. Get the xy-locations of the velocity values by creating arrays that cover the minimum and maximum *xy*-world limits and is shifted to the grid-center locations. The *y*-locations are flipped when converting between matrix to world coordinates. Visualize the velocities corresponding to those grid-center locations using the `quiver` function.

```
v = getMapData(vLayer);

R = 1/(2*vLayer.Resolution);
xLim = vLayer.XWorldLimits;
yLim = vLayer.YWorldLimits;
xLoc = (xLim(1)+R):R*2:(xLim(2)-R);
yLoc = (yLim(2)-R):-R*2:(yLim(1)+R);

quiver(xLoc,yLoc,v(:,:,1),v(:,:,2))
```



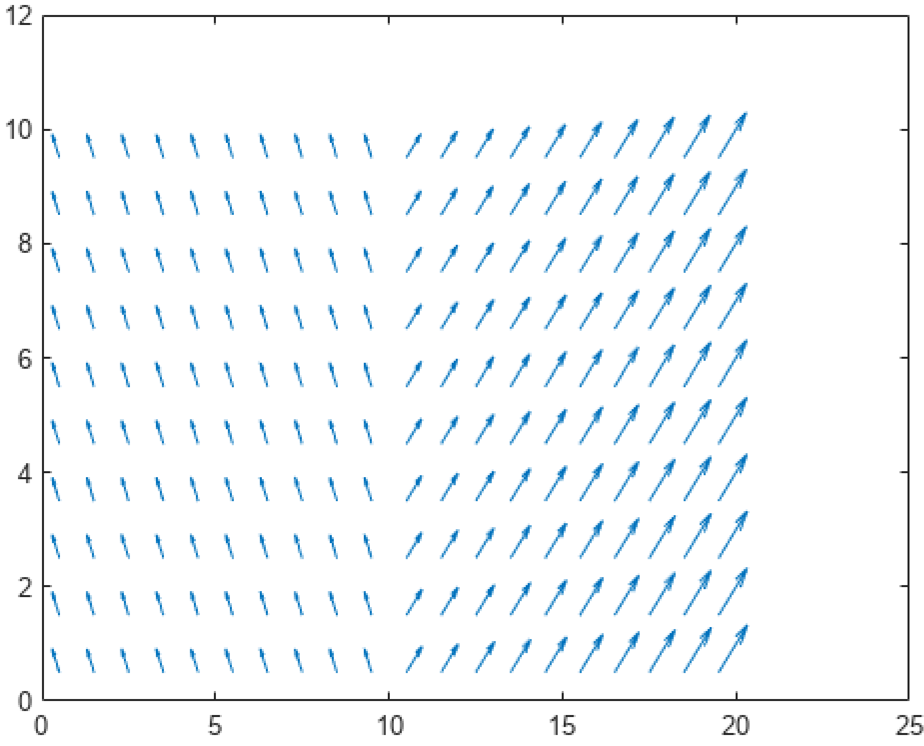

Set the bottom-left quadrant to new updated values. Create the values as a matrix and specify the bottom-left corner (0,0) in map coordinates to the `setData` function.

```
updateValues = repmat(reshape([-50,100],[1 1 2]),5,10);

setMapData(vLayer,[0 0],updateValues)
v = getMapData(vLayer);
quiver(xLoc,yLoc,v(:,:,1),v(:,:,2))
```




Set new values for the top-left quadrant using grid coordinates. For maps, the top-left grid location is (1,1).

```
setMapData(vLayer,[1 1],updateValues,'grid')
v = getMapData(vLayer);
quiver(xLoc,yLoc,v(:,:,1),v(:,:,2))
```




### Write Custom Transform Functions for Map Layers

The `mapLayer` object enables you to apply custom element-wise transformations when setting and getting data in the map. To transform data you set or get from the map, specify function handles for the `GetTransfomFcn` and `SetTransformFcn` properties. This example shows how to implement a log-odds probabilitistic map layer by creating a lookup table for probability and log-odds values. The transform functions use these lookup tables to convert between these values when setting or getting data.

### Create Lookup Tables

Generate a full lookup table of values that map the probability values to the minimum and maximum limits of `int16` values.

Create an array of `int16` values from `intmin` to `intmax`. Define the probablilty limits.

```
intType = 'int16';
intLinSpace = intmin(intType):intmax(intType);
numOfPoints = length(intLinSpace);
probLimits = [0.001 .999];
```

The `exampleHelperProbToLogodds` and `examplerHelperLogoddsToProb` functions covert between the log-odds and probability values. Use the helper functions to get the log-odds limits and

generate the array for looking up log-odds values. Create an interpolated grid for the entire lookup table.

```
logOddsLimits = exampleHelperProbToLogodds([0.001 .999]);
logOddsLookup = single(exampleHelperLogoddsToProb(linspace(logOddsLimits(1),logOddsLimits(2),num(
interpTable = griddedInterpolant(logOddsLookup,single(intLinSpace),'nearest');
```

### Specify Transform Function Handles

The transform function handles utilize example helpers that define how to convert between log-odds integer values and the probability values with an applied saturation limit. The probability saturation limits are `[0.001 .999]` as previously specified. This behavior is similar to the `occupancyMap` object.

```
getXformFcn = @(obj,logodds,varargin)...
    exampleHelperIntLogoddsToProb(logodds,logOddsLookup(:),intLinSpace);

setXformFcn = @(obj,prob,varargin)...
    exampleHelperProbToIntLogodds(prob,interpTable,logOddsLookup(:),intLinSpace,probLimits);
```

### Create Map Layer

Generate an occupancy map layer object from a matrix of probability values. Specify the get and set transform functions.

```
occupancyLayer = mapLayer(repmat(0.5,10,10),...
                            'LayerName','Occupancy',...
                            'GetTransformFcn',getXformFcn,...
                            'SetTransformFcn',setXformFcn);
```

Notice that when you create the map, the default value is 0.001 instead of 0. This difference is because the `SetTransformFcn` function has been applied to the default value of 0 when you create the object, which saturates the value to 0.001.

```
disp(occupancyLayer.DefaultValue)
```

```
    0.0010
```

### Get and Set Map Data

The map data matches the matrix you set on creation.

```
extData = getMapData(occupancyLayer)
```

```
extData = 10×10

    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5
    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5
    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5
    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5
    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5
    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5
    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5
    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5
    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5
    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5
```

Set specific map locations to values that are:

- Outside of the probability saturation limits.
- Higher precision than the resolution of the lookup tables.

```
setMapData(occupancyLayer,[0 0],0.00001)
setMapData(occupancyLayer,[5 5],0.25999)
```

For the first location, the probability is bound to the saturation limits.

```
extData = getMapData(occupancyLayer,[0 0])
```

```
extData = 0.0010
```

The second location returns the value closest to the probability value in the lookup table.

```
extData2 = getMapData(occupancyLayer,[5 5])
```

```
extData2 = 0.2600
```

The generated map layer can now be used for updating a probability occupany map that are stored as `int16` values. To combine this map with other layers or map types, see the `multiLayerMap` object.

## Input Arguments

**`map` — Map layer**
`mapLayer` object

Map layer, specified as a `mapLayer` object.

**`xy` — World or local coordinates**
*n*-by-2 matrix

World or local coordinates, specified as an *n*-by-2 matrix of `[x y]` pairs, where *n* is the number of coordinates.

Data Types: `double`

**`ij` — Grid positions**
*n*-by-2 matrix

Grid positions, specified as an *n*-by-2 matrix of `[i j]` pairs in `[rows cols]` format, where *n* is the number of grid positions.

Data Types: `double`

**`bottomLeft` — Location of output matrix in world or local coordinates**
two-element vector | `[xCoord yCoord]`

Location of bottom left corner of output matrix in world or local coordinates, specified as a two-element vector, `[xCoord yCoord]`. Location is in world or local coordinates based on syntax.

Data Types: `double`

**`mapSize` — Subregion map size**
two-element vector | `[x y]`

Subregion map size, specified as a two-element vector `[x y]` in world or local coordinates.

Data Types: `double`

**`gridSize` — Output grid size**
two-element vector | `[row col]`

Output grid size, specified as a two-element vector `[row col]`.

Data Types: `double`

**`topLeft` — Location of grid**
two-element vector | `[iCoord jCoord]`

Location of top left corner of grid, specified as a two-element vector, `[iCoord jCoord]`.

Data Types: `double`

## Output Arguments

**`mapData` — Data values from map layer**
matrix

Data values from map layer, returned as a matrix. By default, the function returns all data on the layer as an *M*-by-*N*-by-*DataDims* matrix. *M* and *N* are the grid rows and columns respectively. *DataDims* are the dimensions of the map data, `map.DataSize(3:end)`.

For other syntaxes, the map data may be returned as an array of values with size *N*-by-*DataDims* or as a subregion of the full matrix.

**`inBounds` — Valid map locations**
*n*-by-1 column vector

Valid map locations, returned as an *n*-by-1 column vector equal in length to `xy` or `ij`. Locations inside the map limits return a value of 1. Locations outside the map limits return a value of 0.

# Version History

**Introduced in R2021a**

**R2023a: Signed Distance Map Support**

The `getMapData` function now supports the `signedDistanceMap` object as a new map representation for the `map` argument.

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
`multiLayerMap` | `occupancyMap3D` | `occupancyMap` | `binaryOccupancyMap` | `signedDistanceMap`

**Functions**
`setMapData` | `move` | `syncWith`

# setMapData

Assign data to map layer

## Syntax

```
setMapData(map,mapData)
setMapData(map,xy,mapData)
setMapData(map,xy,mapData,"local")
setMapData(map,ij,mapData,"grid")
inBounds = setMapData( ___ )

setMapData(map,bottomLeft,mapData)
setMapData(map,bottomLeft,mapData,"local")
setMapData(map,topLeft,mapData,"grid")
```

## Description

`setMapData(map,mapData)` overwrites all values in the map layer using a matrix with dimensions that match the map layer data dimensions, `map.DataSize`.

`setMapData(map,xy,mapData)` specifies an array of values for the given *xy*-locations in world coordinates. The `mapData` input must be an *X*-by-1-by-*DataDims* array. *DataDims* are the dimensions of the map data, `map.DataSize(3:end)`. Locations outside the map boundaries are ignored.

`setMapData(map,xy,mapData,"local")` specifies locations in local coordinates.

`setMapData(map,ij,mapData,"grid")` specifies an array of values for the given *ij*-locations in grid coordinates. Each row of `ij` refers to a grid cell index `[i j]`

`inBounds = setMapData( ___ )` also returns a vector of logical values indicating whether the corresponding input location `xy` or `ij` is valid using the previous syntaxes.

`setMapData(map,bottomLeft,mapData)` specifies a matrix of values `mapData` for a subregion of the map layer, `map`. The subregion starts in the bottom-left *xy*-position `bottomLeft` and updates a subregion based on the size of `mapData`.

`setMapData(map,bottomLeft,mapData,"local")` specifies the bottom-left corner of the subregion in local coordinates.

`setMapData(map,topLeft,mapData,"grid")` specifies the top-left corner of a sub region in grid coordinates. The subregion is updated with values in `mapData`.

## Examples

### Store and Modify XY Velocities Using A Single Map Layer

Create a map layer that stores two values per grid location as *xy*-velocities.

Create an *m*-by-*n*-by-2 matrix of values. The first element in the third dimension is d*x* and the second is d*y* as velocities.

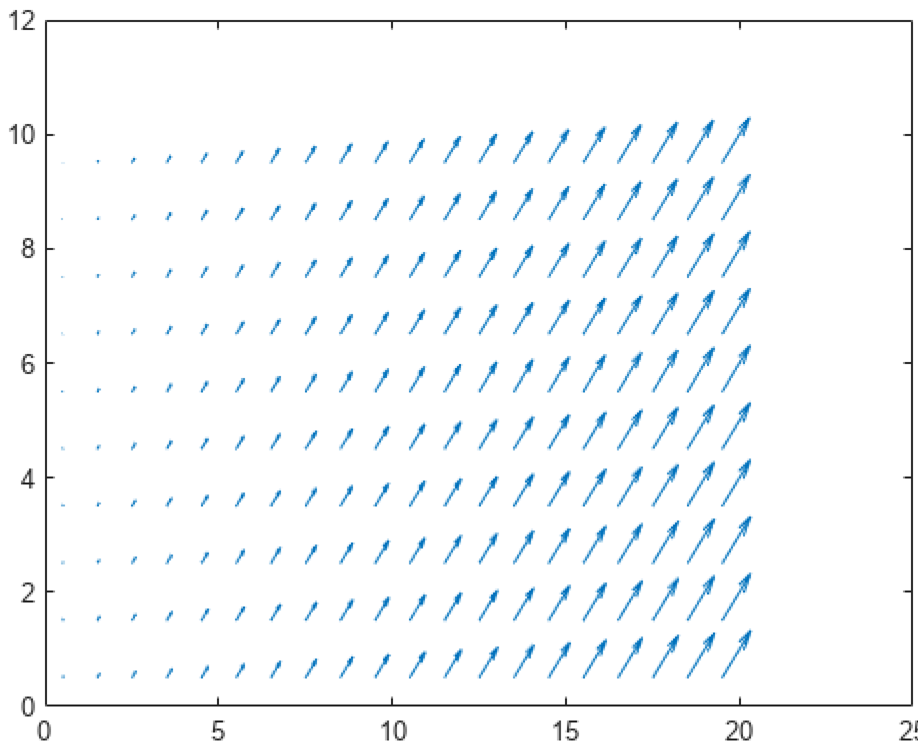
```
dXY = reshape(1:200,10,20);
dXY(:,:,2) = dXY;
```

Create a map layer from the matrix. Specify the resolution and layer name.

```
vLayer = mapLayer(dXY,'Resolution',1,'LayerName','dXY');
```

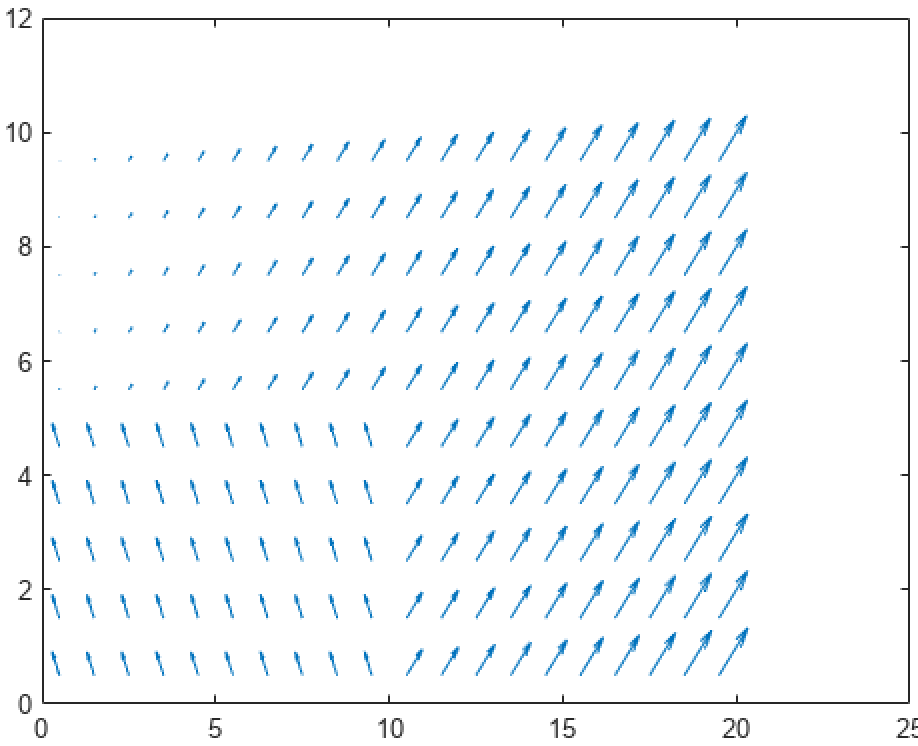
Get all the map data out as a matrix. Get the xy-locations of the velocity values by creating arrays that cover the minimum and maximum *xy*-world limits and is shifted to the grid-center locations. The *y*-locations are flipped when converting between matrix to world coordinates. Visualize the velocities corresponding to those grid-center locations using the `quiver` function.

```
v = getMapData(vLayer);

R = 1/(2*vLayer.Resolution);
xLim = vLayer.XWorldLimits;
yLim = vLayer.YWorldLimits;
xLoc = (xLim(1)+R):R*2:(xLim(2)-R);
yLoc = (yLim(2)-R):-R*2:(yLim(1)+R);

quiver(xLoc,yLoc,v(:,:,1),v(:,:,2))
```



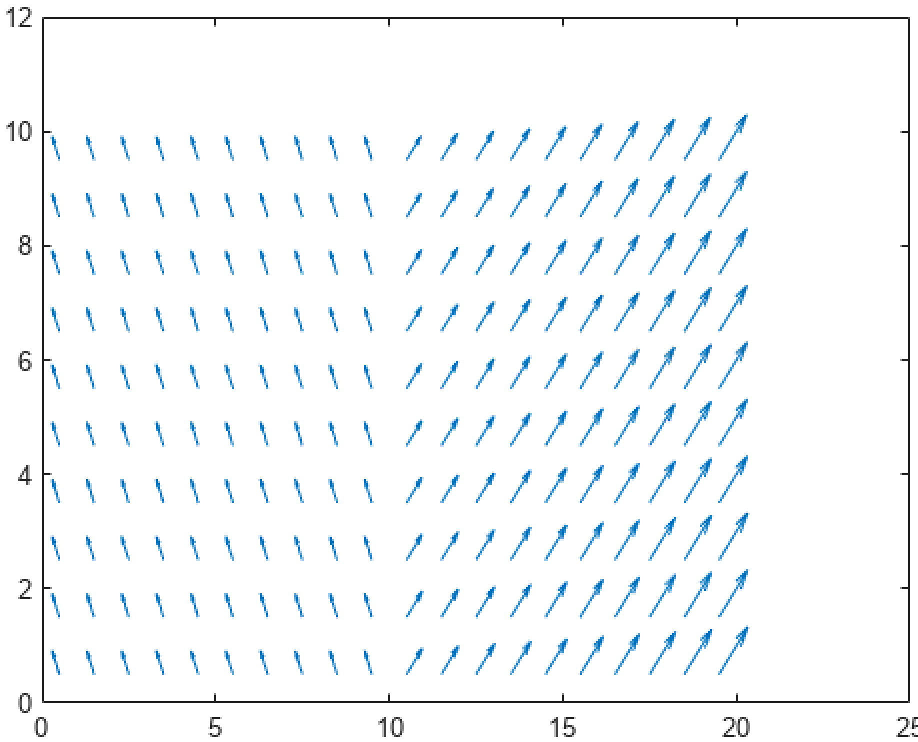

Set the bottom-left quadrant to new updated values. Create the values as a matrix and specify the bottom-left corner (0,0) in map coordinates to the `setData` function.

```
updateValues = repmat(reshape([-50,100],[1 1 2]),5,10);

setMapData(vLayer,[0 0],updateValues)
v = getMapData(vLayer);
quiver(xLoc,yLoc,v(:,:,1),v(:,:,2))
```




Set new values for the top-left quadrant using grid coordinates. For maps, the top-left grid location is (1,1).

```
setMapData(vLayer,[1 1],updateValues,'grid')
v = getMapData(vLayer);
quiver(xLoc,yLoc,v(:,:,1),v(:,:,2))
```




#### Write Custom Transform Functions for Map Layers

The `mapLayer` object enables you to apply custom element-wise transformations when setting and getting data in the map. To transform data you set or get from the map, specify function handles for the `GetTransfomFcn` and `SetTransformFcn` properties. This example shows how to implement a log-odds probabilitistic map layer by creating a lookup table for probability and log-odds values. The transform functions use these lookup tables to convert between these values when setting or getting data.

#### Create Lookup Tables

Generate a full lookup table of values that map the probability values to the minimum and maximum limits of `int16` values.

Create an array of `int16` values from `intmin` to `intmax`. Define the probablilty limits.

```
intType = 'int16';
intLinSpace = intmin(intType):intmax(intType);
numOfPoints = length(intLinSpace);
probLimits = [0.001 .999];
```

The `exampleHelperProbToLogodds` and `examplerHelperLogoddsToProb` functions covert between the log-odds and probability values. Use the helper functions to get the log-odds limits and

generate the array for looking up log-odds values. Create an interpolated grid for the entire lookup table.

```
logOddsLimits = exampleHelperProbToLogodds([0.001 .999]);
logOddsLookup = single(exampleHelperLogoddsToProb(linspace(logOddsLimits(1),logOddsLimits(2),num(
interpTable = griddedInterpolant(logOddsLookup,single(intLinSpace),'nearest');
```

#### Specify Transform Function Handles

The transform function handles utilize example helpers that define how to convert between log-odds integer values and the probability values with an applied saturation limit. The probability saturation limits are `[0.001 .999]` as previously specified. This behavior is similar to the `occupancyMap` object.

```
getXformFcn = @(obj,logodds,varargin)...
    exampleHelperIntLogoddsToProb(logodds,logOddsLookup(:),intLinSpace);

setXformFcn = @(obj,prob,varargin)...
    exampleHelperProbToIntLogodds(prob,interpTable,logOddsLookup(:),intLinSpace,probLimits);
```

#### Create Map Layer

Generate an occupancy map layer object from a matrix of probability values. Specify the get and set transform functions.

```
occupancyLayer = mapLayer(repmat(0.5,10,10),...
                           'LayerName','Occupancy',...
                           'GetTransformFcn',getXformFcn,...
                           'SetTransformFcn',setXformFcn);
```

Notice that when you create the map, the default value is 0.001 instead of 0. This difference is because the `SetTransformFcn` function has been applied to the default value of 0 when you create the object, which saturates the value to 0.001.

```
disp(occupancyLayer.DefaultValue)

    0.0010
```

#### Get and Set Map Data

The map data matches the matrix you set on creation.

```
extData = getMapData(occupancyLayer)

extData = 10×10

    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5
    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5
    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5
    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5
    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5
    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5
    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5
    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5
    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5
    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5
```

Set specific map locations to values that are:

- Outside of the probability saturation limits.
- Higher precision than the resolution of the lookup tables.

```
setMapData(occupancyLayer,[0 0],0.00001)
setMapData(occupancyLayer,[5 5],0.25999)
```

For the first location, the probability is bound to the saturation limits.

```
extData = getMapData(occupancyLayer,[0 0])
```

```
extData = 0.0010
```

The second location returns the value closest to the probability value in the lookup table.

```
extData2 = getMapData(occupancyLayer,[5 5])
```

```
extData2 = 0.2600
```

The generated map layer can now be used for updating a probability occupany map that are stored as `int16` values. To combine this map with other layers or map types, see the `multiLayerMap` object.

## Input Arguments

### `map` — Map representation

`mapLayer` object | `signedDistanceMap`

Map layer, specified as a `mapLayer` or `signedDistanceMap` object.

### `mapData` — Data values for setting map layer

matrix

Data values for setting map layer, specified as a matrix. By default, the function sets all data on the layer as an *M*-by-*N*-by-*DataDims* matrix. *M* and *N* are the grid height and width respectively. *DataDims* are the dimensions of the map data, `map.DataSize(3,:)`.

For other syntaxes, the map data may be specified as a matrix with size *N*-by-*DataDims*, where *N* is the number of elements in `xy` or `ij`, or as a subregion of the full matrix.

### `topLeft` — Location of grid

two-element vector | `[iCoord jCoord]`

Location of top left corner of grid, specified as a two-element vector, `[iCoord jCoord]`.

Data Types: `double`

### `bottomLeft` — Location of output matrix in world or local coordinates

two-element vector | `[xCoord yCoord]`

Location of bottom left corner of output matrix in world or local coordinates, specified as a two-element vector, `[xCoord yCoord]`. Location is in world or local coordinates based on syntax.

Data Types: `double`

### `ij` — Grid positions

*n*-by-2 matrix

Grid positions, specified as an *n*-by-2 matrix of `[i j]` pairs in `[rows cols]` format, where *n* is the number of grid positions.

Data Types: `double`

**xy — World or local coordinates**
*n*-by-2 matrix

World or local coordinates, specified as an *n*-by-2 matrix of `[x y]` pairs, where *n* is the number of coordinates.

Data Types: `double`

## Output Arguments

**inBounds — Valid map locations**
*n*-by-1 column vector

Valid map locations, returned as an *n*-by-1 column vector equal in length to `xy` or `ij`. Locations inside the map limits return a value of 1. Locations outside the map limits return a value of 0.

# Version History

**Introduced in R2021a**

**R2023a: Signed Distance Map Support**

The `setMapData` function now supports the `signedDistanceMap` object as a new map representation for the `map` argument.

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
`multiLayerMap` | `occupancyMap3D` | `occupancyMap` | `binaryOccupancyMap` | `signedDistanceMap`

**Functions**
`getMapData` | `move` | `syncWith`

# signedDistanceMap

Discrete signed distance map of 2-D region

## Description

Use the `signedDistanceMap` object to represent distances to surfaces or contours in space using signed distance functions. Query points return positive values if they lie outside an occupied region of space and negative if they lie inside a space. This map object also provides gradient information and the location to nearest occupied cell in the scene.

## Creation

### Syntax

```
map = signedDistanceMap
map = signedDistanceMap(width,height)
map = signedDistanceMap(width,height,resolution)
map = signedDistanceMap(width,height,resolution,"world")
map = signedDistanceMap(rows,cols,resolution,"grid")

map = signedDistanceMap(mapmatrix)
map = signedDistanceMap(mapmatrix,resolution)
map = signedDistanceMap(sourcemap)
map = signedDistanceMap(sourcemap,resolution)

map = signedDistanceMap( ___ ,Name=Value)
```

#### Description

##### Dimensions

`map = signedDistanceMap` creates an empty 2-D signed distance map object occupying 10-by-10 meters of space with a resolution of 1 cell per meter.

`map = signedDistanceMap(width,height)` creates a map with the specified width `width`, and height `height` with a resolution of 1 cell per meter.

`map = signedDistanceMap(width,height,resolution)` creates a map with the specified width `width`, and height `height` with a resolution of `resolution` cell per meter. The `Resolution` property is set to `resolution`.

`map = signedDistanceMap(width,height,resolution,"world")` creates a map with a grid size of `width`-by-`height` in world coordinates. The `Resolution` property is set to `resolution`.

`map = signedDistanceMap(rows,cols,resolution,"grid")` creates a map with a grid size of `rows`-by-`cols` in grid coordinates. The `Resolution` property is set to `resolution`.

#### Other Maps

`map = signedDistanceMap(mapmatrix)` creates a map of the same size and value as the matrix `mapmatrix`.

`map = signedDistanceMap(mapmatrix,resolution)` creates a map from the values in the matrix or matrix array `mapmatrix` with a resolution `resolution`. The `Resolution` property is set to `resolution`.

`map = signedDistanceMap(sourcemap)` creates a new object using the occupancy data copied from another `signedDistanceMap` object.

`map = signedDistanceMap(sourcemap,resolution)` creates a new object using the occupancy data copied from another `signedDistanceMap` object but resamples the matrix to have the specified resolution `resolution`. The `Resolution` property is set to `resolution`.

#### Additional Options

`map = signedDistanceMap( ___ ,Name=Value)` specifies property values using name-value arguments.

For example, `signedDistanceMap(__,LocalOriginInWorld=[15 20])` sets the local origin to a specific world location.

### Input Arguments

**`width` — Width of map**
`10` (default) | nonnegative numeric scalar

Width of map, specified as nonnegative numeric scalar, in meters.

**`height` — Height of map**
nonnegative numeric scalar

Height of map, specified as nonnegative numeric scalar, in meters.

**`rows` — Number of rows in map**
nonnegative numeric scalar

Number of rows in map, specified as nonnegative numeric scalar.

**`cols` — Number of columns in map**
`10` (default) | nonnegative numeric scalar

Number of columns in map, specified as nonnegative numeric scalar.

**`mapmatrix` — Map matrix**
*M*-by-*N* matrix

Map matrix, specified as a *M*-by-*N* matrix, where each cell contains `1` for occupied and `0` for unoccupied.

**`sourcemap` — Signed distance map to copy values from**
`signedDistanceMap` object

Signed distance map to copy values from, specified as a `signedDistanceMap` object.

## Properties

**`DataType` — Data type of the values stored**
`'double'` (default) | character vector

Data type of the values stored in the map, specified as a character vector.

This property is set based on the data type of the input `p` or the data type of DefaultValue. After you create the object, this property is read-only.

Data Types: `char`

**`DefaultValue` — Default value for unspecified map locations**
`0` (default) | numeric scalar

Default value for unspecified map locations including areas outside the map, specified as a numeric scalar.

**`InterpolationMethod` — Interpolation method for distance matrix**
`"none"` (default) | `"linear"`

Interpolation method for distance matrix, specified as a string scalar:

- `"none"` — Distance is constant within cells. The gradient is `NaN`.
- `"linear"` — Bilinearly interpolate distance. The gradient is piecewise continuous between cell-centers.

Data Types: `char` | `string`

**`GridLocationInWorld` — Location of bottom-left corner of grid in world coordinates**
`[0 0]` (default) | two-element vector | `[xWorld yWorld]`

Location of the bottom-left corner of the grid in world coordinates, specified as a two-element vector, `[xWorld yWorld]`.

You can set this property when you create the object.

**`GridOriginInLocal` — Location of bottom-left corner of grid in local coordinates**
`[0 0]` (default) | two-element vector | `[xLocal yLocal]`

Location of the bottom-left corner of the grid in local coordinates, specified as a two-element vector, `[xLocal yLocal]`.

You can set this property when you create the object.

**`GridSize` — Number of rows and columns in grid**
two-element integer-valued vector

Number of rows and columns in grid, stored as a two-element integer-valued vector representing the number of rows and columns, in that order.

This property is set when you create the object based on the first two dimensions of the input matrix `mapmatrix`, the inputs `width` and `height`, or the inputs `row` and `col`.

**`LayerName` — Name of map layer**
`'distanceLayer'` (default) | character vector | string scalar

Name of map layer, specified as a character vector or string scalar.

You can set this property as a name-value argument when you create the object. After you create the object, this property is read-only.

Data Types: `char` | `string`

**`LocalOriginInWorld` — Location of local frame origin in world coordinates**
`[0 0]` (default) | two-element vector | `[xWorld yWorld]`

Location of the local frame origin in world coordinates, specified as a two-element vector, `[xLocal yLocal]`. Use the `move` function to shift the local frame as your vehicle moves.

You can set this property as a name-value argument when you create the object.

**`Resolution` — Grid resolution**
`1` (default) | positive numeric scalar

This property is read-only.

Grid resolution, specified as a positive numeric scalar in cells per meter representing the number and size of grid locations.

You can set this property as a name-value argument when you create the object. After you create the object, this property is read-only.

**`XLocalLimits` — Minimum and maximum values of *x*-coordinates in local frame**
two-element row vector

This property is read-only.

Minimum and maximum values of *x*-coordinates in the local frame, stored as a two-element row vector of the form `[min max]`. Local frame is defined by the `LocalOriginInWorld` property.

**`YLocalLimits` — Minimum and maximum values of *y*-coordinates in local frame**
two-element row vector

This property is read-only.

Minimum and maximum values of *y*-coordinates in the local frame, stored as a two-element row vector of the form `[min max]`. Local frame is defined by the `LocalOriginInWorld` property.

**`XWorldLimits` — Minimum and maximum values of *x*-coordinates of world frame**
two-element row vector

This property is read-only.

Minimum and maximum values of *x*-coordinates of the world frame, stored as a two-element row vector representing the minimum and maximum values, in that order.

**`YWorldLimits` — Minimum and maximum values of *y*-coordinates of world frame**
two-element row vector

This property is read-only.

Minimum and maximum values of *y*-coordinates of the world frame, stored as a two-element row vector representing the minimum and maximum values, in that order.

## Object Functions

| | |
|---|---|
| copy | Create copy of 2-D signed distance map |
| closestBoundary | Get nearest boundary to location |
| distance | Get distance at locations |
| getMapData | Retrieve data from map layer |
| gradient | Get gradient at locations |
| grid2world | Convert grid indices to world coordinates |
| grid2local | Convert grid indices to local coordinates |
| local2grid | Convert local coordinates to grid indices |
| local2world | Convert local coordinates to world coordinates |
| move | Move map in world frame |
| setMapData | Assign data to map layer |
| show | Display signed distance map |
| syncWith | Sync map with overlapping map |
| world2grid | Convert world coordinates to grid indices |
| world2local | Convert world coordinates to local coordinates |

## Examples

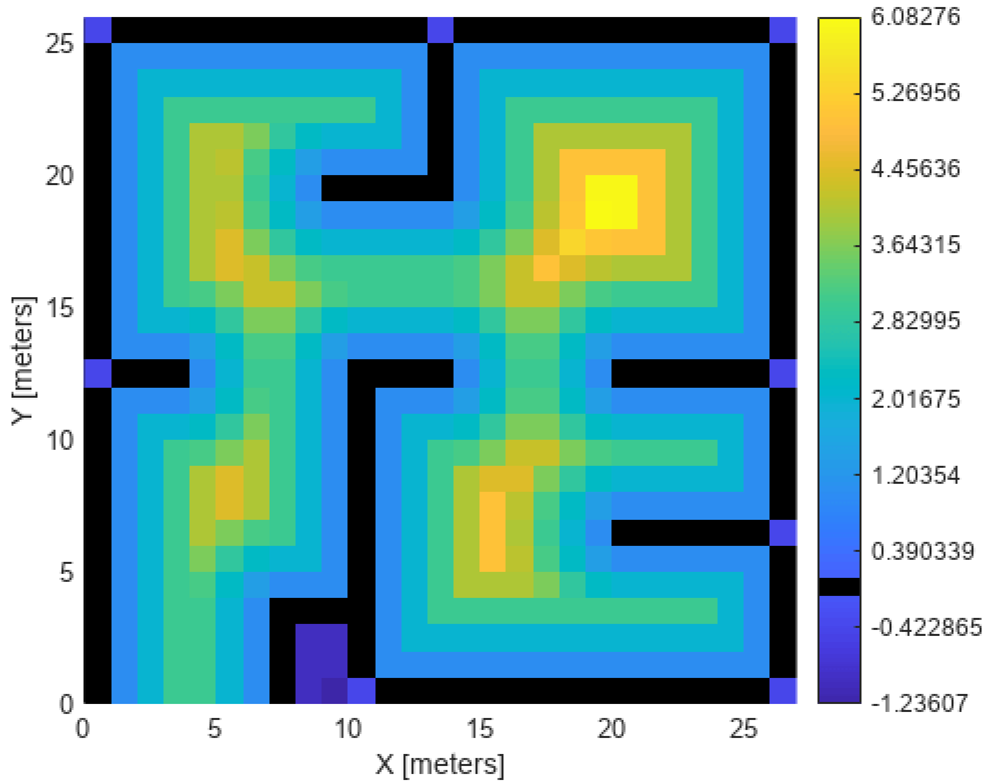
### Get Distance to Nearest Obstacles in Signed Distance Map

Load the `exampleMaps` MAT file.

```
load exampleMaps.mat
```

Create a signed distance map using the `simpleMap` data.

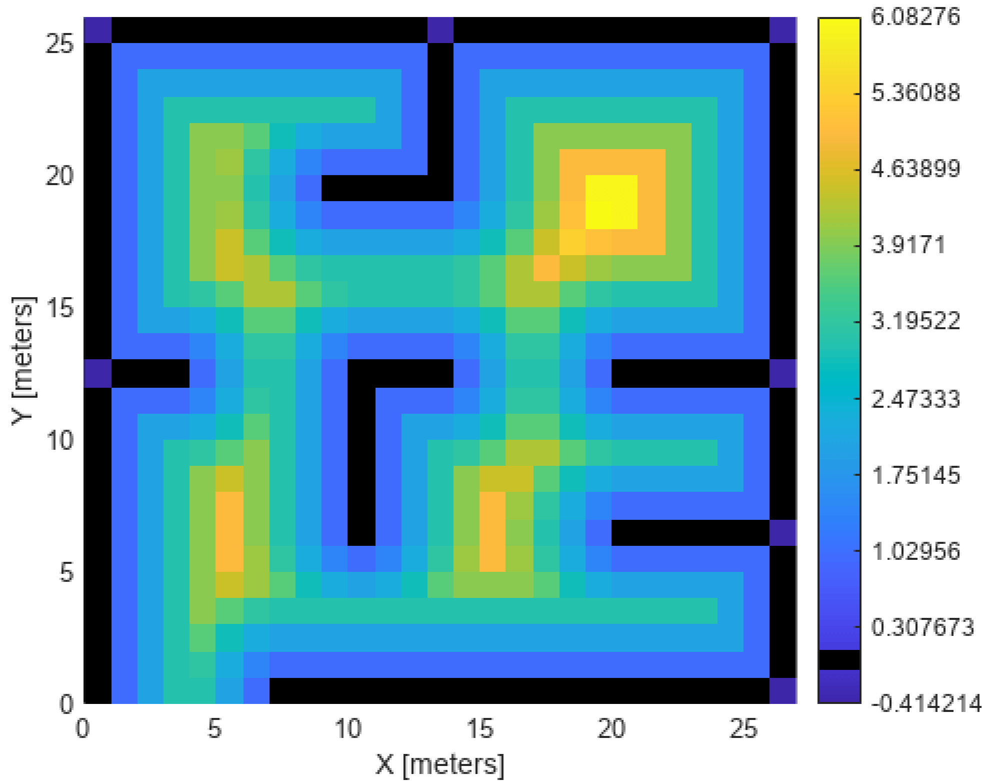
```
sdm = signedDistanceMap(simpleMap,InterpolationMethod="none");
show(sdm,BoundaryColor=[0 0 0],Colorbar="on");
```




```
setMapData(sdm,[7 1],zeros(5,5))
getMapData(sdm,[9 2])
```

```
ans = logical
   0
```

```
show(sdm,BoundaryColor=[0 0 0],Colorbar="on");
```




Find the closest boundary to the coordinate, `[16.25 6.25]` and calculate the distance to the nearest boundary.

```
coord = [16.25 6.25];
boundary = closestBoundary(sdm,coord,"world")
```

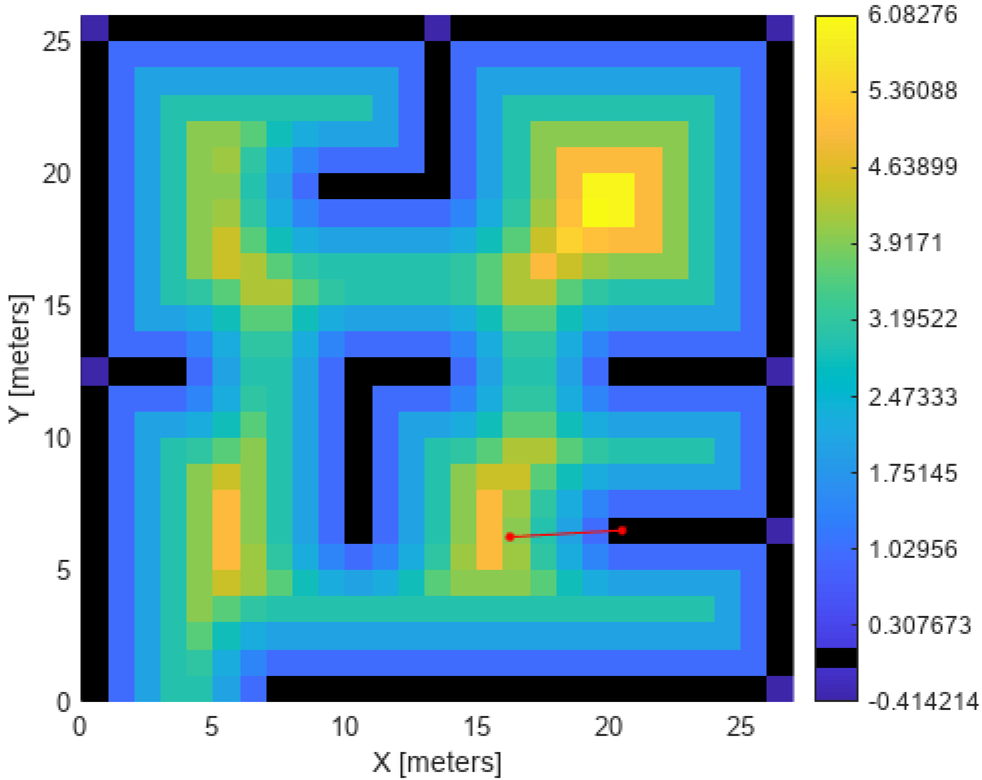
```
boundary = 
boundary(:,:,1) =

   20.5000


boundary(:,:,2) =

    6.5000
```

```
dist = distance(sdm,coord)
```

```
dist = 4
```

Plot the line between the queried point and the closest obstacle cell center

```
hold on
plot([coord(1) boundary(:,:,1)],[coord(2) boundary(:,:,2)],"-r",Marker=".",MarkerSize=10)
```




Note that even though distance from the queried point appears greater than 4 when plotted, the distance function calculates the distance from the nearest cell center of the queried point.

# Version History

**Introduced in R2023a**

## See Also

**Objects**
`multiLayerMap` | `occupancyMap3D` | `occupancyMap` | `binaryOccupancyMap`

**Functions**
`distance` | `getMapData` | `setMapData` | `move` | `syncWith`

# closestBoundary

Get nearest boundary to location

## Syntax

```
boundary = closestBoundary(map)
boundary = closestBoundary(map,location)
boundary = closestBoundary(map,location,frame)
[boundary,isValid] = closestBoundary(map,location, ___ )
boundary = closestBoundary(map,cornerLocation,matSize)
boundary = closestBoundary(map,cornerLocation,matSize,frame)
```

## Description

`boundary = closestBoundary(map)` returns the locations of the closest obstacles `boundary` for each cell of the specified signed distance map `map`.

`boundary = closestBoundary(map,location)` returns the closest boundary locations for the specified *xy*-locations `locations` in world coordinates.

`boundary = closestBoundary(map,location,frame)` returns the closest boundary locations for the specified locations `locations` in the coordinate frame `frame`.

`[boundary,isValid] = closestBoundary(map,location, ___ )` returns `isValid`, indicating which of the specified locations `locations` are within the map bounds.

`boundary = closestBoundary(map,cornerLocation,matSize)` returns the closest boundary locations for a subregion of the signed distance map, `map`. The subregion starts in the minimum corner location `cornerLocation` in the world coordinate frame with a given map size `matSize`.

`boundary = closestBoundary(map,cornerLocation,matSize,frame)` returns the closest boundary locations for a subregion of the signed distance map, `map`. The subregion starts in the minimum corner location `cornerLocation` in the coordinate frame `frame`.

---

**Note** When specifying a corner location and map size, `closestBoundary` determines the closest boundary locations using the distances between cell centers within the rectangular query region.

---

## Examples

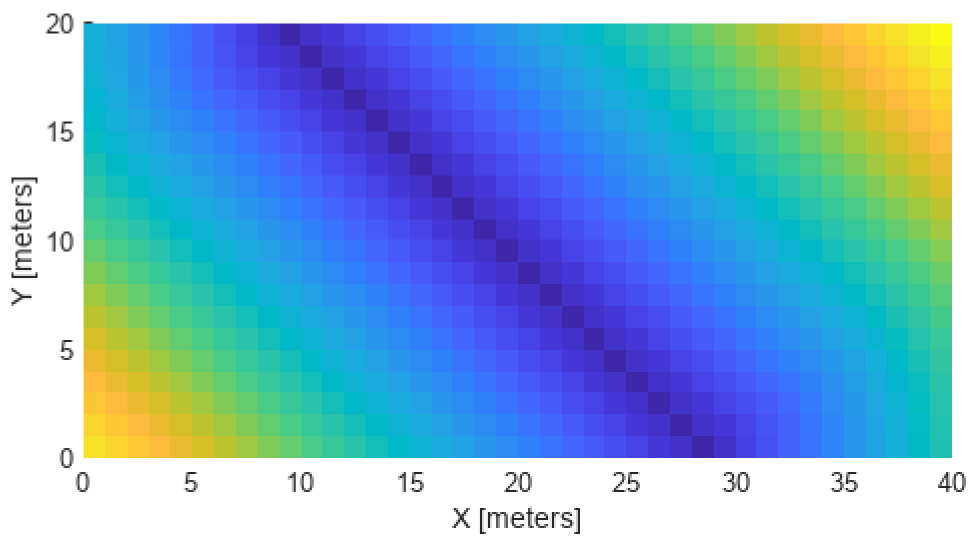
### Find Closest Boundary in Signed Distance Map

Create a signed distance map with a width of 40 cells and a height of 20 cells.

```
map = signedDistanceMap(40,20);
```

Update the map occupancy with an identity matrix.

```
setMapData(map,[1 10],eye(20),"grid");
show(map);
```




Find nearest boundary for each corner cell of map.

```
queryIJ = [1 1; 20 1; 1 40; 20 40];
nearestCornerIJ = closestBoundary(map,queryIJ,"grid")
```

```
nearestCornerIJ =
nearestCornerIJ(:,:,1) =

     1
     6
    16
    20


nearestCornerIJ(:,:,2) =

    10
    15
    25
    29
```

Find nearest XY boundary cell for cells in the first 5-by-5 quadrant in the top-left.

```
nearestQuadrantXY = closestBoundary(map,[0 5],[5 5])
```

```
nearestQuadrantXY =
nearestQuadrantXY(:,:,1) =
```

```
    9.5000   10.5000   10.5000   11.5000   11.5000
   10.5000   10.5000   11.5000   11.5000   12.5000
   10.5000   11.5000   11.5000   12.5000   12.5000
   11.5000   11.5000   12.5000   12.5000   13.5000
   11.5000   12.5000   12.5000   13.5000   13.5000


nearestQuadrantXY(:,:,2) =

   19.5000   18.5000   18.5000   17.5000   17.5000
   18.5000   18.5000   17.5000   17.5000   16.5000
   18.5000   17.5000   17.5000   16.5000   16.5000
   17.5000   17.5000   16.5000   16.5000   15.5000
   17.5000   16.5000   16.5000   15.5000   15.5000
```

## Input Arguments

**`map` — Signed distance map**
`signedDistanceMap` object

Signed distance map, specified as a `signedDistanceMap` object.

**`location` — World or local coordinates, or grid locations**
*N*-by-2 matrix

World or local coordinates, or grid locations, specified as an *N*-by-2 matrix. *N* is the number of locations. The format of the rows depends on the value of the `frame` argument:

- `"world"` — [*x y*] coordinates in the world frame.
- `"local"` — [*x y*] coordinates in the local frame.
- `"grid"` — [*row column*] location in the grid frame.

**`cornerLocation` — Minimum corner location of output matrix**
two-element vector

Minimum corner location of output matrix, specified as a two-element vector of coordinates in the form, [*x y*]. The location is in world or local coordinates if the `frame` argument is set to `"world"` and `"local"`, respectively. When `frame` is `"grid"`, the coordinates are in the form [*row column*] and `cornerLocation` is the top-left corner of the world frame.

**`matSize` — Subregion map size**
two-element vector | `[x y]`

Subregion map size, specified as a two-element vector [*x y*] in world or local coordinates. Location is in world or local coordinates if the `frame` argument is set to `"world"` and `"local"`, respectively. When `frame` is `"grid"`, `cornerLocation` is the top-left corner of the world frame.

**`frame` — Coordinate frame**
`"world"` (default) | `"local"` | `"grid"`

Coordinate frame, specified as one of these options:

- `"world"` — Specify coordinates in the world frame.
- `"local"` — Specify coordinates in the local frame.
- `"grid"` — Specify grid locations in the grid frame.

Data Types: `char` | `string`

## Output Arguments

**`boundary` — Nearest boundary point**
*L*-by-1-by-2 array | *M*-by-*N*-by-2 array

Nearest boundary point, returned as an *L*-by-1-by-2 array for point queries and an *M*-by-*N*-by-2 array for subregion queries. *L* is the number of locations queried. *M* and *N* are the dimensions of the map or specified map subregion.

**`isValid` — Points in boundary**
*L*-element vector

Points in boundary, returned as an *L*-element vector, where *L* is the total number of queried locations. Each element is a `1` (`true`) if the point is within the boundaries, and `0` (`false`) if the point is outside boundaries.

This output is only returned for point queries.

# Version History

**Introduced in R2023a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

`signedDistanceMap` | `gradient` | `distance`

# distance

Get distance at locations

## Syntax

```
dist = distance(map)
dist = distance(map,location)
dist = distance(map,location,frame)
[dist,isValid] = distance(map,location, ___ )
dist = distance(map,cornerLocation,mapSize)
dist = distance(map,cornerLocation,mapSize,frame)
```

## Description

`dist = distance(map)` returns the signed distances `dist` to the closest obstacle for all cells in the map `map`.

`dist = distance(map,location)` returns the signed distances to the closest boundaries for the specified *xy*-locations `location` in world coordinates.

---

**Note** Note that the `distance` function determines the distance using the interpolation method specified in `InterpolationMethod` property of `map`.

---

`dist = distance(map,location,frame)` returns distances to the closest boundaries for the specified locations `location` in the coordinate frame `frame`.

`[dist,isValid] = distance(map,location, ___ )` returns `isValid`, indicating which of the specified locations `location` are within the map bounds `isValid`.

`dist = distance(map,cornerLocation,mapSize)` returns the distances to the closest boundaries for a subregion of the map layer, `map`. The subregion starts in the corner location `cornerLocation` in the world coordinate frame with a given map size `mapSize`.

`dist = distance(map,cornerLocation,mapSize,frame)` returns the distances to the closest boundaries for a subregion of the map layer, `map`. The subregion starts in the corner location `cornerLocation` in the coordinate frame `frame`.

---

**Note** When specifying a corner location and map size, `distance` determines the distances between cell centers within the rectangular query region.

---

## Examples

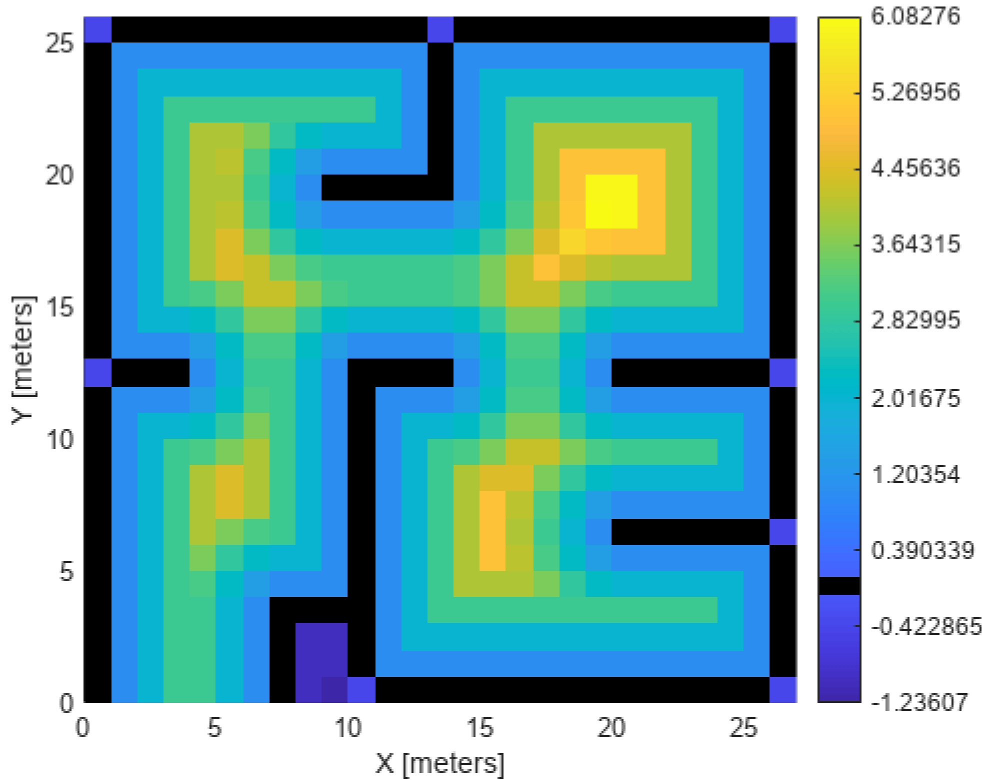
### Get Distance to Nearest Obstacles in Signed Distance Map

Load the `exampleMaps` MAT file.

```
load exampleMaps.mat
```

Create a signed distance map using the `simpleMap` data.

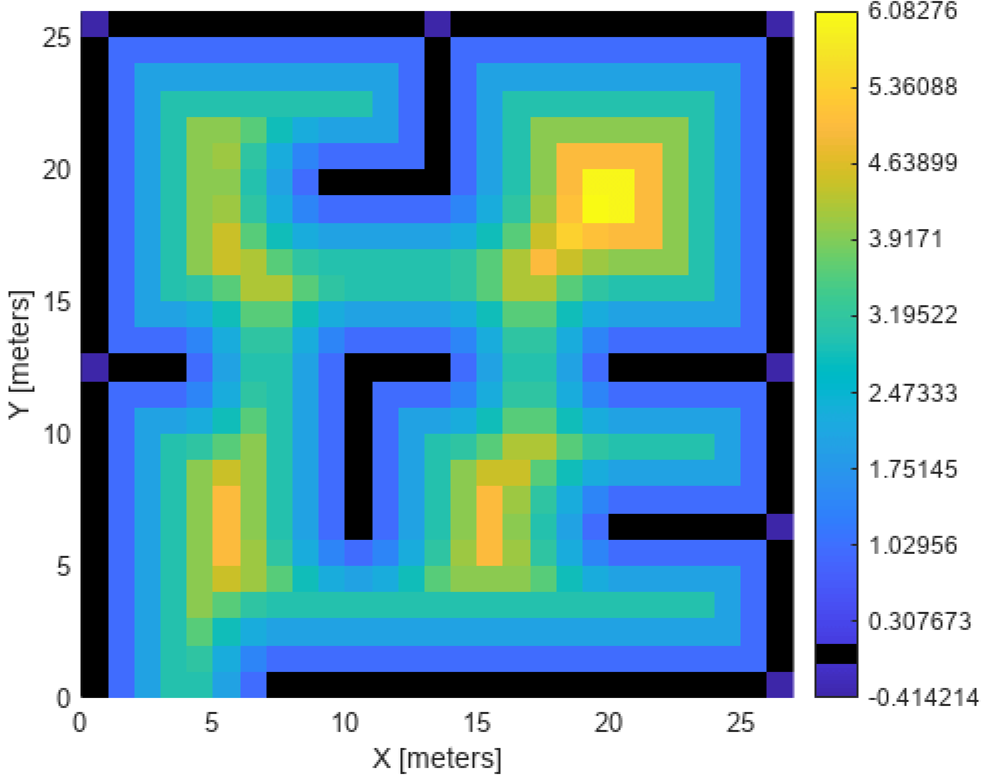
```
sdm = signedDistanceMap(simpleMap,InterpolationMethod="none");
show(sdm,BoundaryColor=[0 0 0],Colorbar="on");
```




```
setMapData(sdm,[7 1],zeros(5,5))
getMapData(sdm,[9 2])
```

```
ans = logical
   0
```

```
show(sdm,BoundaryColor=[0 0 0],Colorbar="on");
```




Find the closest boundary to the coordinate, `[16.25 6.25]` and calculate the distance to the nearest boundary.

```
coord = [16.25 6.25];
boundary = closestBoundary(sdm,coord,"world")
```

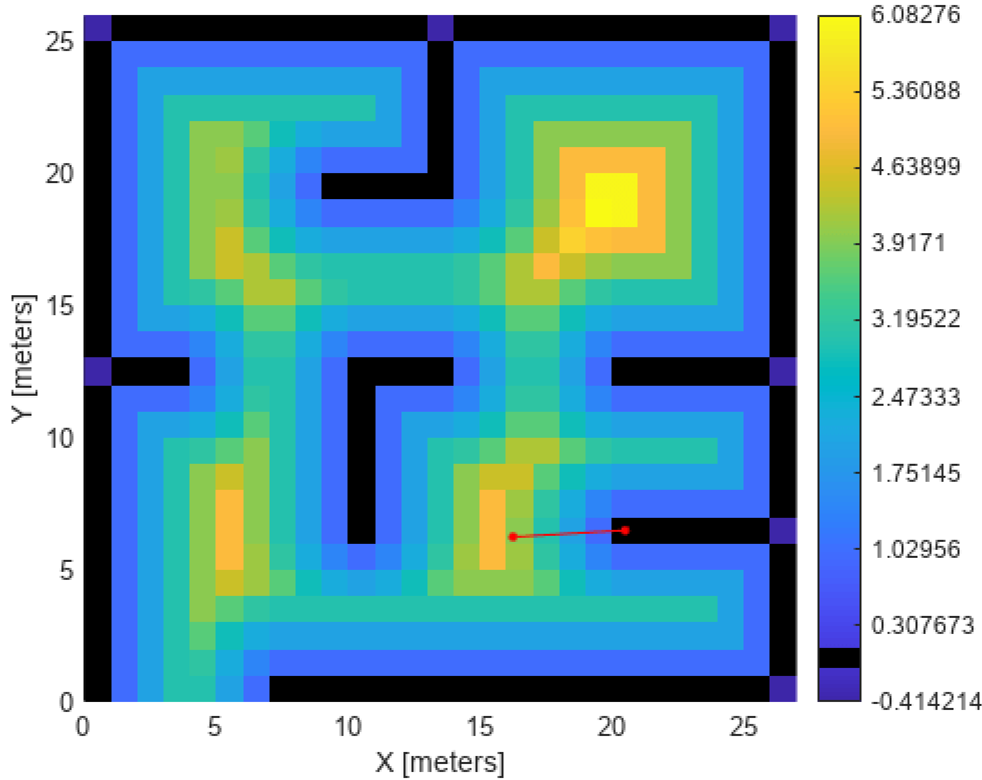
```
boundary = 
boundary(:,:,1) =

   20.5000


boundary(:,:,2) =

    6.5000
```

```
dist = distance(sdm,coord)
```

```
dist = 4
```

Plot the line between the queried point and the closest obstacle cell center

```
hold on
plot([coord(1) boundary(:,:,1)],[coord(2) boundary(:,:,2)],"-r",Marker=".",MarkerSize=10)
```




Note that even though distance from the queried point appears greater than 4 when plotted, the distance function calculates the distance from the nearest cell center of the queried point.

## Input Arguments

**`map` — Signed distance map**
`signedDistanceMap` object

Signed distance map, specified as a `signedDistanceMap` object.

**`location` — World or local coordinates, or grid locations**
*N*-by-2 matrix

World or local coordinates, or grid locations, specified as an *N*-by-2 matrix. *N* is the number of locations. The format of the rows depends on the value of the `frame` argument:

- `"world"` — [*x y*] coordinates in the world frame.
- `"local"` — [*x y*] coordinates in the local frame.
- `"grid"` — [*row column*] location in the grid frame.

Data Types: `double`

**`cornerLocation` — Location of output matrix**
two-element vector

Location of output matrix, specified as a two-element vector of coordinates in the form, [*x y*]. The location is in world or local coordinates if the `frame` argument is set to `"world"` and `"local"`, respectively. When `frame` is `"grid"`, `cornerLocation` is the top-left corner of the world frame.

Data Types: `double`

**`mapSize` — Subregion map size**
two-element vector | `[x y]`

Subregion map size, specified as a two-element vector [*x y*] in world or local coordinates. Location is in world or local coordinates if the `frame` argument is set to `"world"` and `"local"`, respectively. When `frame` is `"grid"`, `cornerLocation` is the top-left corner of the world frame.

Data Types: `double`

**`frame` — Coordinate frame**
`"world"` (default) | `"local"` | `"grid"`

Coordinate frame, specified as one of these options:

- `"world"` — Specify coordinates in the world frame.
- `"local"` — Specify coordinates in the local frame.
- `"grid"` — Specify grid locations in the grid frame.

Data Types: `char` | `string`

## Output Arguments

**`dist` — Distances to closest obstacles**
*L*-element column vector | *M*-by-*N*-by-2 array

Distances to closest obstacles, returned as an *L*-element column vector for location queries and an *M*-by-*N*-by-2 array for subregion queries. *L* is the number of locations queried. *M* and *N* are the dimensions of the map or specified map subregion.

**`isValid` — Points in boundary**
*L*-element vector

Points in boundary, returned as an *L*-element vector, where *L* is the total number of queried locations. Each element is a `1` (`true`) if the point is within the boundaries, and `0` (`false`) if the point is outside boundaries.

This output is only returned for point queries.

# Version History

**Introduced in R2023a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

signedDistanceMap | closestBoundary | gradient

# gradient

Get gradient at locations

## Syntax

```
grad = gradient(map)
grad = gradient(map,location)
grad = gradient(map,location,frame)
[grad,isValid] = gradient(map,location,___)
grad = gradient(map,cornerLocation,mapSize)
grad = gradient(map,cornerLocation,mapSize,frame)
```

## Description

`grad = gradient(map)` returns the *xy*-gradients `grad` for the specified signed distance map `map`.

`grad = gradient(map,location)` returns an array of gradients for the specified *xy*-locations `location` in world coordinates.

`grad = gradient(map,location,frame)` returns an array of gradient values for the specified locations `location`, in the coordinate frame `frame`.

`[grad,isValid] = gradient(map,location,___)` returns `isValid`, indicating which of the specified locations `location` are within the map bounds `isValid`.

`grad = gradient(map,cornerLocation,mapSize)` returns a matrix of values in a subregion of the map layer, `map`. The subregion starts in the corner location `cornerLocation` in the world coordinate frame with a given map size `mapSize`.

`grad = gradient(map,cornerLocation,mapSize,frame)` returns a matrix of distances in a subregion of the map layer, `map`. The subregion starts in the corner location `cornerLocation` in the coordinate frame `frame` with a given map size `mapSize`.

**Note** When the `cornerLoc` and `mapSize` are specified, `gradient` computes gradients at cell centers within the rectangular query region.

## Examples

### Calculate Gradients using Signed Distance Map

Create a linearly interpolated map.

```
map = signedDistanceMap(InterpolationMethod="linear");
```

Set the map data to an identity matrix to set the main diagonal of the map to occupied.

```
setMapData(map,eye(10));
```

Set top left quadrant as occupied.

```
setMapData(map,[0 5],true(5));
```

Calculate gradient in each corner cell of map.

```
queryIJ = [1 1; 1 10; 10 1; 10 10];
gradientAtCornerCell = gradient(map,queryIJ,"grid")
```

```
gradientAtCornerCell = 
gradientAtCornerCell(:,:,1) =

     1
     1
     0
    -1


gradientAtCornerCell(:,:,2) =

    -1
     0
    -1
     1
```

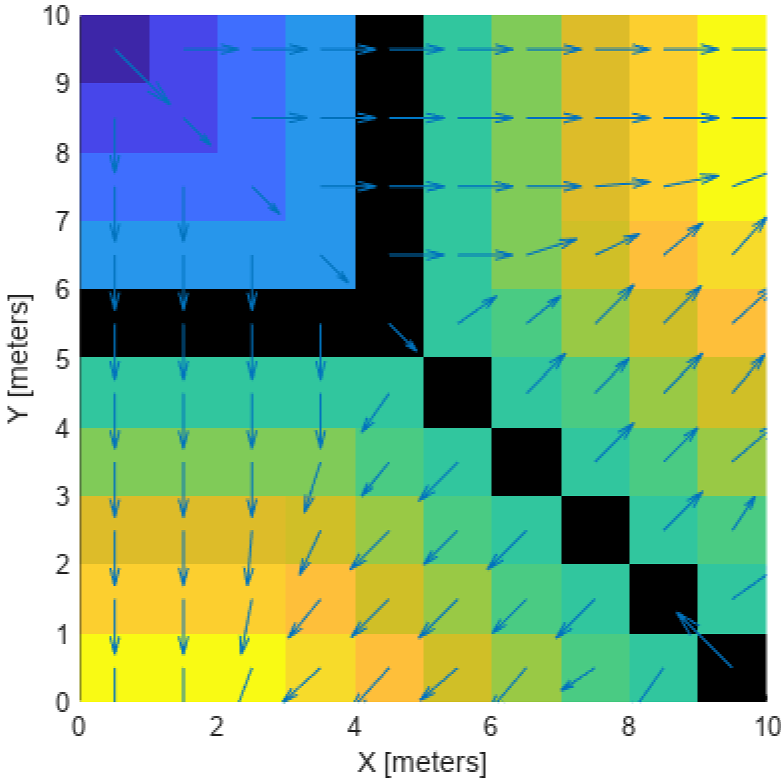
Calculate gradient for cells in top-left quadrant.

```
gradientInQuadrant = gradient(map,[0 5],[5 5])
```

```
gradientInQuadrant = 
gradientInQuadrant(:,:,1) =

    1.0000    1.0000    1.0000    1.0000    1.0000
         0    0.5000    1.0000    1.0000    1.0000
         0         0    0.5000    1.0000    1.0000
         0         0         0    0.5000    1.0000
         0         0         0         0    0.5000


gradientInQuadrant(:,:,2) =

   -1.0000         0         0         0         0
   -1.0000   -0.5000         0         0         0
   -1.0000   -1.0000   -0.5000         0         0
   -1.0000   -1.0000   -1.0000   -0.5000         0
   -1.0000   -1.0000   -1.0000   -1.0000   -0.5000
```

Display gradient vectors over the map.

```
show(map,BoundaryColor=[0 0 0],VectorField="Gradient");
```




## Input Arguments

**`map` — Signed distance map**
`signedDistanceMap` object

Signed distance map, specified as a `signedDistanceMap` object.

**`location` — World or local coordinates, or grid locations**
*N*-by-2 matrix

World or local coordinates, or grid locations, specified as an *N*-by-2 matrix. *N* is the number of locations. The format of the rows depends on the value of the `frame` argument:

- `"world"` — [*x y*] coordinates in the world frame.
- `"local"` — [*x y*] coordinates in the local frame.
- `"grid"` — [*row column*] location in the grid frame.

Data Types: `double`

**`cornerLocation` — Location of output matrix**
two-element vector

Location of output matrix, specified as a two-element vector of coordinates in the form, [*x y*]. The location is in world or local coordinates if the `frame` argument is set to `"world"` and `"local"`, respectively. When `frame` is `"grid"`, `cornerLocation` is the top-left corner of the world frame.

Data Types: double

**mapSize — Subregion map size**
two-element vector | [x y]

Subregion map size, specified as a two-element vector [*x* *y*] in world or local coordinates. Location is in world or local coordinates if the frame argument is set to "world" and "local", respectively. When frame is "grid", cornerLocation is the top-left corner of the world frame.

Data Types: double

**frame — Coordinate frame**
"world" (default) | "local" | "grid"

Coordinate frame, specified as one of these options:

- "world" — Specify coordinates in the world frame.
- "local" — Specify coordinates in the local frame.
- "grid" — Specify grid locations in the grid frame.

Data Types: char | string

## Output Arguments

**grad — *xy*-gradients**
*L*-by-1-by-2 array | *M*-by-*N*-by-2 array

*xy*-gradients, returned as an *L*-by-1-by-2 array for location queries and an *M*-by-*N*-by-2 array for subregion queries. *L* is the number of locations queried. *M* and *N* are the dimensions of the map or specified map subregion.

The *x*-gradients and *y*-gradients are the first and second page, respectively.

**isValid — Points in boundary**
*L*-element vector

Points in boundary, returned as an *L*-element vector, where *L* is the total number of queried locations. Each element is a 1 (true) if the point is within the boundaries, and 0 (false) if the point is outside boundaries.

This output is only returned for point queries.

# Version History

**Introduced in R2023a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

`signedDistanceMap` | `closestBoundary` | `distance`

# show

Display signed distance map

## Syntax

```
show(map)
show(map,frame)
show( ___ ,Name=Value)
mapimage = show( ___ )
[mapimage,colorbar] = show( ___ )
```

## Description

`show(map)` displays the occupancy grid `map` in the current axes, with the axes labels representing the world coordinates.

`show(map,frame)` displays the occupancy grid `map` in the current axes, with the axes labels representing the coordinates in the coordinate frame `frame`.

`show( ___ ,Name=Value)` specifies additional options specified by one or more name-value arguments.

`mapimage = show( ___ )` returns the handle to the image object `mapimage`, created by `show`.

`[mapimage,colorbar] = show( ___ )` returns the handle to the colorbar `colorbar`, created by `show`.

## Examples

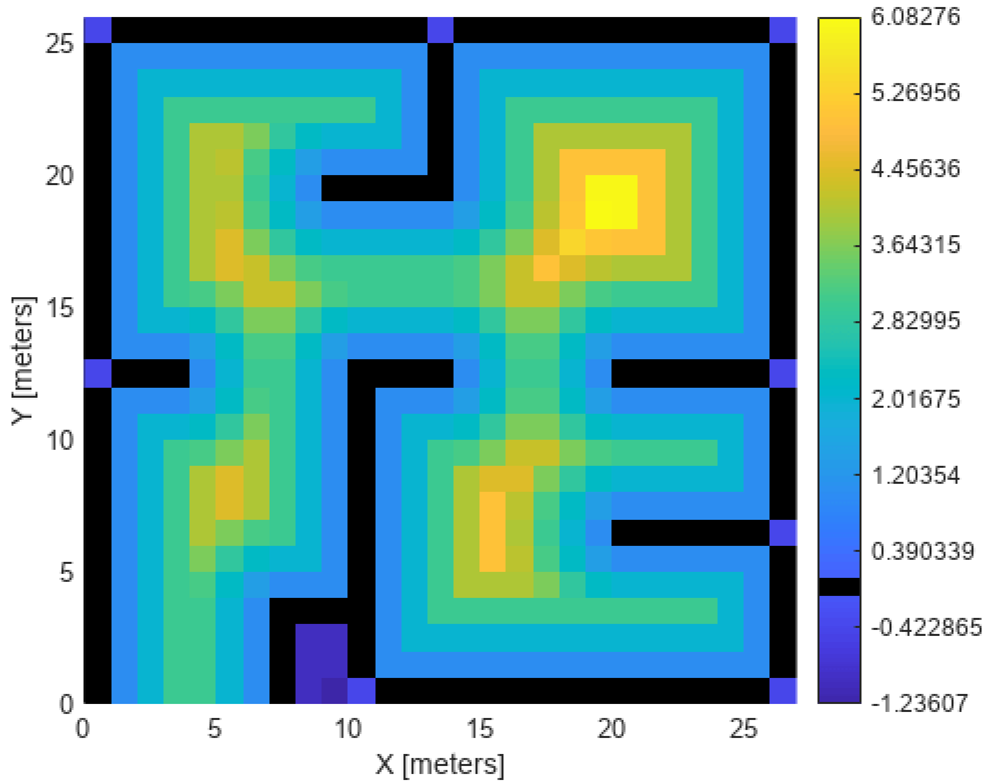
### Get Distance to Nearest Obstacles in Signed Distance Map

Load the `exampleMaps` MAT file.

```
load exampleMaps.mat
```

Create a signed distance map using the `simpleMap` data.

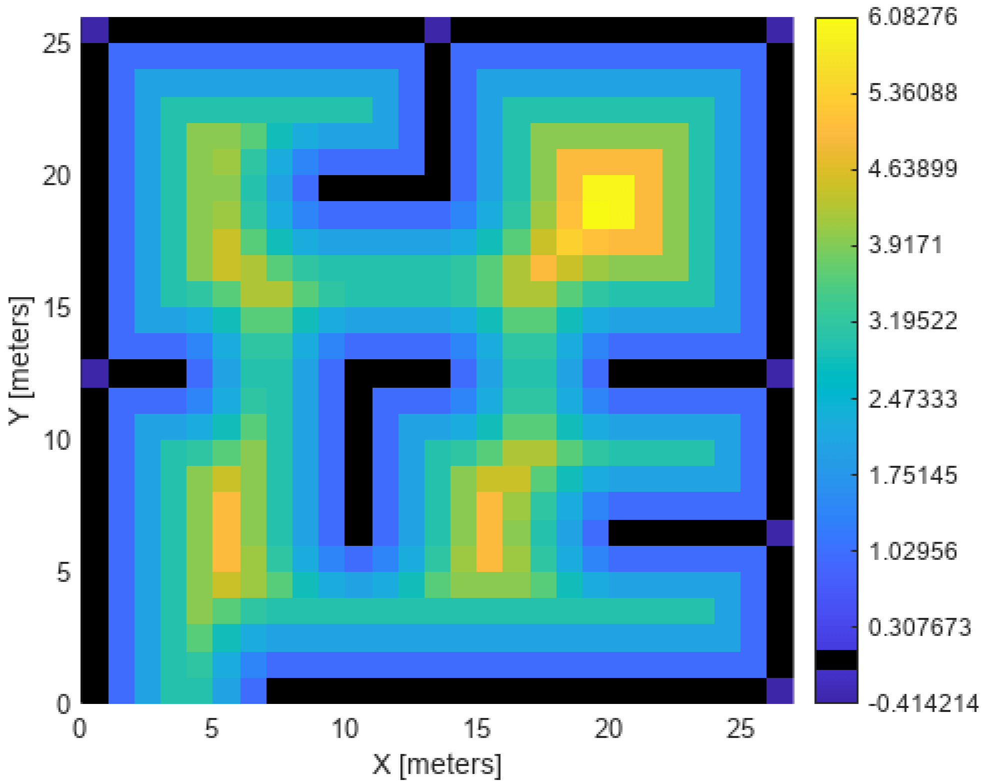
```
sdm = signedDistanceMap(simpleMap,InterpolationMethod="none");
show(sdm,BoundaryColor=[0 0 0],Colorbar="on");
```




```
setMapData(sdm,[7 1],zeros(5,5))
getMapData(sdm,[9 2])
```

```
ans = logical
   0
```

```
show(sdm,BoundaryColor=[0 0 0],Colorbar="on");
```




Find the closest boundary to the coordinate, `[16.25 6.25]` and calculate the distance to the nearest boundary.

```
coord = [16.25 6.25];
boundary = closestBoundary(sdm,coord,"world")
```

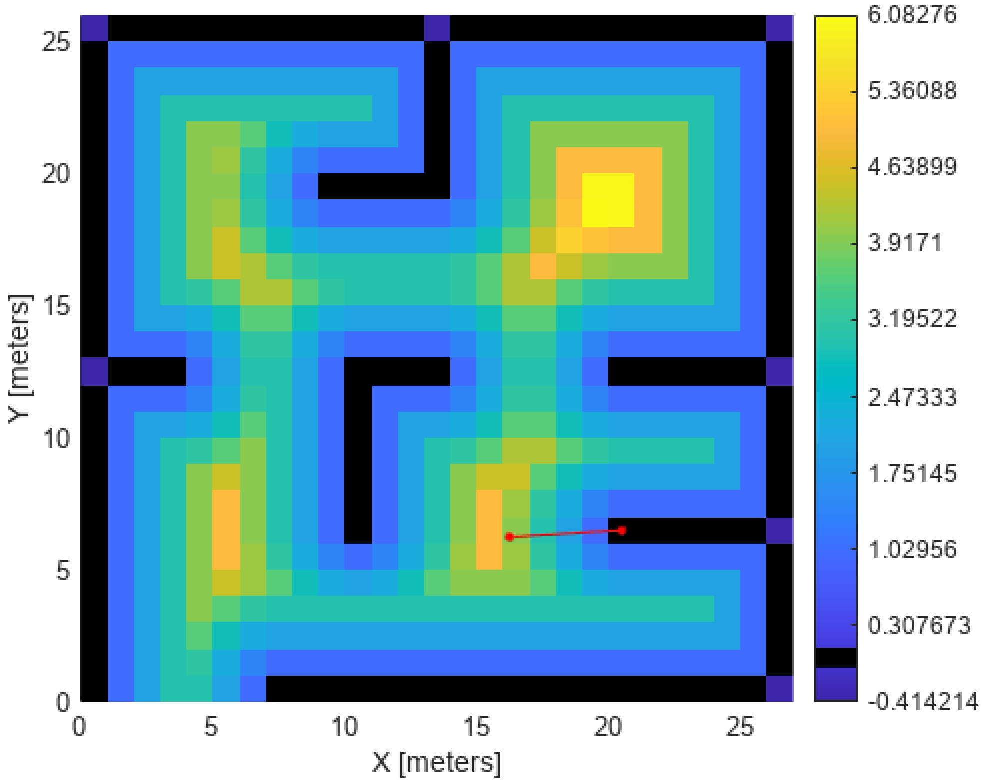
```
boundary =
boundary(:,:,1) =

   20.5000


boundary(:,:,2) =

    6.5000
```

```
dist = distance(sdm,coord)
```

```
dist = 4
```

Plot the line between the queried point and the closest obstacle cell center

```
hold on
plot([coord(1) boundary(:,:,1)],[coord(2) boundary(:,:,2)],"-r",Marker=".",MarkerSize=10)
```




Note that even though distance from the queried point appears greater than 4 when plotted, the distance function calculates the distance from the nearest cell center of the queried point.

## Input Arguments

**`map` — Signed distance map**
`signedDistanceMap` object

Signed distance map, specified as a `signedDistanceMap` object.

**`frame` — Coordinate frame**
`"local"` | `"grid"`

Coordinate frame, specified as either `"local"` or `"grid"`.

### Name-Value Pair Arguments

Specify optional pairs of arguments as `Name1=Value1,...,NameN=ValueN`, where `Name` is the argument name and `Value` is the corresponding value. Name-value arguments must appear after other arguments, but the order of the pairs does not matter.

Example: `signedDistanceMap(sdm,Parent=ax)`

**`Parent` — Axes to plot the map**
`gca` (default) | `Axes` object | `UIAxes` object

Axes to plot the map specified as either an `Axes` or `UIAxes` object. See `axes` or `uiaxes`.

**`Colormap` — Colormap values**
three-column matrix of RGB triplets

Colormap values for the pixel values in the map, specified as a three-column matrix of RGB triplets. If not provided, the current colormap of the axes is used

**`BoundaryColor` — Occupied boundary color**
RGB triplet

Occupied boundary color, specified as an RGB triplet. The occupied boundary cells use the specified color when specified.

**`Colorbar` — Use colorbar**
`false` or `0` (default) | `true` or `1`

Use colorbar, specified as a logical `1` (`true`) or `0` (`false`). When `true`, `show` creates a colorbar that corresponds to the `Colormap` input and adds it to a hidden axis behind the current axis.

Data Types: `logical`

**`VectorField` — Vector field display type**
`"off"` (default) | `"Gradient"` | `"ClosestBoundary"`

Vector field display type, specified as one of these options:

- `"off"` — Show no vector field.
- `"Gradient"` — Show gradient field superimposed on the distance map.
- `"ClosestBoundary"` — Show arrows that point to the nearest occupied boundary cell.

Data Types: `char` | `string`

## Output Arguments

**`mapimage` — Map image handle**
`image` object

Map image handle, specified as a `image` object.

**`colorbar` — Colorbar handle**
`colorbar` object

Colorbar handle, returned as a `colorbar` object.

# Version History

**Introduced in R2023a**

## See Also

`signedDistanceMap`

# copy

Create copy of 2-D signed distance map

## Syntax

```
copyMap = copy(map)
```

## Description

`copyMap = copy(map)` creates a deep copy of the `signedDistanceMap` object with the same properties.

## Input Arguments

**map — Signed distance map**
`signedDistanceMap` object

Map representation, specified as a `signedDistanceMap` object.

## Output Arguments

**copyMap — Copied signed distance map**
`signedDistanceMap` object

Map representation, specified as a `signedDistanceMap` object. The properties are the same as the input object, `map`, but the copy has a different object handle.

# Version History

**Introduced in R2023a**

## See Also

`signedDistanceMap`

# insfilterMARG

Estimate pose from MARG and GPS data

## Description

The `insfilterMARG` object implements sensor fusion of MARG and GPS data to estimate pose in the NED (or ENU) reference frame. MARG (magnetic, angular rate, gravity) data is typically derived from magnetometer, gyroscope, and accelerometer sensors. The filter uses a 22-element state vector to track the orientation quaternion, velocity, position, MARG sensor biases, and geomagnetic vector. The `insfilterMARG` object uses an extended Kalman filter to estimate these quantities.

## Creation

### Syntax

```
filter = insfilterMARG
filter = insfilterMARG('ReferenceFrame',RF)
filter = insfilterMARG( ___ ,Name,Value)
```

#### Description

`filter = insfilterMARG` creates an `insfilterMARG` object with default property values.

`filter = insfilterMARG('ReferenceFrame',RF)` allows you to specify the reference frame, `RF`, of the `filter`. Specify `RF` as `'NED'` (North-East-Down) or `'ENU'` (East-North-Up). The default value is `'NED'`.

`filter = insfilterMARG( ___ ,Name,Value)` also allows you set properties of the created `filter` using one or more name-value pairs. Enclose each property name in single quotes.

### Properties

**`IMUSampleRate` — Sample rate of the IMU (Hz)**
`100` (default) | positive scalar

Sample rate of the inertial measurement unit (IMU) in Hz, specified as a positive scalar.

Data Types: `single` | `double`

**`ReferenceLocation` — Reference location (deg, deg, meters)**
`[0 0 0]` (default) | 3-element positive row vector

Reference location, specified as a 3-element row vector in geodetic coordinates (latitude, longitude, and altitude). Altitude is the height above the reference ellipsoid model, WGS84. The reference location units are [degrees degrees meters].

Data Types: `single` | `double`

**GyroscopeNoise — Multiplicative process noise variance from gyroscope (rad/s)$^2$**
1e-9 (default) | scalar | 3-element row vector

Multiplicative process noise variance from the gyroscope in (rad/s)$^2$, specified as a scalar or 3-element row vector of positive real finite numbers.

- If GyroscopeNoise is specified as a row vector, the elements correspond to the noise in the *x*, *y*, and *z* axes of the gyroscope, respectively.
- If GyroscopeNoise is specified as a scalar, the single element is applied to the *x*, *y*, and *z* axes of the gyroscope.

Data Types: single | double

**GyroscopeBiasNoise — Multiplicative process noise variance from gyroscope bias (rad/s)$^2$**
1e-10 (default) | positive scalar | 3-element row vector

Multiplicative process noise variance from the gyroscope bias in (rad/s)$^2$, specified as a scalar or 3-element row vector of positive real numbers.

- If GyroscopeBiasNoise is specified as a row vector, the elements correspond to the noise in the *x*, *y*, and *z* axes of the gyroscope bias, respectively.
- If GyroscopeBiasNoise is specified as a scalar, the single element is applied to each axis.

Data Types: single | double

**AccelerometerNoise — Multiplicative process noise variance from accelerometer (m/s$^2$)$^2$**
1e-4 (default) | scalar | 3-element row vector

Multiplicative process noise variance from the accelerometer in (m/s$^2$)$^2$, specified as a scalar or 3-element row vector of positive real finite numbers.

- If AccelerometerNoise is specified as a row vector, the elements correspond to the noise in the *x*, *y*, and *z* axes of the accelerometer, respectively.
- If AccelerometerNoise is specified as a scalar, the single element is applied to each axis.

Data Types: single | double

**AccelerometerBiasNoise — Multiplicative process noise variance from accelerometer bias (m/s$^2$)$^2$**
1e-4 (default) | positive scalar | 3-element row vector

Multiplicative process noise variance from the accelerometer bias in (m/s$^2$)$^2$, specified as a scalar or 3-element row vector of positive real numbers.

- If AccelerometerBiasNoise is specified as a row vector, the elements correspond to the noise in the *x*, *y*, and *z* axes of the accelerometer bias, respectively.
- If AccelerometerBiasNoise is specified as a scalar, the single element is applied to each axis.

Data Types: single | double

**GeomagneticVectorNoise — Additive process noise for geomagnetic vector (μT$^2$)**
1e-6 (default) | positive scalar | 3-element row vector

Additive process noise for geomagnetic vector in μT$^2$, specified as a scalar or 3-element row vector of positive real numbers.

- If `GeomagneticVectorNoise` is specified as a row vector, the elements correspond to the noise in the *x*, *y*, and *z* axes of the geomagnetic vector, respectively.
- If `GeomagneticVectorNoise` is specified as a scalar, the single element is applied to each axis.

Data Types: `single` | `double`

**`MagnetometerBiasNoise` — Additive process noise for magnetometer bias (μT²)**
`0.1` (default) | positive scalar | 3-element row vector

Additive process noise for magnetometer bias in μT², specified as a scalar or 3-element row vector.

- If `MagnetometerBiasNoise` is specified as a row vector, the elements correspond to the noise in the *x*, *y*, and *z* axes of the magnetometer bias, respectively.
- If `MagnetometerBiasNoise` is specified as a scalar, the single element is applied to each axis.

Data Types: `single` | `double`

**`State` — State vector of extended Kalman filter**
22-element column vector

State vector of the extended Kalman filter. The state values represent:

| State | Units | Index |
| --- | --- | --- |
| Orientation (quaternion parts) | N/A | 1:4 |
| Position (NED or ENU) | m | 5:7 |
| Velocity (NED or ENU) | m/s | 8:10 |
| Delta Angle Bias (XYZ) | rad | 11:13 |
| Delta Velocity Bias (XYZ) | m/s | 14:16 |
| Geomagnetic Field Vector (NED or ENU) | μT | 17:19 |
| Magnetometer Bias (XYZ) | μT | 20:22 |

Data Types: `single` | `double`

**`StateCovariance` — State error covariance for extended Kalman filter**
`eye(22)*1e-6` (default) | 22-by-22 matrix

State error covariance for the extended Kalman filter, specified as a 22-by-22-element matrix, or real numbers.

Data Types: `single` | `double`

## Object Functions

| | |
| --- | --- |
| correct | Correct states using direct state measurements for insfilterMARG |
| residual | Residuals and residual covariances from direct state measurements for insfilterMARG |
| fusegps | Correct states using GPS data for insfilterMARG |
| residualgps | Residuals and residual covariance from GPS measurements for insfilterMARG |
| fusemag | Correct states using magnetometer data for insfilterMARG |
| residualmag | Residuals and residual covariance from magnetometer measurements for insfilterMARG |
| pose | Current orientation and position estimate for insfilterMARG |

| | |
|---|---|
| predict | Update states using accelerometer and gyroscope data for insfilterMARG |
| reset | Reset internal states for insfilterMARG |
| stateinfo | Display state vector information for insfilterMARG |
| tune | Tune insfilterMARG parameters to reduce estimation error |
| copy | Create copy of insfitlerMARG |

## Examples

### Estimate Pose of UAV

This example shows how to estimate the pose of an unmanned aerial vehicle (UAV) from logged sensor data and ground truth pose.

Load the logged sensor data and ground truth pose of an UAV.

```
load uavshort.mat
```

Initialize the `insfilterMARG` filter object.

```
f = insfilterMARG;
f.IMUSampleRate = imuFs;
f.ReferenceLocation = refloc;
f.AccelerometerBiasNoise = 2e-4;
f.AccelerometerNoise = 2;
f.GyroscopeBiasNoise = 1e-16;
f.GyroscopeNoise = 1e-5;
f.MagnetometerBiasNoise = 1e-10;
f.GeomagneticVectorNoise = 1e-12;
f.StateCovariance = 1e-9*ones(22);
f.State = initstate;

gpsidx = 1;
N = size(accel,1);
p = zeros(N,3);
q = zeros(N,1,'quaternion');
```

Fuse accelerometer, gyroscope, magnetometer, and GPS data.

```
for ii = 1:size(accel,1)               % Fuse IMU
   f.predict(accel(ii,:), gyro(ii,:));

   if ~mod(ii,fix(imuFs/2))            % Fuse magnetometer at 1/2 the IMU rate
       f.fusemag(mag(ii,:),Rmag);
   end

   if ~mod(ii,imuFs)                   % Fuse GPS once per second
       f.fusegps(lla(gpsidx,:),Rpos,gpsvel(gpsidx,:),Rvel);
       gpsidx = gpsidx + 1;
   end

   [p(ii,:),q(ii)] = pose(f);           %Log estimated pose
end
```

Calculate and display RMS errors.

```
posErr = truePos - p;
qErr = rad2deg(dist(trueOrient,q));
```

```
pRMS = sqrt(mean(posErr.^2));
qRMS = sqrt(mean(qErr.^2));
fprintf('Position RMS Error\n\tX: %.2f, Y: %.2f, Z: %.2f (meters)\n\n',pRMS(1),pRMS(2),pRMS(3));

Position RMS Error
    X: 0.57, Y: 0.53, Z: 0.68 (meters)


fprintf('Quaternion Distance RMS Error\n\t%.2f (degrees)\n\n',qRMS);

Quaternion Distance RMS Error
    0.28 (degrees)
```

## Algorithms

*Note: The following algorithm only applies to an NED reference frame.*

`insfilterMARG` uses a 22-axis extended Kalman filter structure to estimate pose in the NED reference frame. The state is defined as:

$$x = \begin{bmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \\ position_{\mathrm{N}} \\ position_{\mathrm{E}} \\ position_{\mathrm{D}} \\ \nu_{\mathrm{N}} \\ \nu_{\mathrm{E}} \\ \nu_{\mathrm{D}} \\ \Delta\theta bias_{\mathrm{X}} \\ \Delta\theta bias_{\mathrm{Y}} \\ \Delta\theta bias_{\mathrm{Z}} \\ \Delta\nu bias_{\mathrm{X}} \\ \Delta\nu bias_{\mathrm{Y}} \\ \Delta\nu bias_{\mathrm{Z}} \\ geomagneticFieldVector_{\mathrm{N}} \\ geomagneticFieldVector_{\mathrm{E}} \\ geomagneticFieldVector_{\mathrm{D}} \\ magbias_{\mathrm{X}} \\ magbias_{\mathrm{Y}} \\ magbias_{\mathrm{Z}} \end{bmatrix}$$

where

- $q_0$, $q_1$, $q_2$, $q_3$ –– Parts of orientation quaternion. The orientation quaternion represents a frame rotation from the platform's current orientation to the local NED coordinate system.
- $position_N$, $position_E$, $position_D$ –– Position of the platform in the local NED coordinate system.
- $\nu_N$, $\nu_E$, $\nu_D$ –– Velocity of the platform in the local NED coordinate system.
- $\Delta\theta bias_X$, $\Delta\theta bias_Y$, $\Delta\theta bias_Z$ –– Bias in the integrated gyroscope reading.
- $\Delta\nu bias_X$, $\Delta\nu bias_Y$, $\Delta\nu bias_Z$ –– Bias in the integrated accelerometer reading.
- $geomagneticFieldVector_N$, $geomagneticFieldVector_E$, $geomagneticFieldVector_D$ –– Estimate of the geomagnetic field vector at the reference location.
- $magbias_X$, $magbias_Y$, $magbias_Z$ –– Bias in the magnetometer readings.

Given the conventional formation of the predicted state estimate,

$$x_{k|k-1} = f(\widehat{x}_{k-1|k-1}, u_k)$$

$u_k$ is controlled by accelerometer and gyroscope data that has been converted to delta velocity and delta angle through trapezoidal integration. The predicted state estimation is:

$x_{k|k-1} =$

$$
\begin{bmatrix}
q_0 q_0' - q_1 q_1' - q_2 q_2' - q_3 q_3' \\
q_1 q_0' + q_0 q_1' - q_3 q_2' + q_2 q_3' \\
q_2 q_0' + q_3 q_1' + q_0 q_2' - q_1 q_3' \\
q_3 q_0' - q_2 q_1' + q_1 q_2' + q_0 q_3' \\
position_{\mathrm{N}} + (\Delta t)(\nu_{\mathrm{N}}) \\
position_{\mathrm{E}} + (\Delta t)(\nu_{\mathrm{E}}) \\
position_{\mathrm{D}} + (\Delta t)(\nu_{\mathrm{D}}) \\
\nu_{\mathrm{N}} + (\Delta t)(g_{\mathrm{N}}) + (\Delta\nu_{\mathrm{X}} - \Delta\nu bias_{\mathrm{X}})\left(q_0^2 + q_1^2 - q_2^2 - q_3^2\right) - 2(\Delta\nu_{\mathrm{Y}} - \Delta\nu bias_{\mathrm{Y}})(q_0 q_3 - q_1 q_2) + 2(\Delta\nu_{\mathrm{Z}} - \Delta\nu bias_{\mathrm{Z}})(q_0 q_2 + \\
\nu_{\mathrm{E}} + (\Delta t)(g_{\mathrm{E}}) + (\Delta\nu_{\mathrm{Y}} - \Delta\nu bias_{\mathrm{Y}})\left(q_0^2 - q_1^2 + q_2^2 - q_3^2\right) + 2(\Delta\nu_{\mathrm{X}} - \Delta\nu bias_{\mathrm{X}})(q_0 q_3 + q_1 q_2) - 2(\Delta\nu_{\mathrm{Z}} - \Delta\nu bias_{\mathrm{Z}})(q_0 q_1 - \\
\nu_{\mathrm{D}} + (\Delta t)(g_{\mathrm{D}}) + (\Delta\nu_{\mathrm{Z}} - \Delta\nu bias_{\mathrm{Z}})\left(q_0^2 - q_1^2 - q_2^2 + q_3^2\right) - 2(\Delta\nu_{\mathrm{X}} - \Delta\nu bias_{\mathrm{X}})(q_0 q_2 - q_1 q_3) + 2(\Delta\nu_{\mathrm{Y}} - \Delta\nu bias_{\mathrm{Y}})(q_0 q_1 + \\
\Delta\theta bias_{\mathrm{X}} \\
\Delta\theta bias_{\mathrm{Y}} \\
\Delta\theta bias_{\mathrm{Z}} \\
\Delta\nu bias_{\mathrm{X}} \\
\Delta\nu bias_{\mathrm{Y}} \\
\Delta\nu bias_{\mathrm{Z}} \\
geomagneticFieldVector_{\mathrm{N}} \\
geomagneticFieldVector_{\mathrm{E}} \\
geomagneticFieldVector_{\mathrm{D}}
\end{bmatrix}
$$

In the equation, ($q_0'$, $q_1'$, $q_2'$, $q_3'$) is the quaternion that accounts for the orientation change from one step to the next step. Assuming the orientation change is small, then the rotation vector can be approximated as ($\Delta\theta_X - \Delta\theta bias_X$, $\Delta\theta_Y - \Delta\theta bias_Y$, $\Delta\theta_Z - \Delta\theta bias_Z$), where $\Delta\theta_X$, $\Delta\theta_Y$, $\Delta\theta_Z$ are the integrated gyroscope readings. ($q_0'$, $q_1'$, $q_2'$, $q_3'$) is then obtained by converting the approximated rotation vector to a quaternion. In each calculation, the quaternion is normalized such that the length of the quaternion is 1 and its real part $q_0$ is nonnegative.

Additionally,

- $\Delta\nu_X$, $\Delta\nu_Y$, $\Delta\nu_Z$ -– Integrated accelerometer readings.
- $\Delta t$ -– IMU sample time.
- $g_N$, $g_E$, $g_D$ -– Constant gravity vector in the NED frame.

# Version History

**Introduced in R2018b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`insfilterNonholonomic` | `insfilterErrorState` | `insfilterAsync`

# correct

Correct states using direct state measurements for `insfilterMARG`

## Syntax

```
correct(FUSE,idx,measurement,measurementCovariance)
```

## Description

`correct(FUSE,idx,measurement,measurementCovariance)` corrects the state and state estimation error covariance based on the measurement and measurement covariance. The measurement maps directly to the state specified by the indices `idx`.

## Input Arguments

**`FUSE` — `insfilterMARG` object**
object

`insfilterMARG`, specified as an object.

**`idx` — State vector Index of measurement to correct**
*N*-element vector of increasing integers in the range [1,22]

State vector index of measurement to correct, specified as an *N*-element vector of increasing integers in the range [1, 22].

The state values represent:

| State | Units | Index |
| --- | --- | --- |
| Orientation (quaternion parts) | | 1:4 |
| Position (NED) | m | 5:7 |
| Velocity (NED) | m/s | 8:10 |
| Delta Angle Bias (XYZ) | rad | 11:13 |
| Delta Velocity Bias (XYZ) | m/s | 14:16 |
| Geomagnetic Field Vector (NED) | µT | 17:19 |
| Magnetometer Bias (XYZ) | µT | 20:22 |

Data Types: `single` | `double`

**`measurement` — Direct measurement of state**
*N*-element vector

Direct measurement of state, specified as a *N*-element vector. *N* is the number of elements of the index argument, idx.

Data Types: `single` | `double`

**`measurementCovariance` — Covariance of measurement**
scalar | *N*-element vector | *N*-by-*N* matrix

Covariance of measurement, specified as a scalar, *N*-element vector, or *N*-by-*N* matrix. *N* is the number of elements of the index argument, idx.

Data Types: `single` | `double`

# Version History

**Introduced in R2018b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`insfilterMARG` | `insfilter`

# copy

Create copy of `insfitlerMARG`

## Syntax

`newFilter = copy(filter)`

## Description

`newFilter = copy(filter)` returns a copy of the `insfilterMARG`, `filter`, with the exactly same property values.

## Input Arguments

**`filter` — Filter to be copied**
`insfitlerMARG`

Filter to be copied, specified as an `insfilterMARG` object.

## Output Arguments

**`newFilter` — New copied filter**
`insfitlerMARG`

New copied filter, returned as an `insfilterMARG` object.

# Version History

**Introduced in R2020b**

## See Also

`insfilterMARG`

# fusegps

Correct states using GPS data for `insfilterMARG`

## Syntax

```
[res,resCov] = fusegps(FUSE,position,positionCovariance)
[res,resCov] = fusegps(FUSE,position,positionCovariance,velocity,
velocityCovariance)
```

## Description

`[res,resCov] = fusegps(FUSE,position,positionCovariance)` fuses GPS position data to correct the state estimate.

`[res,resCov] = fusegps(FUSE,position,positionCovariance,velocity, velocityCovariance)` fuses GPS position and velocity data to correct the state estimate.

## Input Arguments

**`FUSE` — `insfilterMARG` object**
object

`insfilterMARG`, specified as an object.

**`position` — Position of GPS receiver (LLA)**
3-element row vector

Position of GPS receiver in geodetic latitude, longitude, and altitude (LLA) specified as a real finite 3-element row vector. Latitude and longitude are in degrees with north and east being positive. Altitude is in meters.

Data Types: `single` | `double`

**`positionCovariance` — Position measurement covariance of GPS receiver ($m^2$)**
3-by-3 matrix

Position measurement covariance of GPS receiver in $m^2$, specified as a 3-by-3 matrix.

Data Types: `single` | `double`

**`velocity` — Velocity of GPS receiver in local NED coordinate system (m/s)**
3-element row vector

Velocity of the GPS receiver in the local NED coordinate system in m/s, specified as a 3-element row vector.

Data Types: `single` | `double`

**`velocityCovariance` — Velocity measurement covariance of GPS receiver ($m/s^2$)**
3-by-3 matrix

Velocity measurement covariance of the GPS receiver in the local NED coordinate system in $m/s^2$, specified as a 3-by-3 matrix.

Data Types: `single` | `double`

## Output Arguments

**`res` — Position and velocity residual**
1-by-6 vector of real values

Position and velocity residual, returned as a 1-by-6 vector of real values in m and m/s, respectively.

**`resCov` — Residual covariance**
6-by-6 matrix of real values

Residual covariance, returned as a 6-by-6 matrix of real values.

# Version History

**Introduced in R2018b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

`insfilter` | `insfilterMARG`

# fusemag

Correct states using magnetometer data for `insfilterMARG`

## Syntax

```
[res,resCov] = fusemag(FUSE,magReadings,magReadingsCovariance)
```

## Description

`[res,resCov] = fusemag(FUSE,magReadings,magReadingsCovariance)` fuses magnetometer data to correct the state estimate.

## Input Arguments

**`FUSE` — `insfilterMARG` object**
object

`insfilterMARG`, specified as an object.

**`magReadings` — Magnetometer readings (µT)**
3-element row vector

Magnetometer readings in µT, specified as a 3-element row vector of finite real numbers.

Data Types: `single` | `double`

**`magReadingsCovariance` — Magnetometer readings error covariance (µT$^2$)**
scalar | 3-element row vector | 3-by-3 matrix

Magnetometer readings error covariance in µT$^2$, specified as a scalar, 3-element row vector, or 3-by-3 matrix.

Data Types: `single` | `double`

## Output Arguments

**`res` — Residual**
1-by-3 vector of real values

Residual, returned a 1-by-3 vector of real values in µT.

Data Types: `single` | `double`

**`resCov` — Residual covariance**
3-by-3 matrix of real values

Residual covariance, returned a 3-by-3 matrix of real values in (µT)$^2$.

# Version History

**Introduced in R2018b**

## Extended Capabilities

### C/C++ Code Generation
Generate C and C++ code using MATLAB® Coder™.

## See Also
`insfilterMARG` | `insfilter`

# pose

Current orientation and position estimate for `insfilterMARG`

## Syntax

```
[position,orientation,velocity] = pose(FUSE)
[position,orientation,velocity] = pose(FUSE,format)
```

## Description

`[position,orientation,velocity] = pose(FUSE)` returns the current estimate of the pose and velocity.

`[position,orientation,velocity] = pose(FUSE,format)` returns the current estimate of the pose with orientation in the specified orientation format.

## Input Arguments

**`FUSE` — `insfilterMARG` object**
object

`insfilterMARG`, specified as an object.

**`format` — Output orientation format**
`'quaternion'` (default) | `'rotmat'`

Output orientation format, specified as either `'quaternion'` for a `quaternion` or `'rotmat'` for a rotation matrix.

Data Types: `char` | `string`

## Output Arguments

**`position` — Position estimate expressed in the local coordinate system (m)**
3-element row vector

Position estimate expressed in the local coordinate system of the filter in meters, returned as a 3-element row vector.

Data Types: `single` | `double`

**`orientation` — Orientation estimate expressed in the local coordinate system**
quaternion (default) | 3-by-3 rotation matrix

Orientation estimate expressed in the local coordinate system of the filter, returned as a scalar quaternion or 3-by-3 rotation matrix. The quaternion or rotation matrix represents a frame rotation from the local reference frame of the filter to the body reference frame.

Data Types: `single` | `double` | `quaternion`

**`velocity` — Velocity estimate expressed in local coordinate system (m/s)**
3-element row vector

Velocity estimate expressed in the local coordinate system of the filter in m/s, returned as a 3-element row vector.

Data Types: `single` | `double`

# Version History

**Introduced in R2018b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

`insfilterMARG` | `insfilter`

# predict

Update states using accelerometer and gyroscope data for `insfilterMARG`

## Syntax

`predict(FUSE,accelReadings,gyroReadings)`

## Description

`predict(FUSE,accelReadings,gyroReadings)` fuses accelerometer and gyroscope data to update the state estimate.

## Input Arguments

**FUSE — `insfilterMARG` object**
object

`insfilterMARG`, specified as an object.

**`accelReadings` — Accelerometer readings in local sensor body coordinate system ($m/s^2$)**
3-element row vector

Accelerometer readings in $m/s^2$, specified as a 3-element row vector.

Data Types: `single` | `double`

**`gyroReadings` — Gyroscope readings in local sensor body coordinate system (rad/s)**
3-element row vector

Gyroscope readings in rad/s, specified as a 3-element row vector.

Data Types: `single` | `double`

# Version History

**Introduced in R2018b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

`insfilterMARG` | `insfilter`

# reset

Reset internal states for `insfilterMARG`

## Syntax

`reset(FUSE)`

## Description

`reset(FUSE)` resets the State, StateCovariance, and internal integrators to their default values.

## Input Arguments

**FUSE — `insfilterMARG` object**
object

`insfilterMARG`, specified as an object.

# Version History

**Introduced in R2018b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

`insfilterMARG` | `insfilter`

# residual

Residuals and residual covariances from direct state measurements for `insfilterMARG`

## Syntax

`[res, resCov]= residual(FUSE,idx,measurement,measurementCovariance)`

## Description

`[res, resCov]= residual(FUSE,idx,measurement,measurementCovariance)` computes the residual, `res`, and the residual covariance, `resCov`, based on the direct state measurement and measurement covariance. The `measurement` maps directly to the states specified by indices, `idx`.

## Input Arguments

**`FUSE` — `insfilterMARG` object**
object

`insfilterMARG`, specified as an object.

**`idx` — State vector index of measurement**
*N*-element vector of increasing integers in the range [1,22]

State vector index of measurement, specified as an *N*-element vector of increasing integers in the range [1, 22].

The state values represent:

| State | Units | Index |
| --- | --- | --- |
| Orientation (quaternion parts) | | 1:4 |
| Position (NED) | m | 5:7 |
| Velocity (NED) | m/s | 8:10 |
| Delta Angle Bias (XYZ) | rad | 11:13 |
| Delta Velocity Bias (XYZ) | m/s | 14:16 |
| Geomagnetic Field Vector (NED) | μT | 17:19 |
| Magnetometer Bias (XYZ) | μT | 20:22 |

**`measurement` — Direct measurement of state**
*N*-element vector

Direct measurement of state, specified as a *N*-element vector. *N* is the number of elements of the index argument, `idx`.

**`measurementCovariance` — Covariance of measurement**
*N*-by-*N* matrix

Covariance of measurement, specified as an *N*-by-*N* matrix. *N* is the number of elements of the index argument, `idx`.

## Output Arguments

### `res` — Measurement residual
1-by-*N* vector of real values

Measurement residual, returned as a 1-by-*N* vector of real values.

### `resCov` — Residual covariance
*N*-by-*N* matrix of real values

Residual covariance, returned as a *N*-by-*N* matrix of real values.

# Version History
**Introduced in R2020a**

## See Also
`insfilterMARG`

# residualgps

Residuals and residual covariance from GPS measurements for `insfilterMARG`

## Syntax

```
[res,resCov] = residualgps(FUSE,position,positionCovariance)
[res,resCov] = residualgps(FUSE,position,positionCovariance,velocity,
velocityCovariance)
```

## Description

`[res,resCov] = residualgps(FUSE,position,positionCovariance)` computes the residual, `res`, and the residual covariance, `resCov`, based on the GPS position measurement and covariance.

`[res,resCov] = residualgps(FUSE,position,positionCovariance,velocity, velocityCovariance)` computes the residual, `res`, and the residual covariance, `resCov`, based on the GPS position measurement and covariance.

## Input Arguments

**FUSE — `insfilterMARG` object**
object

`insfilterMARG`, specified as an object.

**`position` — Position of GPS receiver (LLA)**
3-element row vector

Position of GPS receiver in geodetic latitude, longitude, and altitude (LLA) specified as a real finite 3-element row vector. Latitude and longitude are in degrees with north and east being positive. Altitude is in meters.

Data Types: `single` | `double`

**`positionCovariance` — Position measurement covariance of GPS receiver ($m^2$)**
3-by-3 matrix

Position measurement covariance of GPS receiver in $m^2$, specified as a 3-by-3 matrix.

Data Types: `single` | `double`

**`velocity` — Velocity of GPS receiver in local NED coordinate system (m/s)**
3-element row vector

Velocity of the GPS receiver in the local NED coordinate system in m/s, specified as a 3-element row vector.

Data Types: `single` | `double`

**`velocityCovariance` — Velocity measurement covariance of GPS receiver ($m/s^2$)**
3-by-3 matrix

Velocity measurement covariance of the GPS receiver in the local NED coordinate system in m/s$^2$, specified as a 3-by-3 matrix.

Data Types: `single` | `double`

### Output Arguments

**`res` — Position and velocity residual**
1-by-3 vector of real values | 1-by-6 vector of real values

Position and velocity residual, returned as a 1-by-3 vector of real values if the inputs only contain position information, and returned as 1-by-6 vector of real values if the inputs also contain velocity information.

**`resCov` — Residual covariance**
3-by-3 matrix of real values | 6-by-6 matrix of real values

Residual covariance, returned as a 3-by-3 matrix of real values if the inputs only contain position information, and a 6-by-6 matrix of real values if the inputs also contain velocity information.

## Version History

**Introduced in R2020a**

### See Also

`insfilter` | `insfilterMARG`

# residualmag

Residuals and residual covariance from magnetometer measurements for `insfilterMARG`

## Syntax

```
[res,resCov] = residualmag(FUSE,magReadings,magReadingsCovariance)
```

## Description

`[res,resCov] = residualmag(FUSE,magReadings,magReadingsCovariance)` computes the residual, `residual`, and the residual covariance, `resCov`, based on the magnetometer readings and the corresponding covariance.

## Input Arguments

**`FUSE` — `insfilterMARG` object**
object

`insfilterMARG`, specified as an object.

**`magReadings` — Magnetometer readings (µT)**
3-element row vector

Magnetometer readings in µT, specified as a 3-element row vector of finite real numbers.

Data Types: `single` | `double`

**`magReadingsCovariance` — Magnetometer readings error covariance (µT$^2$)**
scalar | 3-element row vector | 3-by-3 matrix

Magnetometer readings error covariance in µT$^2$, specified as a scalar, 3-element row vector, or 3-by-3 matrix.

Data Types: `single` | `double`

## Output Arguments

**`res` — Residual**
1-by-3 vector of real values

Residual, returned as a 1-by-3 vector of real values in µT.

Data Types: `single` | `double`

**`resCov` — Residual covariance**
3-by-3 matrix of real values

Residual covariance, returned a 3-by-3 matrix of real values in (µT)$^2$.

## Version History

**Introduced in R2020a**

## See Also

`insfilterMARG` | `insfilter`

# stateinfo

Display state vector information for `insfilterMARG`

## Syntax

```
stateinfo(FUSE)
info = stateinfo(FUSE)
```

## Description

`stateinfo(FUSE)` displays the meaning of each index of the State property and the associated units.

`info = stateinfo(FUSE)` returns a structure with fields containing descriptions of the elements of the state vector of the filter, `FUSE`.

## Examples

### State Information of `insfilterMARG`

Create an `insfilterMARG` object.

```
filter = insfilterMARG;
```

Display the state information of the created filter.

```
stateinfo(filter)
```

```
States                            Units    Index
Orientation (quaternion parts)             1:4
Position (NAV)                    m        5:7
Velocity (NAV)                    m/s      8:10
Delta Angle Bias (XYZ)            rad      11:13
Delta Velocity Bias (XYZ)         m/s      14:16
Geomagnetic Field Vector (NAV)    μT       17:19
Magnetometer Bias (XYZ)           μT       20:22
```

Output the state information of the filter as a structure.

```
info = stateinfo(filter)
```

```
info = struct with fields:
               Orientation: [1 2 3 4]
                  Position: [5 6 7]
                  Velocity: [8 9 10]
            DeltaAngleBias: [11 12 13]
         DeltaVelocityBias: [14 15 16]
    GeomagneticFieldVector: [17 18 19]
           MagnetometerBias: [20 21 22]
```

## Input Arguments

**`FUSE` — `insfilterMARG` object**
object

`insfilterMARG`, specified as an object.

**`info` — State information**
structure

State information, returned as a structure. The field names of the structure are names of the elements of the state vector in the filter. The values of each field are the corresponding indices of the state vector.

# Version History

**Introduced in R2018b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

`insfilterMARG` | `insfilter`

# tune

Tune `insfilterMARG` parameters to reduce estimation error

## Syntax

```
tunedMeasureNoise = tune(filter,measureNoise,sensorData,groundTruth)
tunedMeasureNoise = tune( ___ ,config)
```

## Description

`tunedMeasureNoise = tune(filter,measureNoise,sensorData,groundTruth)` adjusts the properties of the `insfilterMARG` filter object, `filter`, and measurement noises to reduce the root-mean-squared (RMS) state estimation error between the fused sensor data and the ground truth. The function also returns the tuned measurement noise, `tunedMeasureNoise`. The function uses the property values in the filter and the measurement noise provided in the `measureNoise` structure as the initial estimate for the optimization algorithm.

`tunedMeasureNoise = tune( ___ ,config)` specifies the tuning configuration based on a `tunerconfig` object, `config`.

## Examples

### Tune `insfilterMARG` to Optimize Pose Estimate

Load the recorded sensor data and ground truth data.

```
load('insfilterMARGTuneData.mat');
```

Create tables for the sensor data and the truth data.

```
sensorData = table(Accelerometer, Gyroscope, ...
    Magnetometer, GPSPosition, GPSVelocity);
groundTruth = table(Orientation, Position);
```

Create an `insfilterMARG` filter object that has a few noise properties.

```
filter = insfilterMARG('State',initialState,...
        'StateCovariance',initialStateCovariance,...
        'AccelerometerBiasNoise',1e-7,...
        'GyroscopeBiasNoise',1e-7,...
        'MagnetometerBiasNoise',1e-7,...
        'GeomagneticVectorNoise',1e-7);
```

Create a tuner configuration object for the filter. Set the maximum iterations to eight. Also, set the tunable parameters.

```
cfg = tunerconfig('insfilterMARG', 'MaxIterations', 8);
cfg.TunableParameters = setdiff(cfg.TunableParameters, ...
    {'GeomagneticFieldVector', 'AccelerometerBiasNoise', ...
    'GyroscopeBiasNoise', 'MagnetometerBiasNoise'});
```

Use the tuner noise function to obtain a set of initial sensor noises used in the filter.

```
measNoise = tunernoise('insfilterMARG')
```

```
measNoise = struct with fields:
    MagnetometerNoise: 1
     GPSPositionNoise: 1
     GPSVelocityNoise: 1
```

Tune the filter and obtain the tuned parameters.

```
tunedParams = tune(filter, measNoise, sensorData, ...
        groundTruth, cfg);
```

```
    Iteration    Parameter                 Metric
    _________    _________                 ______
    1            AccelerometerNoise        2.5701
    1            GPSPositionNoise          2.5446
    1            GPSVelocityNoise          2.5279
    1            GeomagneticVectorNoise    2.5268
    1            GyroscopeNoise            2.5268
    1            MagnetometerNoise         2.5204
    2            AccelerometerNoise        2.5203
    2            GPSPositionNoise          2.4908
    2            GPSVelocityNoise          2.4695
    2            GeomagneticVectorNoise    2.4684
    2            GyroscopeNoise            2.4684
    2            MagnetometerNoise         2.4615
    3            AccelerometerNoise        2.4615
    3            GPSPositionNoise          2.4265
    3            GPSVelocityNoise          2.4000
    3            GeomagneticVectorNoise    2.3988
    3            GyroscopeNoise            2.3988
    3            MagnetometerNoise         2.3911
    4            AccelerometerNoise        2.3911
    4            GPSPositionNoise          2.3500
    4            GPSVelocityNoise          2.3164
    4            GeomagneticVectorNoise    2.3153
    4            GyroscopeNoise            2.3153
    4            MagnetometerNoise         2.3068
    5            AccelerometerNoise        2.3068
    5            GPSPositionNoise          2.2587
    5            GPSVelocityNoise          2.2166
    5            GeomagneticVectorNoise    2.2154
    5            GyroscopeNoise            2.2154
    5            MagnetometerNoise         2.2063
    6            AccelerometerNoise        2.2063
    6            GPSPositionNoise          2.1505
    6            GPSVelocityNoise          2.0981
    6            GeomagneticVectorNoise    2.0971
    6            GyroscopeNoise            2.0971
    6            MagnetometerNoise         2.0875
    7            AccelerometerNoise        2.0874
    7            GPSPositionNoise          2.0240
    7            GPSVelocityNoise          1.9601
    7            GeomagneticVectorNoise    1.9594
    7            GyroscopeNoise            1.9594
    7            MagnetometerNoise         1.9499
```

```
    8           AccelerometerNoise        1.9499
    8           GPSPositionNoise          1.8802
    8           GPSVelocityNoise          1.8035
    8           GeomagneticVectorNoise    1.8032
    8           GyroscopeNoise            1.8032
    8           MagnetometerNoise         1.7959
```

Fuse the sensor data using the tuned filter.

```
N = size(sensorData,1);
qEstTuned = quaternion.zeros(N,1);
posEstTuned = zeros(N,3);
for ii=1:N
    predict(filter,Accelerometer(ii,:),Gyroscope(ii,:));
    if all(~isnan(Magnetometer(ii,1)))
        fusemag(filter,Magnetometer(ii,:),...
            tunedParams.MagnetometerNoise);
    end
    if all(~isnan(GPSPosition(ii,1)))
        fusegps(filter,GPSPosition(ii,:),...
            tunedParams.GPSPositionNoise,GPSVelocity(ii,:),...
            tunedParams.GPSVelocityNoise);
    end
    [posEstTuned(ii,:),qEstTuned(ii,:)] = pose(filter);
end
```

Compute the RMS errors.

```
orientationErrorTuned = rad2deg(dist(qEstTuned,Orientation));
rmsOrientationErrorTuned = sqrt(mean(orientationErrorTuned.^2))
```

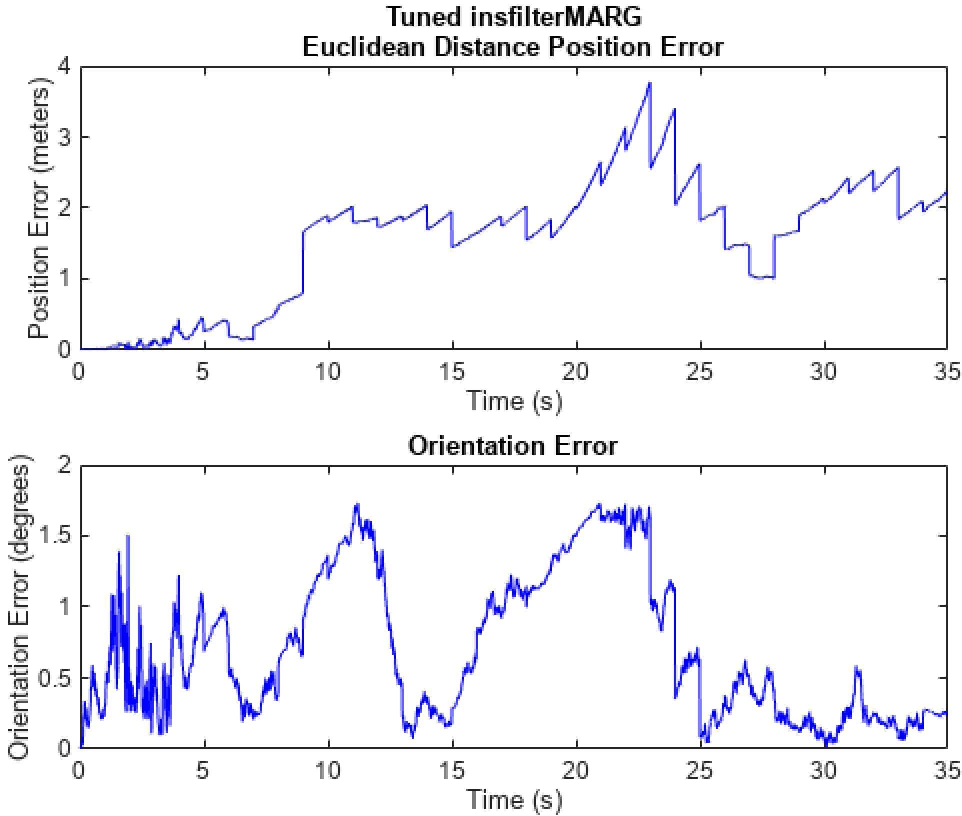
```
rmsOrientationErrorTuned = 0.8580
```

```
positionErrorTuned = sqrt(sum((posEstTuned - Position).^2,2));
rmsPositionErrorTuned = sqrt(mean(positionErrorTuned.^2))
```

```
rmsPositionErrorTuned = 1.7946
```

Visualize the results.

```
figure();
t = (0:N-1)./filter.IMUSampleRate;
subplot(2,1,1)
plot(t,positionErrorTuned,'b');
title("Tuned insfilterMARG" + newline + ...
    "Euclidean Distance Position Error")
xlabel('Time (s)');
ylabel('Position Error (meters)')
subplot(2,1,2)
plot(t, orientationErrorTuned,'b');
title("Orientation Error")
xlabel('Time (s)');
ylabel('Orientation Error (degrees)');
```




## Input Arguments

**`filter` — Filter object**
`infilterMARG` object

Filter object, specified as an `insfilterMARG` object.

**`measureNoise` — Measurement noise**
structure

Measurement noise, specified as a structure. The function uses the measurement noise input as the initial guess for tuning the measurement noise. The structure must contain these fields:

| Field name | Description |
| --- | --- |
| `MagnetometerNoise` | Variance of magnetometer noise, specified as a scalar in $(\mu T)^2$ |
| `GPSPositionNoise` | Variance of GPS position noise, specified as a scalar in $m^2$ |
| `GPSVelocityNoise` | Variance of GPS velocity noise, specified as a scalar in $(m/s)^2$ |

**`sensorData` — Sensor data**
`table`

Sensor data, specified as a `table`. In each row, the sensor data is specified as:

- `Accelerometer` — Accelerometer data, specified as a 1-by-3 vector of scalars in $m^2/s$.
- `Gyroscope` — Gyroscope data, specified as a 1-by-3 vector of scalars in rad/s.
- `Magnetometer` — Magnetometer data, specified as a 1-by-3 vector of scalars in µT.
- `GPSPosition` — GPS position data, specified as a 1-by-3 vector of scalars in [degrees, degrees, meters].
- `GPSVelocity` — GPS velocity data, specified as a 1-by-3 vector of scalars in m/s.

If the GPS sensor does not produce complete measurements, specify the corresponding entry for `GPSPosition` and/or `GPSVelocity` as `NaN`. If you set the `Cost` property of the tuner configuration input, `config`, to `Custom`, then you can use other data types for the `sensorData` input based on your choice.

**`groundTruth` — Ground truth data**
`table`

Ground truth data, specified as a `table`. In each row, the table can optionally contain any of these variables:

- `Orientation` — Orientation from the navigation frame to the body frame, specified as a `quaternion` or a 3-by-3 rotation matrix.
- `Position` — Position in navigation frame, specified as a 1-by-3 vector of scalars in meters.
- `Velocity` — Velocity in navigation frame, specified as a 1-by-3 vector of scalars in m/s.
- `DeltaAngleBias` — Delta angle bias, specified as a 1-by-3 vector of scalars in radians.
- `DeltaVelocityBias` — Delta velocity bias, specified as a 1-by-3 vector of scalars in m/s.
- `GeomagneticFieldVector` — Geomagnetic field vector in navigation frame, specified as a 1-by-3 vector of scalars.
- `MagnetometerBias` — Magnetometer bias in body frame, specified as a 1-by-3 vector of scalars in µT.

The function processes each row of the `sensorData` and `groundTruth` tables sequentially to calculate the state estimate and RMS error from the ground truth. State variables not present in `groundTruth` input are ignored for the comparison. The `sensorData` and the `groundTruth` tables must have the same number of rows.

If you set the `Cost` property of the tuner configuration input, `config`, to `Custom`, then you can use other data types for the `groundTruth` input based on your choice.

**`config` — Tuner configuration**
`tunerconfig` object

Tuner configuration, specified as a `tunerconfig` object.

## Output Arguments

**`tunedMeasureNoise` — Tuned measurement noise**
structure

Tuned measurement noise, returned as a structure. The structure contains these fields.

| Field name | Description |
|---|---|
| MagnetometerNoise | Variance of magnetometer noise, specified as a scalar in $(\mu T)^2$ |
| GPSPositionNoise | Variance of GPS position noise, specified as a scalar in $m^2$ |
| GPSVelocityNoise | Variance of GPS velocity noise, specified as a scalar in $(m/s)^2$ |

# Version History

**Introduced in R2021a**

## References

[1] Abbeel, P., Coates, A., Montemerlo, M., Ng, A.Y. and Thrun, S. Discriminative Training of Kalman Filters. In *Robotics: Science and systems*, Vol. 2, pp. 1, 2005.

## See Also

`tunerconfig` | `tunernoise`

# gnssMeasurementGenerator

**Package:** nav

Simulate GNSS measurements for scenarios

## Description

The gnssMeasurementGenerator System object simulates global navigation satellite system (GNSS) receiver measurements. The object calculates pseudoranges based on the sensor time and data that specifies the satellite orbital parameters on page 2-730. The object uses only the Global Positioning System (GPS) constellations for calculations. To set the starting positions of the satellites, set the InitialTime property.

To simulate GNSS measurements:

1. Create the gnssMeasurementGenerator object and set its properties.
2. Call the object with arguments, as if it were a function.

To learn more about how System objects work, see What Are System Objects?

# Creation

## Syntax

```
GNSS = gnssMeasurementGenerator
GNSS = gnssMeasurementGenerator(Name=Value)
```

### Description

GNSS = gnssMeasurementGenerator returns a gnssMeasurementGenerator System object GNSS that simulates raw global navigation satellite system receiver measurements.

GNSS = gnssMeasurementGenerator(Name=Value) specifies properties using one or more name-value arguments.

## Properties

Unless otherwise indicated, properties are *nontunable*, which means you cannot change their values after calling the object. Objects lock when you call them, and the release function unlocks them.

If a property is *tunable*, you can change its value at any time.

For more information on changing property values, see System Design in MATLAB Using System Objects.

**SampleRate — Sample rate of GNSS receiver**
1 (default) | positive scalar

Sample rate of the GNSS receiver, specified as a positive scalar in Hz.

**`InitialTime` — Initial time of GNSS receiver**
`datetime("now",TimeZone="UTC")` (default) | `datetime` object

Initial time of the GNSS receiver, specified as a `datetime` object. The object accounts for leap seconds in the conversion between the UTC and the GNSS time.

**`ReferenceLocation` — Origin of local navigation reference frame**
`[0 0 0]` (default) | three-element row vector

Origin of the local navigation reference frame, specified as a three-element row vector in geodetic coordinates of the form [*latitude longitude altitude*]. Specify latitude in degrees, longitude in degrees, and altitude in meters. Altitude is the height above the reference ellipsoid model WGS84.

**`MaskAngle` — Elevation mask angle**
`10` (default) | scalar in range [0, 90]

Elevation mask angle, specified as a scalar in the range [0, 90], in degrees. The object does not use satellites that are in view, but below the mask angle, in estimating the position of the receiver.

**Tunable:** Yes

**`RangeAccuracy` — Standard deviation of pseudorange measurement noise**
`1` (default) | nonnegative scalar

Standard deviation of the pseudorange measurement noise, specified as a nonnegative scalar in meters.

**Tunable:** Yes

**`RandomStream` — Random number source**
`"Global stream"` (default) | `"mt19937ar with seed"`

Random number source, specified as one of these options::

- `"Global stream"` –– Generate random numbers using the current global random number stream.
- `"mt19937ar with seed"` –– Generate random numbers using the mt19937ar algorithm with the seed specified by the `Seed` property.

Data Types: `char` | `string`

**`Seed` — Initial seed of mt19937ar random number generator algorithm**
`67` (default) | nonnegative integer

Initial seed of the mt19937ar random number generator algorithm, specified as a nonnegative integer.

**Dependencies**

To enable this property, specify `RandomStream` property as `"mt19937ar with seed"`.

## Usage

## Syntax

`[pseudorangeMeasurements,satellitePositions,status] = GNSS`

### Description

`[pseudorangeMeasurements,satellitePositions,status] = GNSS` computes the GNSS receiver measurements.

### Output Arguments

**`pseudorangeMeasurements` — Pseudorange measurements of the GNSS receiver**
*N*-element vector

Pseudorange measurements of the GNSS receiver, returned as an *N*-element vector, in meters. *N* is the number of satellites in view.

**`satellitePositions` — Satellite positions in Earth-centered Earth-fixed coordinate system**
*N*-by-3 matrix

Satellite positions in Earth-centered Earth-fixed coordinate system, returned as an *N*-by-3 matrix. *N* is the number of satellites in view. Each row is a Cartesian coordinate in meters.

**`status` — Status of satellite measurements**
structure

Status of the satellite measurements, returned as a structure containing the field:

- `LOS` — Line of sight for each satellite, returned as a logical *N*-element vector. *N* is the number of satellites in view. A status of `1` or `true` indicates that there is line of sight from the receiver to the satellite, and a status of `0` or `false` indicates there is no line of sight from the receiver to the satellite.

## Object Functions

To use an object function, specify the System object as the first input argument. For example, to release system resources of a System object named `obj`, use this syntax:

```
release(obj)
```

## Common to All System Objects

| | |
|---|---|
| clone | Create duplicate System object |
| step | Run System object algorithm |
| isLocked | Determine if System object is in use |
| release | Release resources and allow changes to System object property values and input characteristics |
| reset | Reset internal states of System object |

## Examples

### Generate GNSS Measurements in Driving Scenario

Create variables for the sample rate and the geodetic reference location. Set the sample rate to 1 Hz, and set the reference location to Natick, Massachusetts.

```
Fs = 1;
refLocNatick = [42.2825 -71.343 53.0352];
```

Create a driving scenario with the reference location set to Natick, and add a car to the scenario.

```
scene = drivingScenario(GeoReference=refLocNatick);
car = vehicle(scene);
```

Create a GNSS measurement generator System object with the previously specified sample rate and reference location.

```
gnss = gnssMeasurementGenerator(SampleRate=Fs,ReferenceLocation=refLocNatick);
```

Mount the GNSS measurement generator, as a sensor, on the car in the scene.

```
mountingPosition = [0 0 1.5];
addSensors(scene,{gnss},car.ActorID,mountingPosition)
```

Initialize and advance the scenario.

```
advance(scene);
```

Get the raw GNSS measurements.

```
[pr,satPos,status] = gnss()
```

```
pr = 8×1
10^7 ×

    2.3626
    2.4540
    2.1476
    2.0239
    2.1728
    2.3950
    2.1945
    2.0567


satPos = 8×3
10^7 ×

    2.4931   -0.5781    0.7103
   -2.0368   -0.9335    1.4263
    1.3903   -0.6416    2.1701
    0.5968   -1.6666    1.9800
    1.4855   -2.1626    0.4134
    0.6832   -2.4433   -0.7859
   -0.9903   -1.2772    2.1076
   -0.0796   -2.1541    1.5517
```

```
status = struct with fields:
    LOS: [8x1 logical]
```

## Version History

**Introduced in R2023a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Objects

`gpsSensor` | `imuSensor` | `gnssSensor` | `drivingScenario`

### Functions

`skyplot` | `gnssconstellation` | `lookangles` | `pseudoranges` | `receiverposition`

### Topics

"Simulate GNSS Multipath Effects in Urban Canyon Environment"

# gnssSensor

Simulate GNSS to generate position and velocity readings

## Description

The gnssSensor System object simulates a global navigation satellite system (GNSS) to generate position and velocity readings based on local position and velocity data. The object calculates satellite positions and velocities based on the sensor time and data that specifies the satellite orbital parameters on page 2-730. The object uses only the Global Positioning System (GPS) constellations for calculations. To set the starting positions of the satellites, set the InitialTime property.

To generate GNSS position and velocity readings:

1. Create the gnssSensor object and set its properties.
2. Call the object with arguments, as if it were a function.

To learn more about how System objects work, see What Are System Objects?

Calling the object increments the time of the sensor and propagates the satellite position and velocities based on the orbital parameters.

# Creation

## Syntax

```
GNSS = gnssSensor
GNSS = gnssSensor(ReferenceFrame=frame)
GNSS = gnssSensor( ___ ,Name=Value)
```

### Description

GNSS = gnssSensor returns a gnssSensor System object GNSS that computes global navigation satellite system receiver readings based on local position and velocity input.

GNSS = gnssSensor(ReferenceFrame=frame) specifies the reference frame in which the GNSS readings are reported. Specify frame as 'NED' (north-east-down) or 'ENU' (east-north-up). The default value is 'NED'.

GNSS = gnssSensor( ___ ,Name=Value) sets properties using one or more name-value pairs. For example, gnssSensor("SampleRate",2) creates a simulated GNSS with a sample rate of 2 Hz. Enclose each property name in quotes.

## Properties

Unless otherwise indicated, properties are *nontunable*, which means you cannot change their values after calling the object. Objects lock when you call them, and the release function unlocks them.

If a property is *tunable*, you can change its value at any time.

For more information on changing property values, see System Design in MATLAB Using System Objects.

**SampleRate — Sample rate of GNSS receiver (Hz)**
1 (default) | positive scalar

Sample rate of the GNSS receiver, specified as a positive scalar in Hz.

Data Types: single | double

**InitialTime — Initial time of GNSS receiver**
datetime('now',TimeZone="UTC") (default) | datetime object

Initial time of the GNSS receiver, specified as a datetime object. The object accounts for leap seconds in the conversion between the UTC and the GNSS time.

**ReferenceLocation — Origin of local navigation reference frame**
[0 0 0] (default) | three-element row vector

Origin of the local navigation reference frame, specified as a three-element row vector in geodetic coordinates (latitude in degrees, longitude in degrees, and altitude in meters). Altitude is the height above the reference ellipsoid model WGS84.

Data Types: single | double

**MaskAngle — Elevation mask angle (deg)**
10 (default) | scalar in [0, 90]

Elevation mask angle, specified as a scalar in the range [0, 90] in degrees. Satellites in view but below the mask angle are not used in estimating the position of the receiver.

**Tunable:** Yes

Data Types: single | double

**RangeAccuracy — Standard deviation of measurement noise of pseudorange (m)**
1 (default) | nonnegative scalar

Standard deviation of the measurement noise of pseudorange, specified as a nonnegative scalar in meters.

**Tunable:** Yes

Data Types: single | double

**RangeRateAccuracy — Standard deviation of measurement noise of pseudorange rate (m/s)**
0.02 (default) | nonnegative scalar

Standard deviation of the measurement noise of pseudorange rate, specified as a nonnegative scalar in meters per second.

**Tunable:** Yes

Data Types: single | double

**RandomStream — Random number source**
"Global stream" (default) | "mt19937ar with seed"

Random number source, specified as one of these options::

- `"Global stream"` –– Random numbers are generated using the current global random number stream.
- `"mt19937ar with seed"` –– Random numbers are generated using the mt19937ar algorithm with the seed specified by the `Seed` property.

Data Types: `char` | `string`

**Seed — Initial seed of mt19937ar random number generator algorithm**
`67` (default) | nonnegative integer

Initial seed of an mt19937ar random number generator algorithm, specified as a nonnegative integer.

#### Dependencies

To enable this property, set `RandomStream` to `"mt19937ar with seed"`.

Data Types: `integer`

## Usage

## Syntax

`[positionReadings,velocityReadings,status] = GNSS(position,velocity)`

### Description

`[positionReadings,velocityReadings,status] = GNSS(position,velocity)` computes global navigation satellite system receiver readings from the position and velocity inputs.

### Input Arguments

**`position` — Cartesian position of GNSS receiver in local navigation coordinate system**
*N*-by-3 matrix

Cartesian position of the GNSS receiver in the local navigation coordinate system, specified as an *N*-by-3 matrix in meters. *N* is the number of samples.

The default reference frame is NED (north-east-down). For ENU (east-north-up), set the `ReferenceFrame` name-value argument to`"ENU"` on creation.

Data Types: `single` | `double`

**`velocity` — Velocity of GNSS receiver in local navigation coordinate system**
*N*-by-3 matrix

Velocity of the GNSS receiver in the local navigation coordinate system, specified as an *N*-by-3 matrix in meters per second. *N* is the number of samples.

Data Types: `single` | `double`

The default reference frame is NED (north-east-down). For ENU (east-north-up), set the `ReferenceFrame` name-value argument to`"ENU"` on creation.

### Output Arguments

**`positionReadings` — Position readings in LLA coordinate system**
*N*-by-3 matrix

Position readings of the GNSS receiver in the geodetic latitude, longitude, and altitude (LLA) coordinate system, returned as an *N*-by-3 matrix. Altitude is the height above the reference ellipsoid model, WGS84. *N* is the number of samples in the input argument. Latitude and longitude are in degrees. Altitude is in meters.

Data Types: `single` | `double`

**`velocityReadings` — Velocity readings in local navigation coordinate system**
*N*-by-3 matrix

Velocity reading of the GNSS receiver in the local navigation coordinate system in meters per second, returned as an *N*-by-3 matrix. *N* is the number of samples in the input arguments.

Data Types: `single` | `double`

**`status` — Status information of visible satellites**
*N*-element array of structures

Status information of visible satellites, returned as an *N*-element array of structures. *N* is the number of samples in the input arguments. Each structure contains these four fields:

| Field Name | Description |
|---|---|
| `SatelliteAzimuth` | Azimuth angles of visible satellites, returned as an *M*-element vector in degrees. *M* is the number of visible satellites. |
| `SatelliteElevation` | Elevation angles of visible satellites, returned as an *M*-element vector in degrees. *M* is the number of visible satellites. |
| `HDOP` | Horizontal dilution of precision, returned as a scalar. |
| `VDOP` | Vertical dilution of precision, returned as a scalar. |

To plot the satellite positions, see the `skyplot` function.

## Object Functions

To use an object function, specify the System object as the first input argument. For example, to release system resources of a System object named `obj`, use this syntax:

```
release(obj)
```

## Common to All System Objects

| | |
|---|---|
| clone | Create duplicate System object |
| step | Run System object algorithm |
| release | Release resources and allow changes to System object property values and input characteristics |
| reset | Reset internal states of System object |

isDone End-of-data status

## Examples

### Generate GNSS Position and Velocity Readings

Generate target positions and velocities based on a waypoint trajectory.

```
rng(2020) % For repeatable results
fs = 0.1;
tArrival = 50;
tspan = 0:1/fs:tArrival;
% Create a waypoint trajectory.
trajectory = waypointTrajectory([0,0,0;1,1,1]*500,[0,tArrival]);
[positions,~,velocities] = lookupPose(trajectory,tspan)
```

```
positions = 6×3

         0         0         0
  100.0000  100.0000  100.0000
  200.0000  200.0000  200.0000
  300.0000  300.0000  300.0000
  400.0000  400.0000  400.0000
  500.0000  500.0000  500.0000


velocities = 6×3

   10.0000   10.0000   10.0000
   10.0000   10.0000   10.0000
   10.0000   10.0000   10.0000
   10.0000   10.0000   10.0000
   10.0000   10.0000   10.0000
   10.0000   10.0000   10.0000
```

Create a GNSS System object. Use the LLA position for Natick, MA as the local reference frame origin of the trajectory.

```
refLocNatick = [42.2825 -71.343 53.0352];
gnss = gnssSensor('SampleRate',fs, ...
    'ReferenceLocation',refLocNatick);
```

Generate position and velocity readings based on the GNSS object.

```
[llaReadings,velocityReadings,status] = gnss(positions,velocities)
```

```
llaReadings = 6×3

   42.2825  -71.3430   54.1047
   42.2834  -71.3418  -47.3405
   42.2843  -71.3406 -143.5760
   42.2852  -71.3394 -246.7009
   42.2861  -71.3382 -348.6732
   42.2870  -71.3369 -448.2822
```

```
velocityReadings = 6×3

    9.9685    9.9977    9.9860
    9.9987    9.9799   10.0363
    9.9858    9.9958   10.0195
    9.9720    9.9917   10.0058
   10.0099    9.9952    9.9997
   10.0194   10.0044   10.0312
```

```
status=6×1 struct array with fields:
    SatelliteAzimuth
    SatelliteElevation
    HDOP
    VDOP
```

#### View Satellite Positions from GNSS Sensor

Create a GNSS sensor model as a `gnssSensor` System object™.

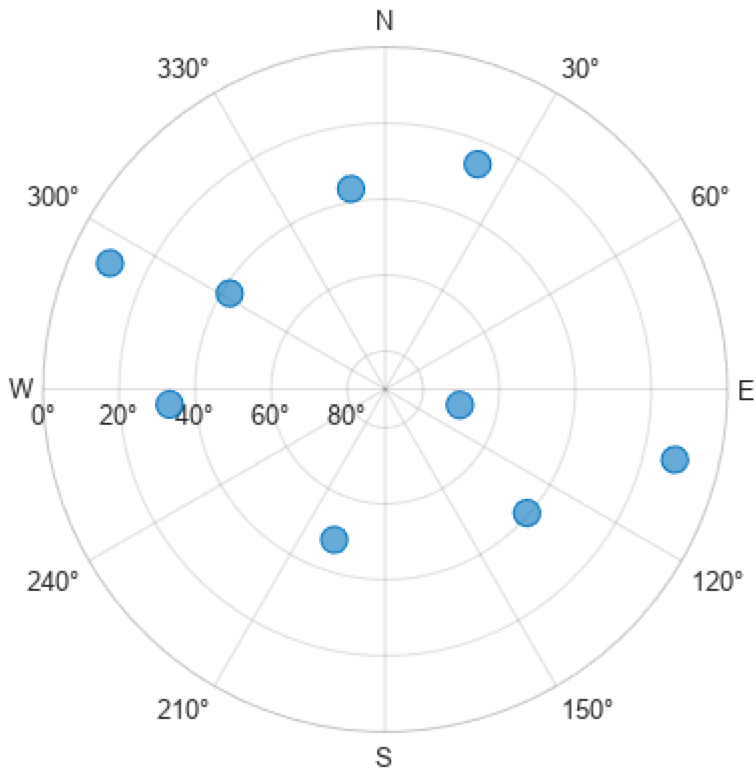
```
gnss = gnssSensor;
```

Specify the position and velocity of the sensor. This example assumes a stationary sensor at the position of `[0 0 0]` in the NED reference frame. Simulate the sensor readings and get the status from visible satellites. Store the azimuth and elevation angles as vectors.

```
pos = [0 0 0];
vel = [0 0 0];
[~,~,status] = gnss(pos,vel);
satAz = status.SatelliteAzimuth;
satEl = status.SatelliteElevation;
```

Plot the satellite positions.

```
skyplot(satAz,satEl)
```




## More About

### Orbital Parameters

The satellite positions and velocities are defined by orbital parameters from IS-GPS-200M Interface Specification, and are given in the Earth-Centered Earth-Fixed (ECEF) coordinates.

Position calculations use equations from Table 30-II in the same IS-GPS-200M Interface Specification.

Velocity calculations use equations 8.21-8.27 in *Principles of GNSS, Inertial, and Multisensor Integrated Navigation Systems* [1].

# Version History

**Introduced in R2020b**

## References

[1] Groves, Paul D. *Principles of GNSS, Inertial, and Multisensor Integrated Navigation Systems*. 2nd ed, Artech House, 2013.

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

Usage notes and limitations:

See "System Objects in MATLAB Code Generation" (MATLAB Coder).

## See Also

### Objects

`gpsSensor` | `imuSensor` | `gnssMeasurementGenerator`

### Functions

`skyplot` | `gnssconstellation` | `lookangles` | `pseudoranges` | `receiverposition`

# mobileRobotPropagator

State propagator for wheeled robotic systems

## Description

The `mobileRobotPropagator` object is a state propagator that propagates and validates the state of a mobile robot based on control commands, durations, and target states. The object supports different kinematic models, integrator types, and control policies.

## Creation

### Syntax

```
mobileProp = mobileRobotPropagator
mobileProp = mobileRobotPropagator(Name,Value)
```

#### Description

`mobileProp = mobileRobotPropagator` creates a mobile robot propagator for a bicycle kinematic model using a linear-pursuit control policy.

`mobileProp = mobileRobotPropagator(Name,Value)` specifies properties using name-value arguments. For example, `mobileRobotPropagator("ControlStepSize"=0.01)` creates a mobile robot propagator with a control step size of 0.01.

### Properties

**`StateSpace` — State space for sampling during planning**
`stateSpaceSE2` object (default) | object of subclass of `nav.StateSpace` object

State space for sampling during planning, specified as an object of a subclass of `nav.StateSpace` object.

The state space is responsible for representing the configuration space of a system. The object should include all state information related to the propagated system. Systems employing multi-layer cascade controllers can append persistent low-level control information directly to the state vector, whereas the state propagator directly manages top-level control commands.

**`Environment` — Environment for validating states**
`[]` (default) | `binaryOccupancyMap` object | `occupancyMap` object | `vehicleCostmap` object

Environment for validating states, specified as a `binaryOccupancyMap`, `occupancyMap`, or `vehicleCostmap` object.

The `mobileRobotPropagator` object validates discrete states along the propagated motion. By default, the environment is empty, so the object only rejects states outside the state space bounds.

This property can only be set during construction.

### `DistanceEstimator` — Distance metric for estimating propagation cost

`'euclidean'` (default) | `'dubins'` | `'reedsshepp'`

Distance metric for estimating propagation cost, specified as one of these options:

- `'euclidean'` — Standard Euclidean distance.
- `'dubins'` — Distance along a Dubins path that connects the two states. For more information, see `dubinsPathSegment`.
- `'reedsshepp'` — Distance along a Reeds Shepp path that connects the two states. For more information, see `reedsSheppPathSegment`.

This property can only be set during construction.

### `GoalDistance` — Threshold of distance for reaching goal states

`1` (default) | positive scalar

Threshold of distance for reaching goal states, specified as a positive scalar. When propagating states, a state is considered equal to the goal state when it is closer than this distance threshold.

This property can only be set during construction.

### `KinematicModel` — Kinematic model for propagating state

`'bicycle'` (default) | `'ackermann'`

Kinematic model for propagating the state, which determines the state variables, size of the control inputs, and other system parameters that you can specify in the `SystemParameters` property.

**Kinematic Model States and Controls**

| Type | State Vector | Control input |
|---|---|---|
| `'bicycle'` | `[x y theta]` | `[v psi]` |
| `'ackermann'` | `[x y theta psi]` | `[v psiDot]` |

This property can only be set during construction and selecting the Ackermann kinematic model requires the Robotics System Toolbox™.

### `Integrator` — Integration method when propagating state

`'rungekutta4'` (default) | `'euler'`

Integration method when propagating state. Integration step size can be updated through the `SystemParameters` property.

`'rungekutta4'` provides a more accurate integration result than `'euler'` at the cost of speed.

This property can only be set during construction.

### `SystemParameters` — Parameters for kinematic model, integrator, and control policy

structure

Parameters for the kinematic model, integrator, and control policy, specified as a structure with these fields:

- `KinematicModel` — Parameters for the kinematic model type specified in the `KinematicModel` property.

    - `WheelBase` — Size of wheel base in meters
    - `SpeedLimit` — Velocity in the forward and backward directions in meters per second.
    - `SteerRatelimit` — Limits on steering rate in radians per second
- `Integrator` — Parameters for the integrator type specified in the `Integrator` property.
- `ControlPolicy` — Parameters for the control policy specified in the `ControlPolicy` property.

#### Control Parameters

**`ControlPolicy` — Control command generation policy**
`'linearpursuit'` (default) | `'arcpursuit'` | `'randomsamples'`

Control command generation policy, specified as one of these options:

- `'linearpursuit'` — Samples a random velocity and calculates a lookahead point along the vector that connects the initial state to the target state.
- `'arcpursuit'` — Samples a random velocity and calculates a lookahead point along an arc that is tangential to the target state and intersects the initial *xy*-position.
- `'randomsamples'` — Draws a finite set of random control samples from the control space and propagates to each. The propagator selects the sample that gets the closest to the goal and then performs a validation.

**`ControlLimits` — Limits on control commands for each state**
`[-1 1; -pi/4 pi/4]` (default) | *n*-by-2 matrix

Limits on control commands for each state, specified as an *n*-by-2 matrix. *n* is the number of control inputs for your system model.

**`NumControlOutput` — Number of control outputs**
2 (default) | positive scalar

This property is read-only.

Number of control outputs, specified as a nonnegative scalar.

**`ControlStepSize` — Duration of each control command**
`0.1` (default) | positive scalar

Duration of each control command, specified as a positive scalar.

**`MaxControlSteps` — Maximum number of control steps**
`10` (default) | positive integer

Maximum number of times to propagate the system specified as positive integer.

## Object Functions

| | |
|---|---|
| distance | Estimate cost of propagating to target state |
| propagate | Propagate system without validation |
| propagateWhileValid | Propagate system and return valid motion |
| sampleControl | Generate control command and duration |
| setup | Set up the mobile robot state propagator |

## Examples

### Plan Kinodynamic Path with Controls for Mobile Robot

Plan control paths for a bicycle kinematic model with the `mobileRobotPropagator` object. Specify a map for the environment, set state bounds, and define a start and goal location. Plan a path using the control-based RRT algorithm, which uses a state propagator for planning motion and the required control commands.

#### Set State and State Propagator Parameters

Load a ternary map matrix and create an `occupancyMap` object. Create the state propagator using the map. By default, the state propagator uses a bicycle kinematic model.

```
load('exampleMaps','ternaryMap')
map = occupancyMap(ternaryMap,10);

propagator = mobileRobotPropagator(Environment=map); % Bicycle model
```

Set the state bounds on the state space based on the map world limits.

```
propagator.StateSpace.StateBounds(1:2,:) = ...
                    [map.XWorldLimits; map.YWorldLimits];
```

#### Plan Path

Create the path planner from the state propagator.

```
planner = plannerControlRRT(propagator);
```

Specify the start and goal states.

```
start = [10 15 0];
goal  = [40 30 0];
```

Plan a path between the states. For repeatable results, reset the random number generator before planning. The `plan` function outputs a `navPathControl` object, which contains the states, control commands, and durations.

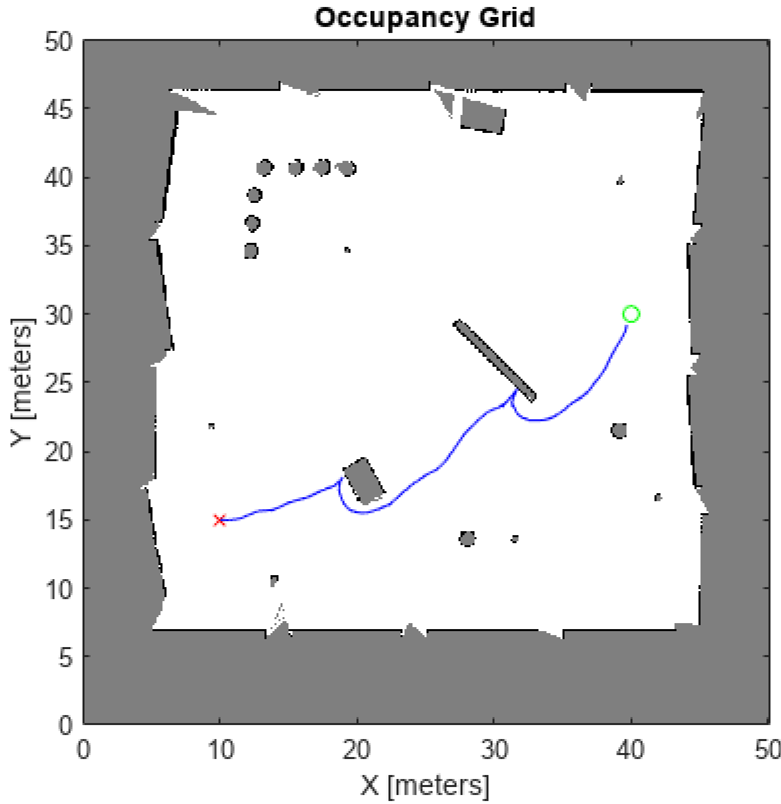
```
rng("default")
path = plan(planner,start,goal)
```

```
path = 
  navPathControl with properties:

    StatePropagator: [1x1 mobileRobotPropagator]
             States: [192x3 double]
           Controls: [191x2 double]
          Durations: [191x1 double]
       TargetStates: [191x3 double]
          NumStates: 192
        NumSegments: 191
```

#### Visualize Results

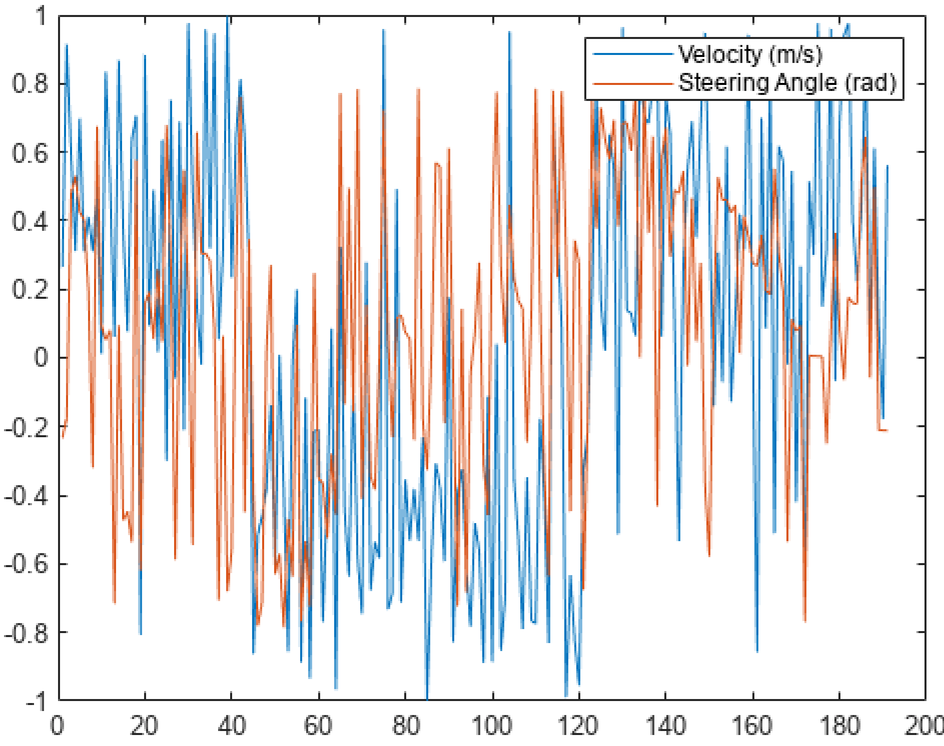
Visualize the map and plot the path states.

```
show(map)
hold on
plot(start(1),start(2),"rx")
plot(goal(1),goal(2),"go")
plot(path.States(:,1),path.States(:,2),"b")
hold off
```




Display the `[v psi]` control inputs of forward velocity and steering angle.

```
plot(path.Controls)
ylim([-1 1])
legend(["Velocity (m/s)","Steering Angle (rad)"])
```




## Limitations

- Deployment using MATLAB Compiler™ is not supported when `KinematicModel` is set to `'ackermann'`.

# Version History

**Introduced in R2021b**

## See Also

**Classes**
`nav.StateSpace`

**Objects**
`stateSpaceSE2` | `stateSpaceDubins` | `stateSpaceReedsShepp`

**Functions**
`distance` | `propagate` | `propagateWhileValid` | `sampleControl` | `setup`

# distance

Estimate cost of propagating to target state

## Syntax

```
h = distance(mobileProp,q1,q2)
```

## Description

`h = distance(mobileProp,q1,q2)` estimates the cost of propagating from one state to another. The `DistanceEstimator` property of the state propagator defines the distance metric for approximating cost.

## Input Arguments

**`mobileProp` — Mobile robot state propagator**
`mobileRobotPropagator` object

Mobile robot state propagator, specified as a `mobileRobotPropagator` object.

**q1 — Initial states**
*n*-by-*s* matrix

Initial states, specified as an *n*-by-*s* matrix. *n* is the number of states and *s* is the size of the state vector.

**q2 — Final states**
*n*-by-*s* matrix

Final states, specified as an *n*-by-*s* matrix. *n* is the number of states and *s* is the size of the state vector.

## Output Arguments

**h — Cost values**
*n*-element vector

Cost values, returned as an *n*-element vector. *n* is the number of `q1` and `q2` pairs.

You can use the cost values returned by this function to find the nearest neighbor for sampled target states when planning a path.

# Version History

**Introduced in R2021b**

## See Also

**Objects**
`mobileRobotPropagator`

**Functions**
`propagate` | `propagateWhileValid` | `sampleControl` | `setup`

# propagate

Propagate system without validation

## Syntax

```
[q,u,steps] = propagate(mobileProp,q0,u0,qTgt,maxSteps)
```

## Description

`[q,u,steps] = propagate(mobileProp,q0,u0,qTgt,maxSteps)` iteratively propagates the system from the current state `q0` towards a target state `qTgt` with an initial control input `u0` for a maximum number of steps `maxSteps`.

At the end of each propagation step `i`, the system returns these values:

- `q(i,:)` — Current state of the system
- `u(i,:)` — Control input for step `i + 1`
- `steps(i)` — Number of steps between `i - 1` and `i`

## Input Arguments

**`mobileProp` — Mobile robot state propagator**
`mobileRobotPropagator` object

Mobile robot state propagator, specified as a `mobileRobotPropagator` object.

**`q0` — Initial state**
*s*-element vector

Initial state of the system, specified as an *s*-element vector. *s* is the number of state variables in the state space.

**`u0` — Initial control on initial state**
*c*-element vector

Initial control on the initial state, specified as an *c*-element vector. *c* is the number of control inputs.

**`qTgt` — Target state**
*s*-element vector

Target state of the system, specified as an *s*-element vector. *s* is the number of state variables in the state space.

**`maxSteps` — Maximum number of steps**
positive scalar

Maximum number of steps, specified as a positive scalar.

## Output Arguments

**q — Propagated states**
*n*-by-*s* matrix

Propagated states of the system, returned as an *s*-element vector. *s* is the number of state variables in the state space.

**u — Control inputs for propagating states**
*n*-by-*c* matrix

Control inputs for propagating states, returned as an *n*-by-*c* matrix. *c* is the number of control inputs

**`steps` — Number of steps between each state and control input to next**
*n*-element vector of positive integers

Number of steps from each state and control input to next, returned as an *n*-element vector of positive integers.

# Version History
**Introduced in R2021b**

## See Also

**Objects**
`mobileRobotPropagator`

**Functions**
`distance` | `propagateWhileValid` | `sampleControl` | `setup`

# propagateWhileValid

Propagate system and return valid motion

## Syntax

```
[q,u,steps] = propagateWhileValid(mobileProp,q0,u0,qTgt,maxSteps)
```

## Description

`[q,u,steps] = propagateWhileValid(mobileProp,q0,u0,qTgt,maxSteps)` iteratively propagates the system from the current state `q0` towards a target state `qTgt` with an initial control input `u0` for a maximum number of steps `maxSteps`.

At the end of each propagation step `i`, the system returns these values:

- `q(i,:)` — Current state of the system
- `u(i,:)` — Control input for step `i + 1`
- `steps(i)` — Number of steps between `i - 1` and `i`

The function validates all propagations and returns system information between `q0` and the last valid state.

## Input Arguments

**`mobileProp` — Mobile robot state propagator**
`mobileRobotPropagator` object

Mobile robot state propagator, specified as a `mobileRobotPropagator` object.

**`q0` — Initial state**
*s*-element vector

Initial state of the system, specified as an *s*-element vector. *s* is the number of state variables in the state space.

**`u0` — Initial control on initial state**
*c*-element vector

Initial control on the initial state, specified as an *c*-element vector. *c* is the number of control inputs.

**`qTgt` — Target state**
*s*-element vector

Target state of the system, specified as an *s*-element vector. *s* is the number of state variables in the state space.

**`maxSteps` — Maximum number of steps**
positive scalar

Maximum number of steps, specified as a positive scalar.

## Output Arguments

**q — Propagated states**
*n*-by-*s* matrix

Propagated states of the system, returned as an *s*-element vector. *s* is the number of state variables in the state space.

**u — Control inputs for propagating states**
*n*-by-*c* matrix

Control inputs for propagating states, returned as an *n*-by-*c* matrix. *c* is the number of control inputs

**`steps` — Number of steps from each state and control input to next**
*n*-element vector of positive integers

Number of steps from each state and control input to next, returned as an *n*-element vector of positive integers.

# Version History

**Introduced in R2021b**

## See Also

**Objects**
`mobileRobotPropagator`

**Functions**
`distance` | `propagate` | `sampleControl` | `setup`

# sampleControl

Generate control command and duration

## Syntax

```
[u,steps] = sampleControl(mobileProp,q0,u0,qTgt)
```

## Description

`[u,steps] = sampleControl(mobileProp,q0,u0,qTgt)` generates a series of control commands and number of steps to move from the current state `q0` with control command `u0` toward the target state `qTgt`.

## Input Arguments

**`mobileProp` — Mobile robot state propagator**
`mobileRobotPropagator` object

Mobile robot state propagator, specified as a `mobileRobotPropagator` object.

**`q0` — Initial state**
*s*-element vector

Initial state of the system, specified as an *s*-element vector. *s* is the number of state variables in the state space.

**`u0` — Initial control on the initial state**
*c*-element vector

Initial control input, specified as an *c*-element vector. *c* is the number of control inputs.

**`qTgt` — Target state**
*s*-element vector

Target state of the system, specified as an *s*-element vector. *s* is the number of state variables in the state space.

## Output Arguments

**`u` — Control inputs for propagating states**
*n*-by-*c* matrix

Control inputs for propagating states, returned as an *c*-element vector. *c* is the number of control inputs.

**`steps` — Number of steps from each state and control input to next**
*n*-element vector of positive integers

Number of steps from each state and control input to next, returned as an *n*-element vector of positive integers.

## Version History

**Introduced in R2021b**

## See Also

**Objects**
`mobileRobotPropagator`

**Functions**
`distance` | `propagate` | `propagateWhileValid` | `setup`

# setup

Set up the mobile robot state propagator

## Syntax

```
setup(mobileProp)
```

## Description

`setup(mobileProp)` sets up the `mobileRobotPropagator` object based on the properties of the object. If you change the properties of the object, use this object function before you use the object to sample controls, propagate the system, or calculate distances.

---

**Note** Override this function to implement custom functionality to run in the setup.

---

## Input Arguments

**`mobileProp` — Mobile robot state propagator**
`mobileRobotPropagator` object

Mobile robot state propagator, specified as a `mobileRobotPropagator` object.

# Version History

**Introduced in R2021b**

## See Also

**Objects**
`mobileRobotPropagator`

**Functions**
`distance` | `propagate` | `propagateWhileValid` | `sampleControl`

# monteCarloLocalization

Localize robot using range sensor data and map

## Description

The `monteCarloLocalization` System object creates a Monte Carlo localization (MCL) object. The MCL algorithm is used to estimate the position and orientation of a vehicle in its environment using a known map of the environment, lidar scan data, and odometry sensor data.

To localize the vehicle, the MCL algorithm uses a particle filter to estimate the vehicle's position. The particles represent the distribution of likely states for the vehicle, where each particle represents a possible vehicle state. The particles converge around a single location as the vehicle moves in the environment and senses different parts of the environment using a range sensor. An odometry sensor measures the vehicle's motion.

A `monteCarloLocalization` object takes the pose and lidar scan data as inputs. The input lidar scan sensor data is given in its own coordinate frame, and the algorithm transforms the data according to the `SensorModel.SensorPose` property that you must specify. The input pose is computed by integrating the odometry sensor data over time. If the change in pose is greater than any of the specified update thresholds, `UpdateThresholds`, then the particles are updated and the algorithm computes a new state estimate from the particle filter. The particles are updated using this process:

1. The particles are propagated based on the change in the pose and the specified motion model, `MotionModel`.
2. The particles are assigned weights based on the likelihood of receiving the range sensor reading for each particle. These likelihood weights are based on the sensor model you specify in `SensorModel`.
3. Based on the `ResamplingInterval` property, the particles are resampled from the posterior distribution, and the particles of low weight are eliminated. For example, a resampling interval of 2 means that the particles are resampled after every other update.

The outputs of the object are the estimated pose and covariance, and the value of `isUpdated`. This estimated state is the mean and covariance of the highest weighted cluster of particles. The output pose is given in the map's coordinate frame that is specified in the `SensorModel.Map` property. If the change in pose is greater than any of the update thresholds, then the state estimate has been updated and `isUpdated` is `true`. Otherwise, `isUpdated` is `false` and the estimate remains the same. For continuous tracking the best estimate of a robot's state, repeat this process of propagating particles, evaluating their likelihood, and resampling.

To estimate robot pose and covariance using lidar scan data:

1. Create the `monteCarloLocalization` object and set its properties.
2. Call the object with arguments, as if it were a function.

To learn more about how System objects work, see What Are System Objects?

# Creation

## Syntax

```
mcl = monteCarloLocalization
mcl = monteCarloLocalization(Name,Value)
```

### Description

`mcl = monteCarloLocalization` returns an MCL object that estimates the pose of a vehicle using a map, a range sensor, and odometry data. By default, an empty map is assigned, so a valid map assignment is required before using the object.

`mcl = monteCarloLocalization(Name,Value)` creates an MCL object with additional options specified by one or more `Name,Value` pair arguments.

`Name` is a property name and `Value` is the corresponding value. `Name` must appear inside single quotes (`''`). You can specify several name-value pair arguments in any order as `Name1,Value1,...,NameN,ValueN`.

## Properties

**`InitialPose` — Initial pose of vehicle**
`[0 0 0]` (default) | three-element vector

Initial pose of the vehicle used to start localization, specified as a three-element vector, `[x y theta]`, that indicates the position and heading of the vehicle. Initializing the MCL object with an initial pose estimate enables you to use a smaller value for the maximum number of particles and still converge on a location.

**`InitialCovariance` — Covariance of initial pose**
`diag([1 1 1])` (default) | diagonal matrix | three-element vector | scalar

Covariance of the Gaussian distribution for the initial pose, specified as a diagonal matrix. Three-element vector and scalar inputs are converted to a diagonal matrix. This matrix gives an estimate of the uncertainty of the `InitialPose`.

**`GlobalLocalization` — Flag to start global localization**
`false` (default) | `true`

Flag indicating whether to perform global localization, specified as `false` or `true`. The default value, `false`, initializes particles using the `InitialPose` and `InitialCovariance` properties. A `true` value initializes uniformly distributed particles in the entire map and ignores the `InitialPose` and `InitialCovariance` properties. Global localization requires a large number of particles to cover the entire workspace. Use global localization only when the initial estimate of vehicle location and orientation is not available.

**`ParticleLimits` — Minimum and maximum number of particles**
`[500 5000]` (default) | two-element vector

Minimum and maximum number of particles, specified as a two-element vector, `[min max]`.

**SensorModel — Likelihood field sensor model**
likelihoodFieldSensor object

Likelihood field sensor model, specified as a likelihoodFieldSensor object. The default value uses the default likelihoodFieldSensorModel object. After using the object to get output, call release on the object to make changes to SensorModel. For example:

```
mcl = monteCarloLocalization;
sm = likelihoodFieldSensorModel;
sm.Map = binaryOccupancyMap(10,10,20);
mcl.SensorModel = sm;
[isUpdated,pose,covariance] = mcl([0 0 0],ones(1,10),linspace(-pi/2,pi/2,10));
% Release object before changing motion model
release(mcl);
mcl.SensorModel.NumBeams = 120;
mcl.MotionModel.Noise = [0.25 0.25 0.4 0.4];
```

**MotionModel — Odometry motion model for differential drive**
odometryMotionModel object

Odometry motion model for differential drive, specified as an odometryMotionModel object. The default value uses the default odometryMotionModel object. After using the object to get output, call release on the object to make changes to MotionModel. For example:

```
mcl = monteCarloLocalization;
sm = likelihoodFieldSensorModel;
sm.Map = binaryOccupancyMap(10,10,20);
mcl.SensorModel = sm;
[isUpdated,pose,covariance] = mcl([0 0 0],ones(1,10),linspace(-pi/2,pi/2,10));
% Release object before changing motion model
release(mcl);
mcl.SensorModel.NumBeams = 120;
mcl.MotionModel.Noise = [0.25 0.25 0.4 0.4];
```

**UpdateThresholds — Minimum change in states required to trigger update**
[0.2 0.2 0.2] (default) | three-element vector

Minimum change in states required to trigger update, specified as a three-element vector. The localization updates the particles if the minimum change in any of the [x y theta] states is met. The pose estimate updates only if the particle filter is updated.

**ResamplingInterval — Number of filter updates between resampling of particles**
1 (default) | positive integer

Number of filter updates between resampling of particles, specified as a positive integer.

**UseLidarScan — Use lidarScan object as scan input**
false (default) | true

Use a lidarScan object as scan input, specified as either false or true.

# Usage

## Syntax

`[isUpdated,pose,covariance] = mcl(odomPose,scan)`

`[isUpdated,pose,covariance] = mcl(odomPose,ranges,angles)`

### Description

`[isUpdated,pose,covariance] = mcl(odomPose,scan)` estimates the pose and covariance of a vehicle using the MCL algorithm. The estimates are based on the pose calculated from the specified vehicle odometry, `odomPose`, and the specified lidar scan sensor data, `scan`. `mcl` is the `monteCarloLocalization` object. `isUpdated` indicates whether the estimate is updated based on the `UpdateThreshold` property.

To enable this syntax, you must set the `UseLidarScan` property to `true`. For example:

```
mcl = monteCarloLocalization('UseLidarScan',true);
...
[isUpdated,pose,covariance] = mcl(odomPose,scan);
```

`[isUpdated,pose,covariance] = mcl(odomPose,ranges,angles)` specifies the lidar scan data as `ranges` and `angles`.

### Input Arguments

**`odomPose` — Pose based on odometry**
three-element vector

Pose based on odometry, specified as a three-element vector, `[x y theta]`. This pose is calculated by integrating the odometry over time.

**`scan` — Lidar scan readings**
`lidarScan` object

Lidar scan readings, specified as a `lidarScan` object.

**Dependencies**

To use this argument, you must set the `UseLidarScan` property to `true`.

```
mcl.UseLidarScan = true;
```

**`ranges` — Range values from scan data**
vector

Range values from scan data, specified as a vector with elements measured in meters. These range values are distances from a laser scan sensor at the specified `angles`. The `ranges` vector must have the same number of elements as the corresponding `angles` vector.

**`angles` — Angle values from scan data**
vector

Angle values from scan data, specified as a vector with elements measured in radians. These angle values are the angles at which the specified `ranges` were measured. The `angles` vector must be the same length as the corresponding `ranges` vector.

### Output Arguments

#### `isUpdated` — Flag for pose update
logical

Flag for pose update, returned as a logical. If the change in pose is more than any of the update thresholds, then the output is `true`. Otherwise, it is `false`. A `true` output means that updated pose and covariance are returned. A `false` output means that pose and covariance are not updated and are the same as at the last update.

#### `pose` — Current pose estimate
three-element vector

Current pose estimate, returned as a three-element vector, `[x y theta]`. The pose is computed as the mean of the highest-weighted cluster of particles.

#### `covariance` — Covariance estimate for current pose
matrix

Covariance estimate for current pose, returned as a matrix. This matrix gives an estimate of the uncertainty of the current pose. The covariance is computed as the covariance of the highest-weighted cluster of particles.

## Object Functions

To use an object function, specify the System object as the first input argument. For example, to release system resources of a System object named `obj`, use this syntax:

```
release(obj)
```

## Specific to monteCarloLocalization

| | |
|---|---|
| getParticles | Get particles from localization algorithm |

## Common to All System Objects

| | |
|---|---|
| step | Run System object algorithm |
| release | Release resources and allow changes to System object property values and input characteristics |
| reset | Reset internal states of System object |

## Examples

### Estimate Vehicle Pose from Range Sensor Data

Create a `monteCarloLocalization` object, assign a sensor model, and calculate a pose estimate.

Create a `monteCarloLocalization` object. Set the `UseLidarScan` property to `true`.

```
mcl = monteCarloLocalization;
mcl.UseLidarScan = true;
```

Assign a sensor model with an occupancy grid map to the object.

```
sm = likelihoodFieldSensorModel;
p = zeros(200,200);
sm.Map = occupancyMap(p,20);
mcl.SensorModel = sm;
```

Create sample laser scan data input.

```
ranges = 10*ones(1,300);
ranges(1,130:170) = 1.0;
angles = linspace(-pi/2,pi/2,300);
odometryPose = [0 0 0];
```

Create a `lidarScan` object by specifying the ranges and angles.

```
scan = lidarScan(ranges,angles);
```

Estimate vehicle pose and covariance.

```
[isUpdated,estimatedPose,covariance] = mcl(odometryPose,scan)
```

```
isUpdated = logical
   1

estimatedPose = 1×3

   -0.0034   -0.0423   -0.0275

covariance = 3×3

    0.9379   -0.0365         0
   -0.0365    0.9656         0
         0         0    0.9870
```

# Version History

**Introduced in R2019b**

## References

[1] Thrun, Sebatian, Wolfram Burgard, and Dieter Fox. *Probabilistic Robotics*. MIT Press, 2005.

[2] Dellaert, F., D. Fox, W. Burgard, and S. Thrun. "Monte Carlo Localization for Mobile Robots." *Proceedings 1999 IEEE International Conference on Robotics and Automation.*

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`lidarScan` | `likelihoodFieldSensorModel` | `odometryMotionModel`

**Topics**

“Localize TurtleBot Using Monte Carlo Localization Algorithm”
“Monte Carlo Localization Algorithm”
Class Attributes
Property Attributes

# getParticles

Get particles from localization algorithm

## Syntax

```
[particles,weights] = getParticles(mcl)
```

## Description

`[particles,weights] = getParticles(mcl)` returns the current particles used by the `monteCarloLocalization` object. `particles` is an *n*-by-3 matrix that contains the location and orientation of each particle. Each row has a corresponding weight value specified in `weights`. The number of rows can change with each iteration of the MCL algorithm. Use this method to extract the particles and analyze them separately from the algorithm.

## Examples

### Get Particles from Monte Carlo Localization Algorithm

Get particles from the particle filter used in the Monte Carlo Localization object.

Create a map and a Monte Carlo localization object.

```
map = binaryOccupancyMap(10,10,20);
mcl = monteCarloLocalization(map);
```

Create robot data for the range sensor and pose.

```
ranges = 10*ones(1,300);
ranges(1,130:170) = 1.0;
angles = linspace(-pi/2,pi/2,300);
odometryPose = [0 0 0];
```

Initialize particles using `step`.

```
[isUpdated,estimatedPose,covariance] = step(mcl,odometryPose,ranges,angles);
```

Get particles from the updated object.

```
[particles,weights] = getParticles(mcl);
```

## Input Arguments

**`mcl` — `monteCarloLocalization` object**
handle

`monteCarloLocalization` object, specified as an object handle.

### Output Arguments

**`particles` — Estimation particles**
*n*-by-3 vector

Estimation particles, returned as an *n*-by-3 vector, `[x y theta]`. Each row corresponds to the position and orientation of a single particle. The length can change with each iteration of the algorithm.

**`weights` — Weights of particles**
*n*-by-1 vector

Weights of particles, returned as a *n*-by-1 vector. Each row corresponds to the weight of the particle in the matching row of `particles`. These weights are used in the final estimate of the pose of the vehicle. The length can change with each iteration of the algorithm.

## Version History

**Introduced in R2019b**

### Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

### See Also

`monteCarloLocalization`

**Topics**
"Monte Carlo Localization Algorithm"

# multiLayerMap

Manage multiple map layers

## Description

The `multiLayerMap` object groups and stores multiple map layers as `mapLayer`, `occupancyMap`, or `binaryOccupancyMap` objects.

Once added to this object, map layers can be modified by either using the `multiLayerMap` object functions or by performing actions on individual map layers using their object functions or the layer name as input. Any modification to common properties on the `multiLayerMap` object are reflected across all associated layers.

## Creation

### Syntax

```
map = multiLayerMap
map = multiLayerMap(maps)
map = multiLayerMap(names,mapData)
map = multiLayerMap(names,width,height)
map = multiLayerMap(names,width,height,cellDims)
map = multiLayerMap(names,rows,cols,'grid')
map = multiLayerMap(names,rows,cols,cellDims,'grid')
map = multiLayerMap(sourceMap)
map = multiLayerMap( ___ ,Name,Value)
```

#### Description

`map = multiLayerMap` creates an empty map object occupying 10-by-10 meters of space with a resolution of 1 cell per meter.

`map = multiLayerMap(maps)` creates a multilayer map from a cell array of `mapLayer`, `occupancyMap`, or `binaryOccupancyMap` objects. Objects combined into a multilayer map must be defined with the same resolution and cover the same region in space, but can represent different categories of information over the shared region.

`map = multiLayerMap(names,mapData)` creates a multilayer map from the cell array of layer names and associated cell array of map matrices. Matrices must have the same first two dimensions to cover the same shared region. Default resolution is 1 cell per meter.

`map = multiLayerMap(names,width,height)` creates a multilayer map with the cell array of layer names covering the specified width and height as scalars in meters.

`map = multiLayerMap(names,width,height,cellDims)` creates a multilayer map where the size of the data stored in each cell of the map is defined by the array of integers, `cellDims`. For multiple layers, `cellDims` is a cell array of integer arrays.

`map = multiLayerMap(names,rows,cols,'grid')` specifies the map width and height as a grid size specified in the `rows` and `cols` inputs.

`map = multiLayerMap(names,rows,cols,cellDims,'grid')` creates a map with a specified grid size and the size of the data stored in each cell is defined by the array of integers or cell array of integer arrays `cellDims`.

`map = multiLayerMap(sourceMap)` creates a new object using the layers copied from another `multiLayerMap` object.

`map = multiLayerMap( ___ ,Name,Value)` specifies property values using name-value pairs.

For example, `multiLayerMap(__,'LocalOriginInWorld',[15 20])` sets the local origin to a specific world location.

## Properties

**`DataSize` — Size of the data in each map layer data array**
cell array of integer vectors

Size of the data in each map layer data array, specified as a cell array of integer vectors. In each vector, the first two dimensions define the footprint of the map layer, and all subsequent dimensions dictate the size and layout of the data stored in each cell.

If the map stores an *n*-element vector of values in each cell, this property would be `[width height n]`.

If the map stores a 10-by-10 grid with each cell containing a 3-by-3-by-3 matrix array, the data size would be `[10 10 3 3 3]`.

After you create the object, this property is read-only.

Data Types: `cell` | `double`

**`DataType` — Data type of the values stored**
cell array of string scalars

Data type of the values stored in each layer, specified as a cell array of character vectors.

When you create this object, the specified map layers determine each data type. After you create the object, this property is read-only.

Data Types: `cell` | `char`

**`DefaultValue` — Default value for unspecified map locations**
`{0}` (default) | cell array of numeric scalars

Default value for unspecified map locations for each layer, specified as a cell array of numeric scalars. This default value is returned for areas outside the map as well.

Data Types: `cell` | `double`

**`GridLocationInWorld` — Location of the grid in local coordinates**
`[0 0]` (default) | two-element vector | `[xWorld yWorld]`

Location of the bottom-left corner of the grid in world coordinates, specified as a two-element vector, `[xWorld yWorld]`.

You can set this property when you create the object.

Data Types: `double`

**`GridOriginInLocal` — Location of the grid in local coordinates**
`[0 0]` (default) | two-element vector | `[xLocal yLocal]`

Location of the bottom-left corner of the grid in local coordinates, specified as a two-element vector, `[xLocal yLocal]`.

You can set this property when you create the object.

Data Types: `double`

**`GridSize` — Number of rows and columns in grid**
two-element integer-valued vector

This property is read-only.

Number of rows and columns in grid, stored as a 1-by-2 real-valued vector representing the number of rows and columns, in that order.

Data Types: `double`

**`LayerNames` — Name of each layer**
cell array of string scalars

Name of each layer, specified as a cell array of string scalars. The order of these names are associated with the order of other properties that are cell arrays.

You can set this property when you create the object. After you create the object, this property is read-only.

Data Types: `cell` | `string`

**`LocalOriginInWorld` — Location of the local frame in world coordinates**
`[0 0]` (default) | two-element vector | `[xWorld yWorld]`

Location of the origin of the local frame in world coordinates, specified as a two-element vector, `[xLocal yLocal]`. Use the `move` function to shift the local frame as your vehicle moves.

You can set this property when you create the object.

Data Types: `double`

**`NumLayers` — Number of map layers**
`1` (default) | positive integer

This property is read-only.

Number of map layers, stored as a positive integer.

Data Types: `double`

**`Resolution` — Grid resolution**
`1` (default) | scalar

This property is read-only.

Grid resolution, stored as a scalar in cells per meter representing the number and size of grid locations.

You can set this property when you create the object. After you create the object, this property is read-only.

Data Types: `double`

**`XLocalLimits` — Minimum and maximum values of *x*-coordinates in local frame**
two-element vector

This property is read-only.

Minimum and maximum values of *x*-coordinates in local frame, stored as a two-element horizontal vector of the form `[min max]`. Local frame is defined by `LocalOriginInWorld` property.

Data Types: `double`

**`YLocalLimits` — Minimum and maximum values of *y*-coordinates in local frame**
two-element vector

This property is read-only.

Minimum and maximum values of *y*-coordinates in local frame, stored as a two-element horizontal vector of the form `[min max]`. Local frame is defined by `LocalOriginInWorld` property.

Data Types: `double`

**`XWorldLimits` — Minimum and maximum world range values of *x*-coordinates**
two-element vector

This property is read-only.

Minimum and maximum world range values of *x*-coordinates, stored as a 1-by-2 vector representing the minimum and maximum values, in that order.

Data Types: `double`

**`YWorldLimits` — Minimum and maximum world range values of *y*-coordinates**
two-element vector

This property is read-only.

Minimum and maximum world range values of *y*-coordinates, stored as a 1-by-2 vector representing the minimum and maximum values, in that order.

Data Types: `double`

## Object Functions

| | |
|---|---|
| getLayer | Return individual layers from multilayer map |
| getMapData | Retrieve data from map layers |
| grid2local | Convert grid indices to local coordinates |
| grid2world | Convert grid indices to world coordinates |
| local2grid | Convert local coordinates to grid indices |

| | |
|---|---|
| local2world | Convert local coordinates to world coordinates |
| move | Move map in world frame |
| setMapData | Assign data to map layers |
| syncWith | Sync map with overlapping map |
| world2grid | Convert world coordinates to grid indices |
| world2local | Convert world coordinates to local coordinates |

## Examples

### Create Listeners Using Dependent Map Layers

The `multiLayerMap` object enables you to group multiple map layers and define behavior for those layers when setting and getting data. Using separate map layers, you can store various map data and specify different behaviors for each. You can also define the `SetTransformFcn` and `GetTransformFcn` function handles for a map layer so that dependencies are created between layers. This example shows how to store data in a map layer and implement event listeners which update other maps. These maps store how many times the data is updated or accessed.

#### Dependent Layers

Create two independent map layers.

```
mapAccessed = mapLayer(zeros(10,10),"LayerName","GetListener");
mapModified = mapLayer(zeros(10,10),"LayerName","SetListener");
```

Specify function handles for the get and set transform functions used in the main map layer. These functions increment the value of a grid location when you get or set map data in the input map `mainMap`. See Listener Function Handles on page 2-762 for the function implementation.

```
getHookFcn = @(mainMap,values,varargin)exampleHelperGetHookFcn(mapAccessed,mainMap,values,vararg
setHookFcn = @(mainMap,values,varargin)exampleHelperSetHookFcn(mapModified,mainMap,values,vararg
```

Create the main map layer with default values of 0.5. Specify the function handles to create the layer depencies.

```
map = mapLayer(repmat(0.5,10,10), ...
                'GetTransformFcn',getHookFcn, ...
                'SetTransformFcn',setHookFcn);
```

Add all maps to the same `multiLayerMap` object.

```
multiMapLayers = multiLayerMap({map,mapAccessed,mapModified})
```

```
multiMapLayers = 
  multiLayerMap with properties:

   Map Properties
              NumLayers: 3
               GridSize: [10 10]
             Resolution: 1
    GridLocationInWorld: [0 0]
      GridOriginInLocal: [0 0]
     LocalOriginInWorld: [0 0]
           XLocalLimits: [0 10]
           YLocalLimits: [0 10]
```

```
         XWorldLimits: [0 10]
         YWorldLimits: [0 10]

   Layer Properties
           LayerNames: {'mapLayer'  'GetListener'  'SetListener'}
             DataSize: {[10 10]  [10 10]  [10 10]}
             DataType: ["double"    "double"    "double"]
         DefaultValue: {[0]  [0]  [0]}
```

Set the (0,0) map location with a value of zero using the `setMapData` object function of `multiLayerMap` object.

```
setMapData(multiMapLayers,"mapLayer",[0 0],0)
```

Check that `SetListener` map layer incremented their value.

```
getMapData(multiMapLayers,"SetListener",[0 0])
```

```
ans = 1
```

Get the data you just set to the main map layer. The expected value of zero is returned.

```
getMapData(multiMapLayers,"mapLayer",[0 0])
```

```
ans = 0
```

Check that `GetListener` map layer incremented their value.

```
getMapData(multiMapLayers,"GetListener",[0 0])
```

```
ans = 1
```

Update the entire map with a matrix of values. Access the data as well.

```
setMapData(multiMapLayers,"mapLayer",rand(10,10))
getMapData(multiMapLayers,"mapLayer")
```

```
ans = 10×10

    0.8147    0.1576    0.6557    0.7060    0.4387    0.2760    0.7513    0.8407    0.3517    0.0
    0.9058    0.9706    0.0357    0.0318    0.3816    0.6797    0.2551    0.2543    0.8308    0.0
    0.1270    0.9572    0.8491    0.2769    0.7655    0.6551    0.5060    0.8143    0.5853    0.5
    0.9134    0.4854    0.9340    0.0462    0.7952    0.1626    0.6991    0.2435    0.5497    0.7
    0.6324    0.8003    0.6787    0.0971    0.1869    0.1190    0.8909    0.9293    0.9172    0.9
    0.0975    0.1419    0.7577    0.8235    0.4898    0.4984    0.9593    0.3500    0.2858    0.1
    0.2785    0.4218    0.7431    0.6948    0.4456    0.9597    0.5472    0.1966    0.7572    0.5
    0.5469    0.9157    0.3922    0.3171    0.6463    0.3404    0.1386    0.2511    0.7537    0.4
    0.9575    0.7922    0.6555    0.9502    0.7094    0.5853    0.1493    0.6160    0.3804    0.0
    0.9649    0.9595    0.1712    0.0344    0.7547    0.2238    0.2575    0.4733    0.5678    0.3
```

Check that `GetListener` and `SetListener` map layers incremented their values.

```
getMapData(multiMapLayers,"SetListener")
```

```
ans = 10×10

     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     1     1     1     1     1     1
```

```
     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     1     1     1     1     1     1
     2     1     1     1     1     1     1     1     1     1
```

```
getMapData(multiMapLayers,"GetListener")
```

```
ans = 10×10

     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     1     1     1     1     1     1
     2     1     1     1     1     1     1     1     1     1
```

The bottom-left location returns two and all other values are one. This confirms the listener functions are working as intended.

#### Listener Function Handles

These functions implement the get and set example helper functions that update the other map layers.

```
function valuesOut = exampleHelperSetHookFcn(modifiedMap,sourceLayer,valueIn,varargin)
    % Pass output through
    valuesOut = valueIn;

    % If no additional inputs are passed, return immediately.
    if numel(varargin) == 0
        return;
    else
        % Otherwise, increment the value in the modifiedMap.
        if numel(varargin) == 1
            currentValue = getMapData(modifiedMap);
            setMapData(modifiedMap,currentValue+1);
        else
            currentValue = getMapData(modifiedMap,varargin{1},varargin{3:end});
            % setMapData syntax <<<<>>>>
            setMapData(modifiedMap,varargin{1},currentValue+1,varargin{3:end});
        end
    end
end

function data = exampleHelperGetHookFcn(accessedMap,sourceLayer,valuesIn,varargin)

    data = valuesIn;
```

```
    % If no additional inputs are passed, check if the values in
    if numel(varargin) == 0
        if isequal(size(valuesIn),sourceLayer.DataSize)
            % Increment the depedent map.
            currentValue = getMapData(accessedMap);
            setMapData(accessedMap,currentValue+1);
        end
    else
        currentValue = getMapData(accessedMap,varargin{:});
        setMapData(accessedMap,varargin{1},currentValue+1,varargin{3:end});
    end
end
```

# Version History

**Introduced in R2021a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

As of MATLAB R2022a, default map behavior during code generation has changed, which may result in backwards compatibility issues. Maps such as `multiLayerMap` now support fixed-size code generation (`DynamicMemoryAllocation="off"`).

1. Maps that are either default-constructed or constructed with compile-time constant size information (or matrices that are of compile-time constant size) produce fixed-size maps.
2. To restore the previous behavior, use the `coder.ignoreConst` function when specifying size inputs, or `coder.varsize` matrix variable name specified as a string scalar or character vector, prior to constructing the map.

## See Also

### Objects

`mapLayer` | `occupancyMap3D` | `occupancyMap` | `binaryOccupancyMap`

### Functions

`getMapData` | `setMapData` | `move` | `syncWith`

### Topics

"Fuse Multiple Lidar Sensors Using Map Layers"

# getLayer

Return individual layers from multilayer map

## Syntax

```
mapLayer = getLayer(map,layerName)
```

## Description

`mapLayer = getLayer(map,layerName)` returns the individual map layer, specified by the layer name `layerName`. For a list of all layer names, see the LayerNames property of the `multiLayerMap` object `map`.

## Examples

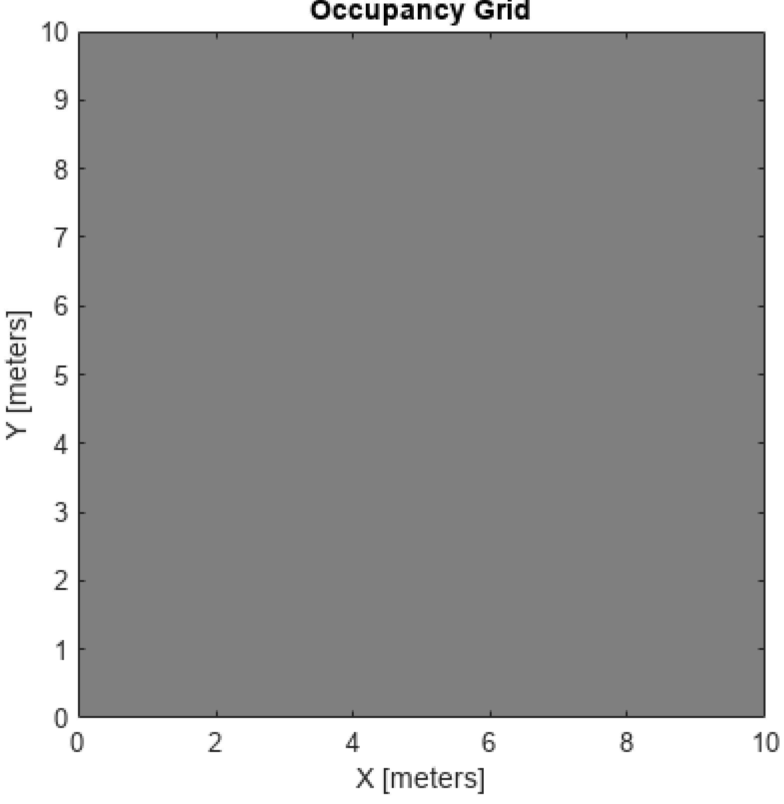
### Get Individual Map Layers from Multilayer Map

Create two occupancy map layers. Then, combine the map layers into a `multiLayerMap` object.

```
map1 = occupancyMap(10,10,"LayerName","Layer1");
map2 = occupancyMap(repmat(0:0.1:0.9,10,1),"LayerName","Layer2");
multiMap = multiLayerMap({map1,map2});
```

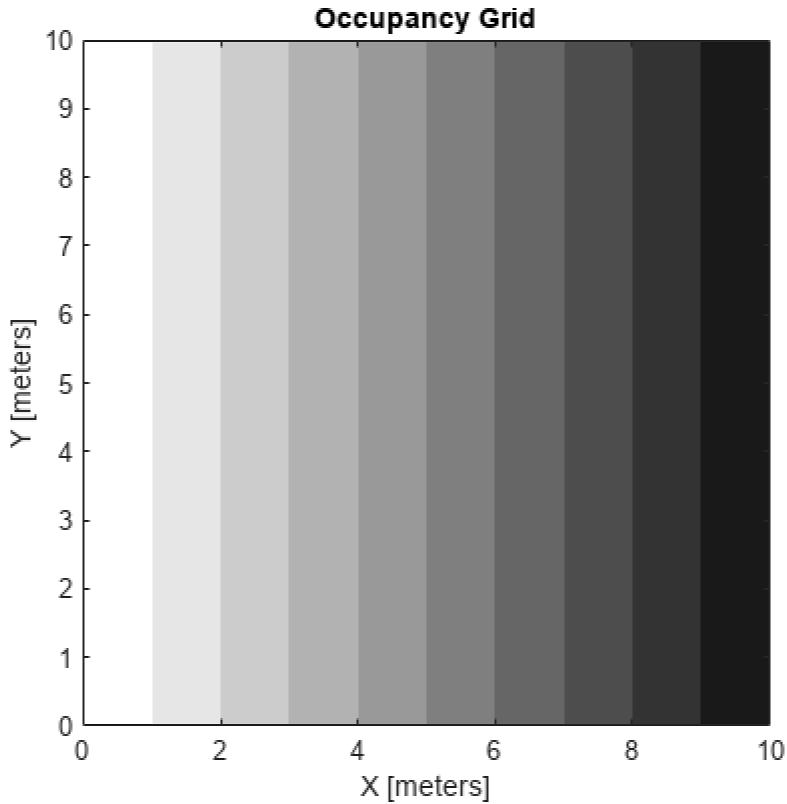
Get the first map layer from the multilayer map.

```
mapLayer1 = getLayer(multiMap,"Layer1");
show(mapLayer1)
```




Get the second map layer from the multilayer map.

```
mapLayer2 = getLayer(multiMap,"Layer2");
show(mapLayer2)
```




## Input Arguments

**`map` — Multilayer map**
`multiLayerMap` object

Multilayer map, specified as a `multiLayerMap` object.

**`layerName` — Name of individual map layer**
string scalar | character vector

Name of individual map layer, specified as a string scalar or character vector.

Data Types: `char` | `string`

## Output Arguments

**`mapLayer` — Individual map layer**
`binaryOccupancyMap` object | `occupancyMap` object | `mapLayer` object

Individual map layer, returned as a `binaryOccupancyMap`, `occupancyMap`, or `mapLayer` object as a handle. For more information, see "Handle Object Behavior".

# Version History

**Introduced in R2021a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Objects

`mapLayer` | `occupancyMap3D` | `occupancyMap` | `binaryOccupancyMap`

### Functions

`getMapData` | `setMapData` | `move` | `syncWith`

### Topics

"Fuse Multiple Lidar Sensors Using Map Layers"

# getMapData

Retrieve data from map layers

## Syntax

```
mapData = getMapData(map)
mapData = getMapData(map,layername)
mapData = getMapData(map,layername,layerinputs)
```

## Description

`mapData = getMapData(map)` returns a cell array of matrices for the data in each layer of the specified `multiLayerMap` object. For binary or occupancy map layers, the values of this function are passed to the `getOccupancy` function. `mapData` is returned as an cell-array of matrices for each layer.

`mapData = getMapData(map,layername)` returns all the map data for the specified layer name. `mapData` is returned as a matrix equal to the DataSize of the specified layer.

`mapData = getMapData(map,layername,layerinputs)` takes the `layerinputs` arguments and passes them to the `getMapData` object function for the specified map layer name. To access individual cells or blocks of data in the world, local, or grid coordinates, see the syntaxes of `getMapData`.

## Examples

### Create Listeners Using Dependent Map Layers

The `multiLayerMap` object enables you to group multiple map layers and define behavior for those layers when setting and getting data. Using separate map layers, you can store various map data and specify different behaviors for each. You can also define the `SetTransformFcn` and `GetTransformFcn` function handles for a map layer so that dependencies are created between layers. This example shows how to store data in a map layer and implement event listeners which update other maps. These maps store how many times the data is updated or accessed.

#### Dependent Layers

Create two independent map layers.

```
mapAccessed = mapLayer(zeros(10,10),"LayerName","GetListener");
mapModified = mapLayer(zeros(10,10),"LayerName","SetListener");
```

Specify function handles for the get and set transform functions used in the main map layer. These functions increment the value of a grid location when you get or set map data in the input map `mainMap`. See Listener Function Handles on page 2-770 for the function implementation.

```
getHookFcn = @(mainMap,values,varargin)exampleHelperGetHookFcn(mapAccessed,mainMap,values,vararg
setHookFcn = @(mainMap,values,varargin)exampleHelperSetHookFcn(mapModified,mainMap,values,vararg
```

Create the main map layer with default values of 0.5. Specify the function handles to create the layer depencies.

```
map = mapLayer(repmat(0.5,10,10), ...
                'GetTransformFcn',getHookFcn, ...
                'SetTransformFcn',setHookFcn);
```

Add all maps to the same `multiLayerMap` object.

```
multiMapLayers = multiLayerMap({map,mapAccessed,mapModified})
```

```
multiMapLayers = 
  multiLayerMap with properties:

   Map Properties
              NumLayers: 3
               GridSize: [10 10]
             Resolution: 1
    GridLocationInWorld: [0 0]
      GridOriginInLocal: [0 0]
     LocalOriginInWorld: [0 0]
           XLocalLimits: [0 10]
           YLocalLimits: [0 10]
           XWorldLimits: [0 10]
           YWorldLimits: [0 10]

   Layer Properties
             LayerNames: {'mapLayer'  'GetListener'  'SetListener'}
               DataSize: {[10 10]  [10 10]  [10 10]}
               DataType: ["double"    "double"    "double"]
           DefaultValue: {[0]  [0]  [0]}
```

Set the (0,0) map location with a value of zero using the `setMapData` object function of `multiLayerMap` object.

```
setMapData(multiMapLayers,"mapLayer",[0 0],0)
```

Check that `SetListener` map layer incremented their value.

```
getMapData(multiMapLayers,"SetListener",[0 0])
```

```
ans = 1
```

Get the data you just set to the main map layer. The expected value of zero is returned.

```
getMapData(multiMapLayers,"mapLayer",[0 0])
```

```
ans = 0
```

Check that `GetListener` map layer incremented their value.

```
getMapData(multiMapLayers,"GetListener",[0 0])
```

```
ans = 1
```

Update the entire map with a matrix of values. Access the data as well.

```
setMapData(multiMapLayers,"mapLayer",rand(10,10))
getMapData(multiMapLayers,"mapLayer")
```

```
ans = 10×10

    0.8147    0.1576    0.6557    0.7060    0.4387    0.2760    0.7513    0.8407    0.3517    0.0
    0.9058    0.9706    0.0357    0.0318    0.3816    0.6797    0.2551    0.2543    0.8308    0.0
    0.1270    0.9572    0.8491    0.2769    0.7655    0.6551    0.5060    0.8143    0.5853    0.5
    0.9134    0.4854    0.9340    0.0462    0.7952    0.1626    0.6991    0.2435    0.5497    0.7
    0.6324    0.8003    0.6787    0.0971    0.1869    0.1190    0.8909    0.9293    0.9172    0.9
    0.0975    0.1419    0.7577    0.8235    0.4898    0.4984    0.9593    0.3500    0.2858    0.1
    0.2785    0.4218    0.7431    0.6948    0.4456    0.9597    0.5472    0.1966    0.7572    0.5
    0.5469    0.9157    0.3922    0.3171    0.6463    0.3404    0.1386    0.2511    0.7537    0.4
    0.9575    0.7922    0.6555    0.9502    0.7094    0.5853    0.1493    0.6160    0.3804    0.0
    0.9649    0.9595    0.1712    0.0344    0.7547    0.2238    0.2575    0.4733    0.5678    0.3
```

Check that `GetListener` and `SetListener` map layers incremented their values.

```
getMapData(multiMapLayers,"SetListener")
```

```
ans = 10×10

     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     1     1     1     1     1     1
     2     1     1     1     1     1     1     1     1     1
```

```
getMapData(multiMapLayers,"GetListener")
```

```
ans = 10×10

     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     1     1     1     1     1     1
     2     1     1     1     1     1     1     1     1     1
```

The bottom-left location returns two and all other values are one. This confirms the listener functions are working as intended.

### Listener Function Handles

These functions implement the get and set example helper functions that update the other map layers.

```
function valuesOut = exampleHelperSetHookFcn(modifiedMap,sourceLayer,valueIn,varargin)
    % Pass output through
    valuesOut = valueIn;
```

```
    % If no additional inputs are passed, return immediately.
    if numel(varargin) == 0
        return;
    else
        % Otherwise, increment the value in the modifiedMap.
        if numel(varargin) == 1
            currentValue = getMapData(modifiedMap);
            setMapData(modifiedMap,currentValue+1);
        else
            currentValue = getMapData(modifiedMap,varargin{1},varargin{3:end});
            % setMapData syntax <<<<>>>>
            setMapData(modifiedMap,varargin{1},currentValue+1,varargin{3:end});
        end
    end
end

function data = exampleHelperGetHookFcn(accessedMap,sourceLayer,valuesIn,varargin)

    data = valuesIn;

    % If no additional inputs are passed, check if the values in
    if numel(varargin) == 0
        if isequal(size(valuesIn),sourceLayer.DataSize)
            % Increment the depedent map.
            currentValue = getMapData(accessedMap);
            setMapData(accessedMap,currentValue+1);
        end
    else
        currentValue = getMapData(accessedMap,varargin{:});
        setMapData(accessedMap,varargin{1},currentValue+1,varargin{3:end});
    end
end
```

## Input Arguments

### `map` — Multilayer map

`multiLayerMap` object

Multilayer map, specified as a `multiLayerMap` object.

### `layername` — Map layer name

string scalar | character array

Map layer name, specified as a string scalar or character array. Map layers have their name specified when creating the `multiLayerMap` object.

### `layerinputs` — Variable-length inputs to map layer

`varargin`

Variable-length inputs to `getMapData` function of map layer, specified as `varargin`. To specify individual cells or blocks of data in the world, local, or grid coordinates, see the syntaxes of `getMapData`.

### Output Arguments

**`mapData` — Data values from map layer**
matrix

Data values from map layer, returned as a matrix. By default, the function returns all data on the layer as an *M*-by-*N*-by-*DataDims* matrix. *M* and *N* are the grid height and width respectively. *DataDims* are the dimensions of the map data, `map.DataSize(3,:)`.

For other syntaxes, the map data may be given as an array of values with size *N*-by-*DataDims* or as a subregion of the full matrix.

## Version History

**Introduced in R2021a**

### See Also

**Objects**
`multiLayerMap` | `mapLayer` | `occupancyMap3D` | `occupancyMap` | `binaryOccupancyMap`

**Functions**
`setMapData` | `move` | `syncWith`

# setMapData

Assign data to map layers

## Syntax

```
setMapData(map,layername,layerinputs)
inBounds = setMapData(map,layername,layerinputs)
```

## Description

`setMapData(map,layername,layerinputs)` takes the `layerinputs` arguments and passes them to the `setMapData` object function for the specified map layer name. To specify individual cells or blocks of data in the world, local, or grid coordinates, see the syntaxes of `setMapData`.

`inBounds = setMapData(map,layername,layerinputs)` returns an array of values for the given locations in the `layerinputs` input argument.

## Examples

### Create Listeners Using Dependent Map Layers

The `multiLayerMap` object enables you to group multiple map layers and define behavior for those layers when setting and getting data. Using separate map layers, you can store various map data and specify different behaviors for each. You can also define the `SetTransformFcn` and `GetTransformFcn` function handles for a map layer so that dependencies are created between layers. This example shows how to store data in a map layer and implement event listeners which update other maps. These maps store how many times the data is updated or accessed.

#### Dependent Layers

Create two independent map layers.

```
mapAccessed = mapLayer(zeros(10,10),"LayerName","GetListener");
mapModified = mapLayer(zeros(10,10),"LayerName","SetListener");
```

Specify function handles for the get and set transform functions used in the main map layer. These functions increment the value of a grid location when you get or set map data in the input map `mainMap`. See Listener Function Handles on page 2-775 for the function implementation.

```
getHookFcn = @(mainMap,values,varargin)exampleHelperGetHookFcn(mapAccessed,mainMap,values,vararg
setHookFcn = @(mainMap,values,varargin)exampleHelperSetHookFcn(mapModified,mainMap,values,vararg
```

Create the main map layer with default values of 0.5. Specify the function handles to create the layer depencies.

```
map = mapLayer(repmat(0.5,10,10), ...
                'GetTransformFcn',getHookFcn, ...
                'SetTransformFcn',setHookFcn);
```

Add all maps to the same `multiLayerMap` object.

```
multiMapLayers = multiLayerMap({map,mapAccessed,mapModified})
```

```
multiMapLayers = 
  multiLayerMap with properties:

   Map Properties
              NumLayers: 3
               GridSize: [10 10]
             Resolution: 1
    GridLocationInWorld: [0 0]
      GridOriginInLocal: [0 0]
     LocalOriginInWorld: [0 0]
           XLocalLimits: [0 10]
           YLocalLimits: [0 10]
           XWorldLimits: [0 10]
           YWorldLimits: [0 10]

   Layer Properties
             LayerNames: {'mapLayer'  'GetListener'  'SetListener'}
               DataSize: {[10 10]  [10 10]  [10 10]}
               DataType: ["double"    "double"    "double"]
           DefaultValue: {[0]  [0]  [0]}
```

Set the (0,0) map location with a value of zero using the `setMapData` object function of `multiLayerMap` object.

```
setMapData(multiMapLayers,"mapLayer",[0 0],0)
```

Check that `SetListener` map layer incremented their value.

```
getMapData(multiMapLayers,"SetListener",[0 0])
```

```
ans = 1
```

Get the data you just set to the main map layer. The expected value of zero is returned.

```
getMapData(multiMapLayers,"mapLayer",[0 0])
```

```
ans = 0
```

Check that `GetListener` map layer incremented their value.

```
getMapData(multiMapLayers,"GetListener",[0 0])
```

```
ans = 1
```

Update the entire map with a matrix of values. Access the data as well.

```
setMapData(multiMapLayers,"mapLayer",rand(10,10))
getMapData(multiMapLayers,"mapLayer")
```

```
ans = 10×10

    0.8147    0.1576    0.6557    0.7060    0.4387    0.2760    0.7513    0.8407    0.3517    0.0
    0.9058    0.9706    0.0357    0.0318    0.3816    0.6797    0.2551    0.2543    0.8308    0.0
    0.1270    0.9572    0.8491    0.2769    0.7655    0.6551    0.5060    0.8143    0.5853    0.5
    0.9134    0.4854    0.9340    0.0462    0.7952    0.1626    0.6991    0.2435    0.5497    0.7
    0.6324    0.8003    0.6787    0.0971    0.1869    0.1190    0.8909    0.9293    0.9172    0.9
```

```
    0.0975    0.1419    0.7577    0.8235    0.4898    0.4984    0.9593    0.3500    0.2858    0.1
    0.2785    0.4218    0.7431    0.6948    0.4456    0.9597    0.5472    0.1966    0.7572    0.5
    0.5469    0.9157    0.3922    0.3171    0.6463    0.3404    0.1386    0.2511    0.7537    0.4
    0.9575    0.7922    0.6555    0.9502    0.7094    0.5853    0.1493    0.6160    0.3804    0.0
    0.9649    0.9595    0.1712    0.0344    0.7547    0.2238    0.2575    0.4733    0.5678    0.3
```

Check that `GetListener` and `SetListener` map layers incremented their values.

```
getMapData(multiMapLayers,"SetListener")
```

```
ans = 10×10

     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     1     1     1     1     1     1
     2     1     1     1     1     1     1     1     1     1
```

```
getMapData(multiMapLayers,"GetListener")
```

```
ans = 10×10

     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     1     1     1     1     1     1
     2     1     1     1     1     1     1     1     1     1
```

The bottom-left location returns two and all other values are one. This confirms the listener functions are working as intended.

#### Listener Function Handles

These functions implement the get and set example helper functions that update the other map layers.

```
function valuesOut = exampleHelperSetHookFcn(modifiedMap,sourceLayer,valueIn,varargin)
    % Pass output through
    valuesOut = valueIn;

    % If no additional inputs are passed, return immediately.
    if numel(varargin) == 0
        return;
    else
        % Otherwise, increment the value in the modifiedMap.
        if numel(varargin) == 1
```

```
            currentValue = getMapData(modifiedMap);
            setMapData(modifiedMap,currentValue+1);
        else
            currentValue = getMapData(modifiedMap,varargin{1},varargin{3:end});
            % setMapData syntax <<<<>>>>
            setMapData(modifiedMap,varargin{1},currentValue+1,varargin{3:end});
        end
    end
end

function data = exampleHelperGetHookFcn(accessedMap,sourceLayer,valuesIn,varargin)

    data = valuesIn;

    % If no additional inputs are passed, check if the values in
    if numel(varargin) == 0
        if isequal(size(valuesIn),sourceLayer.DataSize)
            % Increment the depedent map.
            currentValue = getMapData(accessedMap);
            setMapData(accessedMap,currentValue+1);
        end
    else
        currentValue = getMapData(accessedMap,varargin{:});
        setMapData(accessedMap,varargin{1},currentValue+1,varargin{3:end});
    end
end
```

## Input Arguments

**map — Multilayer map**
`multiLayerMap` object

Multilayer map, specified as a `multiLayerMap` object.

**layername — Map layer name**
string scalar | character array

Map layer name, specified as a string scalar or character array. Map layers have their name specified when creating the `multiLayerMap` object.

**layerinputs — Variable-length inputs to map layer**
`varargin`

Variable-length inputs to `setMapData` function of the map layer, specified as `varargin`. To specify individual cells or blocks of data in the world, local, or grid coordinates, see the syntaxes of `setMapData`.

## Output Arguments

**inBounds — Valid map locations**
*n*-by-1 column vector

Valid map locations, returned as an *n*-by-1 column vector equal in length to `xy` or `ij`. Locations inside the map limits return a value of 1. Locations outside the map limits return a value of 0.

## Version History

**Introduced in R2021a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Objects

`multiLayerMap` | `mapLayer` | `occupancyMap3D` | `occupancyMap` | `binaryOccupancyMap`

### Functions

`getMapData` | `move` | `syncWith`

# gpsdev

Connect to a GPS receiver connected to host computer

## Description

The `gpsdev` System object connects to a GPS receiver connected to the host computer.

To connect to a GPS receiver:

1. Create the `gpsdev` object and set its properties.
2. Call the object with arguments, as if it were a function.

To learn more about how System objects work, see What Are System Objects?

# Creation

## Syntax

```
gps = gpsdev(port)
gps = gpsdev(serialobj)
gps = gpsdev( ___ ,Name,Value)
```

### Description

`gps = gpsdev(port)` connects to a GPS Receiver at the specified serial port of host computer.

`gps = gpsdev(serialobj)` connects to a GPS Receiver specified by a serial object.

`gps = gpsdev( ___ ,Name,Value)` connects to a GPS Receiver on the specified port or specified through a serial object, using one or more name-value pairs.

## Properties

Unless otherwise indicated, properties are *nontunable*, which means you cannot change their values after calling the object. Objects lock when you call them, and the `release` function unlocks them.

If a property is *tunable*, you can change its value at any time.

For more information on changing property values, see System Design in MATLAB Using System Objects.

**`BaudRate` — Baud rate**
`9600`

This property is read-only.

The baud rate for serial communication. The baud rate is set at 9600 bits/sec. The GPS receiver must be configured to work at 9600 bits/sec . If your GPS receiver is configured to some other baud rate, reconfigure it to 9600 bits/sec to use `gpsdev` function.

**ReadMode — Specify which data samples to be returned**
'latest' (default) | 'oldest'

Specify whether to return the latest or the oldest data samples. The number of samples depends on the `SamplesPerRead` value. The data read from the GPS receiver is stored in the MATLAB buffer.

- `latest` — Provides the latest data samples available in the buffer. All previous data samples in the buffer are discarded. For example, if `SamplesPerRead` = 3, the latest three data samples read by the GPS receiver are returned.
- `oldest` — Provides the oldest data samples available in the buffer. In this case, no data samples are discarded. For example, if `SamplesPerRead` = 3, the first three data samples read are returned for the first read, the next three data samples are returned for the second read, and so on.

**Tunable:** No

Data Types: `character vector` | `string`

**SamplesRead — Samples read**
double

This property is read-only.

Number of samples read from the GPS receiver using the `read` function, after the object is locked. The `gpsdev` object gets locked either at the first call of the `read` function after the object creation or at the first call of the read function after the execution of the `release` function.

Data Types: `double`

**SamplesAvailable — Samples in the host buffer**
double

This property is read-only.

Samples available in the host buffer. When you `release` the object, `SamplesAvailable` is set to 0.

Data Types: `double`

**SamplesPerRead — Samples per read**
1 (default)

Samples read from the first `read`, specified as a positive integer in the range [1 10].

**Tunable:** No

Data Types: `double`

**OutputFormat — Set output format**
'timetable' (default) | 'matrix'

Set the output format of the data returned by executing the `read` function.

When the `OutputFormat` is set to `timetable`, the `timetable` returned has the following fields:

- LLA (Latitude, Longitude, Altitude)
- Ground Speed
- Course over ground
- Dilution of Precisions(DOPs), VDOP,HDOP,PDOP
- GPS Receiver Time
- Time — System time when the data is read, in `datetime` or `duration` format

When the `OutputFormat` is set to `matrix`, the data is returned as matrices of Time, LLA, Ground Speed, Course over ground, DOPs, and GPS receiver time. The units for the GPS receiver readings are the same as the `timetable` format.

**Tunable:** Yes

Data Types: `character vector` | `string`

**`TimeFormat` — Set the format of the time displayed when the GPS data is read**
`'datetime'` (default) | `'duration'`

Set the format of the time displayed when the GPS data is read.

- `datetime` — Displays the date and time at which the data is read.
- `duration` — Displays the time elapsed in seconds after the GPS object is locked. The `gpsdev` object gets locked either at the first call of the `read` function after the object creation or at the first call of the read function after the execution of the `release` function.

**Tunable:** Yes

Data Types: `character vector` | `string`

## Object Functions

To use an object function, specify the System object as the first input argument. For example, to release system resources of a System object named `obj`, use this syntax:

```
release(obj)
```

| | |
|---|---|
| flush | Flush all GPS data accumulated in the buffers and reset properties |
| info | Read update rate, GPS lock information and number of satellites in view for the GPS receiver |
| read | Read data from GPS receiver |
| release | Release the GPS object |
| writeBytes | Write raw commands to the GPS receiver |

## Examples

### Plot Geographic Position Using GPS Connected to Host Computer

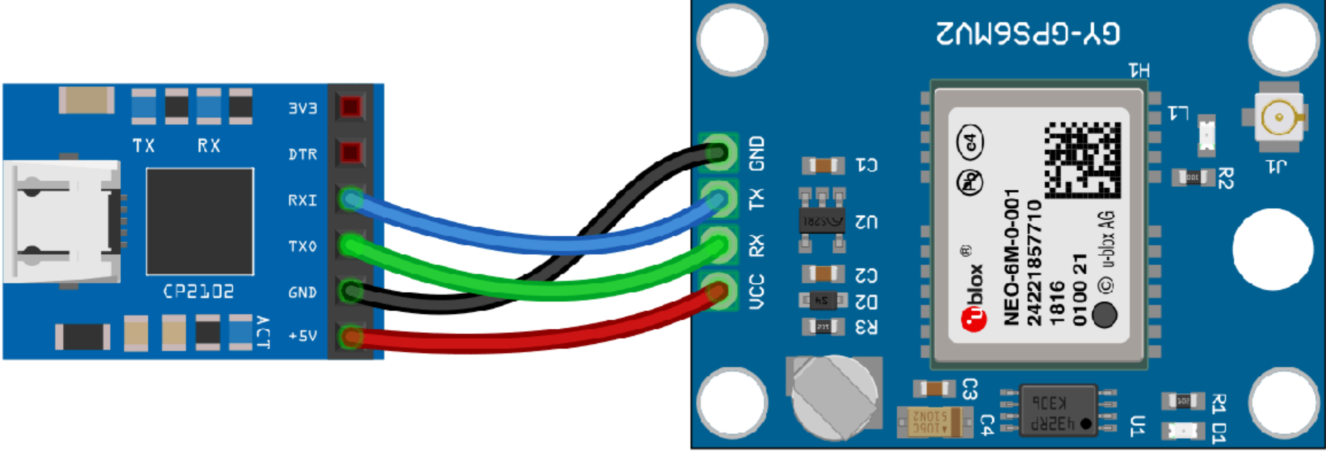
Get the geographic location using the GPS receiver connected to the host computer on a specific serial port and plot the location in a map.

### Required Hardware

To run this example, you need:

- UBlox Neo-6M GPS module
- GPS antenna
- USB to UART module
- USB cable
- Connecting wires

### Hardware Connection




Connect the pins on the UBlox Neo-6M GPS module to the pins on your USB to UART module. The connections are:

- VCC - +5V
- RX - TXO
- TX - RXI
- GND - GND

Connect the GPS antenna to the GPS module. Connect the USB to UART module to the host computer with a USB cable. GPS Fix can be easily acquired in locations that have a clear view of the sky. Wait for the GPS module to acquire satelite signals (Fix).This can be verified by checking the Fix LED (D1) of your GPS module.

### Create GPS Object

Create a `gpsdev` object for the GPS module connected to a specific port.

```
gps = gpsdev('COM4')
```

```
gps = 
  gpsdev with properties:

                         SerialPort: COM4
                           BaudRate: 9600 (bits/s)
```

```
                    SamplesPerRead: 1
                          ReadMode: "latest"
                       SamplesRead: 0
Show all properties all functions
```

**Read the GPS data**

Read the GPS data and extract latitude, longitude, and time from it. GPS returns UTC datetime. Convert it to system time zone.

```
[gpsData,~] = read(gps);
latitude = gpsData.LLA(1);
longitude = gpsData.LLA(2);
gpsTime = gpsData.GPSReceiverTime;
gpsTime.TimeZone = 'local';
```

**Plot the position in a map along with the timestamp**

Plot the position in geographic axes with the data obtained from the GPS module. GPS should have fix to get valid values for latitude, longitude and `gpsTime`.

If the GPS module does not have fix, the above commands give `NaN`s for latitude and longitude and `NaT` for `gpsTime`. In this case, make sure the antenna is exposed to clear sky and wait for some time and try the above steps again.

```
if(~isnan(latitude) && ~isnan(longitude))
 % plot the position in geographic coordinates
 fig = geoplot(latitude,longitude,'Marker',"o",'MarkerSize',6,'Color','red','MarkerFaceColor','re

 % Sets the latitude and longitude limits of the base Map
 geolimits([latitude-0.05 latitude+0.05],[longitude-0.05 longitude+0.05]) ;

 % Selects the basemap
 geobasemap streets;
 timeString = strcat("Timestamp: ",string(gpsTime));

 % Create annotation and display time received from GPS
 annotation('textbox',[0.005 0.98 0.6 0.01],'FitBoxToText','on','string',timeString,'Color','blue
end
```

**Clean Up**

When the connection is no longer needed, clear the associated object.

```
delete(gps);
clear gps;
```

**Write Configuration Commands to GPS Receiver**

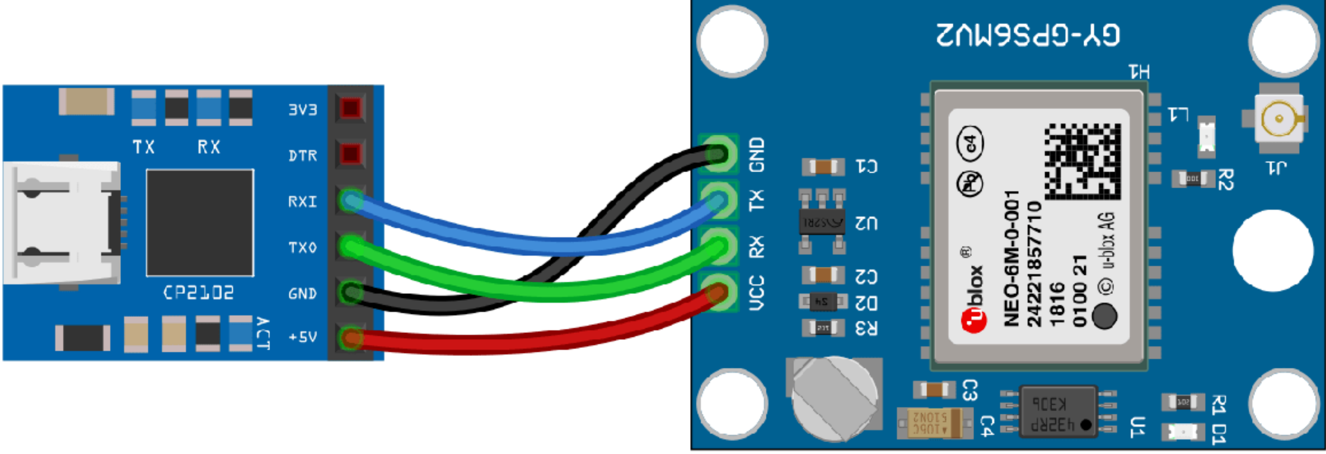
Write configuration commands to the GPS receiver connected to the host computer using `serialport` object.

**Required Hardware**

To run this example, you need:

- UBlox Neo-6M GPS module
- GPS antenna
- USB to UART module
- USB cable
- Connecting wires

**Hardware Connection**




Connect the pins on the UBlox Neo-6M GPS module to the pins on your USB to UART module. The connections are:

- VCC - +5V
- RX - TXO
- TX - RXI
- GND - GND

Connect the GPS antenna to the GPS module. Connect the USB to UART module to the host computer with a USB cable. GPS Fix can be easily acquired in locations that have a clear view of the sky. Wait for the GPS module to acquire satelite signals (Fix).This can be verified by checking the Fix LED (D1) of your GPS module.

**Create GPS Object**

Connect to the GPS receiver using `serialport` object. Specify the port name and the baud rate.

```
s = serialport('COM4',9600)
```

```
s = 
  Serialport with properties:

                 Port: "COM4"
             BaudRate: 9600
    NumBytesAvailable: 0

  Show all properties, functions
```

```
gps = gpsdev(s)
```

```
gps = 
  gpsdev with properties:

                         SerialPort: COM4
                           BaudRate: 9600 (bits/s)

                     SamplesPerRead: 1
                           ReadMode: "latest"
                        SamplesRead: 0
Show all properties all functions
```

#### Write Configuration Commands

In the default configuration the GPS receiver returns the following NMEA messages: GPRMC, GPVTG, GPGGA, GPGSA, GPGSV, and GPGLL. The receiver can be configured to have a user defined set of output messages.

Read few lines of default messages from the serial port the GPS receiver is connected.

```
for i = 1:10
data = readline(s);
disp(data);
end
```

```
$GPRMC,,V,,,,,,,,,,N*53
$GPVTG,,,,,,,,,N*30
$GPGGA,,,,,,0,00,99.99,,,,,,*48
$GPGSA,A,1,,,,,,,,,,,,,99.99,99.99,99.99*30
$GPGSV,2,1,08,01,,,18,08,,,12,09,,,12,15,,,19*77
$GPGSV,2,2,08,23,,,13,24,,,09,25,,,10,27,,,25*79
$GPGLL,,,,,,V,N*64
$GPRMC,,V,,,,,,,,,,N*53
$GPVTG,,,,,,,,,N*30
$GPGGA,,,,,,0,00,99.99,,,,,,*48
```

Write the version monitor command to the GPS receiver to return the software and hardware version of the GPS receiver.

```
configCMD = [0xB5 0x62 0x0A 0x04 0x00 0x00 0x0E 0x34];
% writeBytes(gps,cfg)
write(s,configCMD,'uint8')
```

Read few lines of messages again to verify the version message.

```
for i = 1:10
data = readline(s);
disp(data);
end
```

```
$GPGSA,A,1,,,,,,,,,,,,,99.99,99.99,99.99*30
$GPGSV,2,1,05,01,,,13,09,,,11,15,,,16,23,,,12*74
$GPGSV,2,2,05,25,,,10*7A
$GPGLL,,,,,,V,N*64
µb
( 7.03 (45969)                  00040007  °$GPRMC,,V,,,,,,,,,,N*53
$GPVTG,,,,,,,,,N*30
```

```
$GPGGA,,,,,,0,00,99.99,,,,,,*48
$GPGSA,A,1,,,,,,,,,,,,,99.99,99.99,99.99*30
$GPGSV,2,1,06,01,,,11,09,,,11,23,,,14,24,,,21*75
```

It can be observed from the output, `7.03 (45969)` is the software version and `00040007` is the hardware version.

#### Clean Up

When the connection is no longer needed, clear the associated object.

```
delete(gps);
clear gps;
clear s;
```

### Read Data from GPS Receiver as Timetable

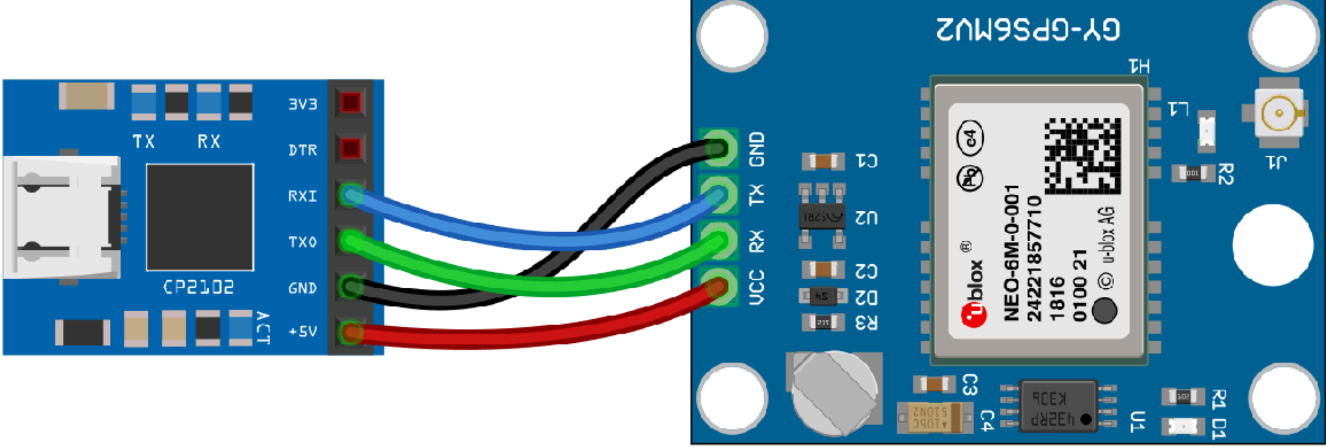
Read data from the GPS receiver connected to the host computer on a specific serial port.

#### Required Hardware

To run this example, you need:

- UBlox Neo-6M GPS module
- GPS antenna
- USB to UART module
- USB cable
- Connecting wires

#### Hardware Connection




Connect the pins on the UBlox Neo-6M GPS module to the pins on your USB to UART module. The connections are:

- VCC - +5V

- RX - TXO
- TX - RXI
- GND - GND

Connect the GPS antenna to the GPS module. Connect the USB to UART module to the host computer with a USB cable. GPS Fix can be easily acquired in locations that have a clear view of the sky. Wait for the GPS module to acquire satelite signals (Fix).This can be verified by checking the Fix LED (D1) of your GPS module.

**Create GPS Object**

Create a `gpsdev` object for the GPS receiver connected to a specific port. Specify the output format of the data as a timetable.

```
gps = gpsdev('COM4','OutputFormat',"timetable")
```

```
gps = 
  gpsdev with properties:

                         SerialPort: COM4
                           BaudRate: 9600 (bits/s)

                     SamplesPerRead: 1
                           ReadMode: "latest"
                        SamplesRead: 0
Show all properties all functions
```

**Read the GPS data**

Read the GPS data and return them as a timetable.

```
[tt,overruns] = read(gps)
```

```
tt=1×5 timetable
              Time                           LLA                  GroundSpeed     Course           DOI
    ________________________    _________________________    ___________    ______     ___________

    22-Mar-2021 15:31:15.190    17.47     78.343      449.6      0.25619         NaN       9.31     1.4
```

```
overruns = 0
```

Display number of samples read and the samples available in the host buffer.

```
gps.SamplesRead
```

```
ans = 1
```

```
gps.SamplesAvailable
```

```
ans = 0
```

Release the GPS object to configure the non tunable properties. The release function also clears the buffer and resets the `SamplesRead` and `SamplesAvailable` properties.

```
release(gps)
```

Specify the number of samples per read to 2. Read the GPS data.

```
gps.SamplesPerRead = 2;
read(gps)
```

```
ans=2×5 timetable
             Time                         LLA                 GroundSpeed    Course          DO
    ________________________    _________________________    ___________    ______    __________

    22-Mar-2021 15:31:17.178    17.47     78.343        450     0.063791       NaN      9.32     1.
    22-Mar-2021 15:31:17.178    17.47     78.343        450     0.063791       NaN      9.32     1.
```

Display number of samples read and the samples available in the host buffer.

```
gps.SamplesRead
```

```
ans = 1
```

```
gps.SamplesAvailable
```

```
ans = 0
```

### Clean Up

When the connection is no longer needed, clear the associated object.

```
delete(gps);
clear gps;
```

## More About

### GPS Modules

To verify the functionality, the following GPS modules were used:

- Adafruit Ultimate GPS
- Ublox NEO 6M
- Ublox NEO 7M

# Version History

**Introduced in R2020b**

## See Also

`nmeaParser`

# nmeaParser

Parse data from standard and manufacturer-specific NMEA sentences sent from marine electronic devices

## Description

The `nmeaParser` System object parses data from any NMEA (National Marine Electronics Association) sentences. The sentences that need parsing of data can be any standard sentences compliant with the NMEA 0183® specifications (which are sent from a GNSS (Global Navigation Satellite System) receiver), or other manufacturer-specific sentences approved by the NMEA (which are sent from other marine electronic devices).

The `nmeaParser` System object provides:

- Built-in support to parse data sent from GNSS receivers and identified by these nine NMEA message types: RMC, GGA, GSA, VTG, GLL, GST, ZDA, GSV, and HDT
- Additional configuration using the `CustomSentence` name-value pair to parse NMEA data from multiple device categories, including manufacturer-specific sentences from different hardware manufacturers

To parse data from NMEA sentences:

1. Create the `nmeaParser` object and set its properties.
2. Call the object with arguments, as if it were a function.

To learn more about how System objects work, see What Are System Objects?

The `nmeaParser` System object outputs an array of structures corresponding to the values extracted from the specified NMEA sentences.

# Creation

## Syntax

```
pnmea = nmeaParser
pnmea = nmeaParser("MessageIDs", 'msgID')
pnmea = nmeaParser("CustomSentence",
{['CustomMessageId1','parserFunctionName1'],
['CustomMessageId2','parserFunctionName2']})
pnmea = nmeaParser("MessageIDs", {'msgID1','msgID2'},"CustomSentence",
{['CustomMessageId1','parserFunctionName1'],
['CustomMessageId2','parserFunctionName2']})
```

### Description

`pnmea = nmeaParser` returns a `nmeaParser` System object, `pnmea`, with default properties, that extracts data from these standard NMEA messages: RMC, GGA, and GSA. The order of structure arrays in the extracted output data is also: RMC, GGA, and GSA.

`pnmea = nmeaParser("MessageIDs", 'msgID')` returns a `nmeaParser` System object, `pnmea`, that extracts data from one of the nine standard NMEA messages with built-in support, specified using the Message IDs. Specify `msgID` as `"RMC"`, `"GGA"`, `"GSA"`, `"GSV"`, `"VTG"`, `"GLL"`, `"GST"`, `"ZDA"`, and `"HDT"`, or a combination of these IDs (for example: `["VTG","GLL","HDT"]`). The order in which you specify the Message IDs determines the order of the structure arrays in the extracted output data. The default value is `["RMC","GGA","GSA"]`.

`pnmea = nmeaParser("CustomSentence", {['CustomMessageId1','parserFunctionName1'], ['CustomMessageId2','parserFunctionName2']})` sets properties using the `CustomSentence` name-value pair and returns a `nmeaParser` System object, `pnmea`, that extracts data from any custom NMEA message (either standard NMEA message or manufacturer-specific NMEA message), specified using the message IDs.

The `CustomSentence` name-value pair accepts a nested cell array where each element is a pair of message ID name (either standard NMEA message ID name or manufacturer-specific message ID) and the corresponding user-defined parser function, which is created by including the `extractNMEASentence` function in a function file. The order in which you specify the message IDs determines the order of the structure arrays in the extracted output data.

`pnmea = nmeaParser("MessageIDs", {'msgID1','msgID2'},"CustomSentence", {['CustomMessageId1','parserFunctionName1'], ['CustomMessageId2','parserFunctionName2']})` returns a `nmeaParser` System object, `pnmea`, that extracts data from two of the nine standard NMEA messages with built-in support and also from custom NMEA messages that you specified using the `CustomSentence` name-value pair.

### Input Arguments

#### Name-Value Pair Arguments

Specify optional pairs of arguments as `Name1=Value1,...,NameN=ValueN`, where `Name` is the argument name and `Value` is the corresponding value. Name-value arguments must appear after other arguments, but the order of the pairs does not matter.

*Before R2021a, use commas to separate each name and value, and enclose* `Name` *in quotes.*

Example: `pnmea = nmeaParser("CustomSentence", {['CustomMessageId1','parserFunctionName1'], ['CustomMessageId2','parserFunctionName2']});`

**`CustomSentence` — Specify message ID of any sentence and the name of its parser function**
cell array of character vectors

Specify the message ID of any NMEA sentence from which you want to extract data and the name of the parser function. You can specify multiple message IDs and parser functions as a cell array of character vectors. The parser function is defined in a function file, which can optionally include the `extractNMEASentence` function.

---

**Note** The function file for the parser function must be present in the current directory or on MATLAB path.

---

`CustomSentence` accepts function name or function handle. For example, both these formats are valid:

- `pnmea = nmeaParser('CustomSentence', {['standardnmeaMessageId1','parserFunctionName1']}`
- `parserFunctionHandle=@parserFunctionName1`
  `pnmea = nmeaParser('CustomSentence', {['standardnmeaMessageId1',parserFunctionHandle]}`

---

**Note** Using `CustomSentence` name-value pair to parse data instead of the built-in parser function results in override of the default fields when data is parsed. For example, `nmeaParser('CustomSentence',{["RMC","parserRMC"]})` overrides the default format of parsed data as RMC is one of the nine sentences with built-in support for parsing data.

---

Data Types: `char` | `string`

## Properties

Unless otherwise indicated, properties are *nontunable*, which means you cannot change their values after calling the object. Objects lock when you call them, and the `release` function unlocks them.

If a property is *tunable*, you can change its value at any time.

For more information on changing property values, see System Design in MATLAB Using System Objects.

#### `MessageIDs` — Message IDs of nine standard NMEA sentences with built-in support to extract data

`["RMC","GGA","GSA"]` (default) | `RMC` | `GGA` | `GSA` | `GSV` | `VTG` | `GLL` | `GST` | `ZDA` | `HDT`

Message IDs of nine NMEA sentences with built-in support, which are compliant with the NMEA 0183 Standard, from which you want to extract data. You can specify multiple message IDs as an array of strings to extract data from NMEA sentences.

Data Types: `char` | `string`

## Usage

## Syntax

```
[rmcData,ggaData,gsaData,vtgData,gllData,gstData,gsvData,zdaData,hdtData] =
pnmea(rawData)
[customNmeaData1,customNmeaData2] = pnmea(rawData)
```

### Description

`[rmcData,ggaData,gsaData,vtgData,gllData,gstData,gsvData,zdaData,hdtData] = pnmea(rawData)` parses data from nine standard NMEA sentences with built-in support, and returns an array of structures, where each structure corresponds to a single Message ID. The sequence that you specify for the output arguments must be the same sequence that you specified for the Message IDs when creating the `nmeaParser` System object.

`[customNmeaData1,customNmeaData2] = pnmea(rawData)` parses data from two custom NMEA sentences (either standard NMEA sentence or manufacturer-specific NMEA sentence), and returns an array of structures, where each structure corresponds to a single Message ID. The

sequence that you specify for the output arguments must be the same sequence that you specified in the `CustomSentence` name-value pair when creating the `nmeaParser` System object.

### Input Arguments

#### `rawData` — NMEA data as obtained from a marine electronic device
string array

NMEA data, which is compliant with NMEA standard, as obtained from a marine electronic device.

Data Types: `string` | `char`

### Output Arguments

#### `rmcData` — Data extracted from RMC sentence
structure

Data extracted from an RMC sentence. The output structure contains the information parsed from an RMC sentence along with the parsing status. If multiple RMC sentences are found in the input data, then an array of structures is returned. For more details, see “RMC Sentences” on page 2-802.

#### `ggaData` — Data extracted from GGA sentence
structure

Data extracted from a GGA sentence. The output structure contains the information parsed from a GGA sentence along with the parsing status. If multiple GGA sentences are found in the input data, then an array of structures is returned. For more details, see “GGA Sentences” on page 2-803.

#### `gsaData` — Data extracted from GSA sentence
structure

Data extracted from a GSA sentence. The output structure contains the information parsed from a GSA sentence along with the parsing status. If multiple GSA sentences are found in the input data, then an array of structures is returned. For more details, see “GSA Sentences” on page 2-805.

#### `vtgData` — Data extracted from VTG sentence
structure

Data extracted from a VTG sentence. The output structure contains the information parsed from a VTG sentence along with the parsing status. If multiple VTG sentences are found in the input data, then an array of structures is returned. For more details, see “VTG Sentences” on page 2-809.

#### `gllData` — Data extracted from GLL sentence
structure

Data extracted from a GLL sentence. The output structure contains the information parsed from a GLL sentence along with the parsing status. If multiple GLL sentences are found in the input data, then an array of structures is returned. For more details, see “GLL Sentences” on page 2-808.

#### `gstData` — Data extracted from GST sentence
structure

Data extracted from a GST sentence. The output structure contains the information parsed from a GST sentence along with the parsing status. If multiple GST sentences are found in the input data, then an array of structures is returned. For more details, see “GST Sentences” on page 2-810.

**`gsvData` — Data extracted from GSV sentence**
structure

Data extracted from a GSV sentence. The output structure contains the information parsed from a GSV sentence along with the parsing status. The complete satellite information is available in multiple gsvData structures. Each gsvData structure can have a maximum of four satellite information. For more details, see “GSV Sentences” on page 2-806.

**`zdaData` — Data extracted from ZDA sentence**
structure

Data extracted from a ZDA sentence. The output structure contains the information parsed from a ZDA sentence along with the parsing status. If multiple ZDA sentences are found in the input data, then an array of structures is returned. For more details, see “ZDA Sentences” on page 2-808.

**`hdtData` — Data extracted from HDT sentence**
structure

Data extracted from an HDT sentence. The output structure contains the information parsed from an HDT sentence along with the parsing status. If multiple HDT sentences are found in the input data, then an array of structures is returned. For more details, see “HDT Sentences” on page 2-811.

**`customNmeaData1` — Data extracted from any standard or manufacturer-specific NMEA sentence**
structure

Data extracted from any standard or manufacturer-specific NMEA sentence. The output structure contains the information parsed from the custom sentence along with the parsing status. If multiple sentences of the same NMEA message type are found in the input data, then an array of structures is returned.

## Object Functions

To use an object function, specify the System object as the first input argument. For example, to release system resources of a System object named `obj`, use this syntax:

```
release(obj)
```

## Examples

### Extract Data from NMEA Sentences Using MessageID Property

Extract data from any of the nine standard NMEA sentences as part of the built-in support using the MessageID property. The NMEA data is obtained from a GNSS receiver.

#### Extract Data from RMC Sentence

Create an nmeaParser System Object by specifying the Message ID as "RMC".

```
pnmea = nmeaParser("MessageID","RMC");
```

Provide the RMC sentence obtained from the GNSS receiver as the input and extract data.

```
unparsedRMCLine='$GNRMC,143909.00,A,5107.0020216,N,11402.3294835,W,0.036,348.3,210307,0.0,E,A*31
rmcData = pnmea(unparsedRMCLine)
```

```
rmcData = struct with fields:
            TalkerID: "GN"
           MessageID: "RMC"
           FixStatus: 'A'
            Latitude: 51.1167
           Longitude: -114.0388
         GroundSpeed: 0.0185
     TrueCourseAngle: 348.3000
         UTCDateTime: 21-Mar-2007 14:39:09.000
   MagneticVariation: 0
       ModeIndicator: 'A'
    NavigationStatus: "NA"
              Status: 0
```

**Extract Data from Multiple NMEA Message Types**

Provide GGA, GSA, and RMC sentences as the input.

```
unparsedGGALine = ['$GPGGA,111357.771,5231.364,N,01324.240,E,1,12,1.0,0.0,M,0.0,M,,*69'];
unparsedGSALine = ['$GPGSA,A,3,01,02,03,04,05,06,07,08,09,10,11,12,1.0,1.0,1.0*30'];
unparsedRMCLine = ['$GPRMC,111357.771,A,5231.364,N,01324.240,E,10903,221.5,020620,000.0,W*44'];
```

Create a string array to include the three sentences

```
rawNMEAData = [unparsedGGALine ,newline,  unparsedGSALine ,newline,  unparsedRMCLine]
```

```
rawNMEAData = 
    '$GPGGA,111357.771,5231.364,N,01324.240,E,1,12,1.0,0.0,M,0.0,M,,*69
     $GPGSA,A,3,01,02,03,04,05,06,07,08,09,10,11,12,1.0,1.0,1.0*30
     $GPRMC,111357.771,A,5231.364,N,01324.240,E,10903,221.5,020620,000.0,W*44'
```

However, consider that you need to extract data only from GGA and GSA sentences. So create the nmeaParser System Object 'pnmea', and specify the 'GGA' and 'GSA' Message IDs as a string array.

```
pnmea=nmeaParser("MessageIDs",["GGA","GSA"]);
```

Specify the output arguments for all the three sentences to extract the data as structures.

```
[ggaData,gsaData] =  pnmea(rawNMEAData)
```

```
ggaData = struct with fields:
                          TalkerID: "GP"
                         MessageID: "GGA"
                           UTCTime: 11:13:57.771
                          Latitude: 52.5227
                         Longitude: 13.4040
                  QualityIndicator: 1
                NumSatellitesInUse: 12
                              HDOP: 1
                          Altitude: 0
                   GeoidSeparation: 0
             AgeOfDifferentialData: NaN
    DifferentialReferenceStationID: NaN
```

```
                            Status: 0


gsaData = struct with fields:
              TalkerID: "GP"
             MessageID: "GSA"
                  Mode: "A"
               FixType: 3
    SatellitesIDNumber: [1 2 3 4 5 6 7 8 9 10 11 12]
                  PDOP: 1
                  VDOP: 1
                  HDOP: 1
              SystemID: NaN
                Status: 0
```

The above output shows that only GGA and GSA sentences are extracted based on the Message IDs specified as input.

Provide another GGA sentence as an additional input, and extract data. In this case, you need not modify the System object as the Message ID has not changed.

```
unparsedGGALine1='$GNGGA,001043.00,4404.14036,N,12118.85961,W,1,12,0.98,1113.0,M,-21.3,M,,*47'

unparsedGGALine1 = 
'$GNGGA,001043.00,4404.14036,N,12118.85961,W,1,12,0.98,1113.0,M,-21.3,M,,*47'

rawNMEAData = [unparsedGGALine ,newline,  unparsedGSALine ,newline,  unparsedGGALine1]

rawNMEAData = 
    '$GPGGA,111357.771,5231.364,N,01324.240,E,1,12,1.0,0.0,M,0.0,M,,*69
     $GPGSA,A,3,01,02,03,04,05,06,07,08,09,10,11,12,1.0,1.0,1.0*30
     $GNGGA,001043.00,4404.14036,N,12118.85961,W,1,12,0.98,1113.0,M,-21.3,M,,*47'


[ggaData,gsaData] =  pnmea(rawNMEAData)

ggaData=2×1 struct array with fields:
    TalkerID
    MessageID
    UTCTime
    Latitude
    Longitude
    QualityIndicator
    NumSatellitesInUse
    HDOP
    Altitude
    GeoidSeparation
    AgeOfDifferentialData
    DifferentialReferenceStationID
    Status


gsaData = struct with fields:
              TalkerID: "GP"
             MessageID: "GSA"
                  Mode: "A"
               FixType: 3
    SatellitesIDNumber: [1 2 3 4 5 6 7 8 9 10 11 12]
```

```
                PDOP: 1
                VDOP: 1
                HDOP: 1
            SystemID: NaN
              Status: 0
```

A status of **0** indicates that the data was parsed successfully.

### Extract Data from GSV Sentence

Create an nmeaParser System Object by specifying the Message ID as "GSV".

```
pnmea = nmeaParser("MessageID","GSV");
```

Provide the GSV sentence obtained from the GNSS receiver as the input and extract data.

```
unparsedGSVLine='$GPGSV,3,3,10,32,69,205,41,46,47,215,39*79';
gsvData = pnmea(unparsedGSVLine)
```

```
gsvData = struct with fields:
            TalkerID: "GP"
           MessageID: "GSV"
        NumSentences: 3
      SentenceNumber: 3
    SatellitesInView: 10
         SatelliteID: [32 46]
           Elevation: [69 47]
             Azimuth: [205 215]
                 SNR: [41 39]
            SignalID: NaN
              Status: 0
```

### Extract Data from Multiple GSV Sentences

Provide multiple GSV sentences as the input.

```
unparsedGSVLine1 = '$GPGSV,3,1,10,01,,,31,03,28,325,40,10,,,33,12,20,047,30*70';
unparsedGSVLine2 = '$GPGSV,3,2,10,14,88,028,42,22,39,299,48,25,,,25,31,79,289,46*49';
unparsedGSVLine3 = '$GPGSV,3,3,10,32,69,205,41,46,47,215,39*79';
```

Create a string array to include the three sentences.

```
CRLF = [char(13),newline];
unparsedGSVLines = [unparsedGSVLine1,CRLF, unparsedGSVLine2, CRLF, unparsedGSVLine3];
```

Create the nmeaParser System Object 'pnmea', specify the 'GSV' Message ID, and extract data.

```
pnmea = nmeaParser("MessageIDs","GSV");
gsvData = pnmea(unparsedGSVLines)
```

```
gsvData=3×1 struct array with fields:
    TalkerID
    MessageID
    NumSentences
    SentenceNumber
    SatellitesInView
    SatelliteID
```

```
    Elevation
    Azimuth
    SNR
    SignalID
    Status
```

#### Read Data from NMEA Log

Read data from a sample NMEA log, so that the data can be parsed using the nmeaParser System Object.

The sample log file is `nmeaLog.nmea`, which is included in this example.

```
f = fopen('nmeaLog.nmea');
unParsedNMEAdata = fread(f);
pnmea = nmeaParser("MessageIDs",["RMC","GGA"]);
[rmcStruct, ggaStruct] = pnmea(unParsedNMEAdata)
```

```
rmcStruct=9×1 struct array with fields:
    TalkerID
    MessageID
    FixStatus
    Latitude
    Longitude
    GroundSpeed
    TrueCourseAngle
    UTCDateTime
    MagneticVariation
    ModeIndicator
    NavigationStatus
    Status

ggaStruct=9×1 struct array with fields:
    TalkerID
    MessageID
    UTCTime
    Latitude
    Longitude
    QualityIndicator
    NumSatellitesInUse
    HDOP
    Altitude
    GeoidSeparation
    AgeOfDifferentialData
    DifferentialReferenceStationID
    Status
```

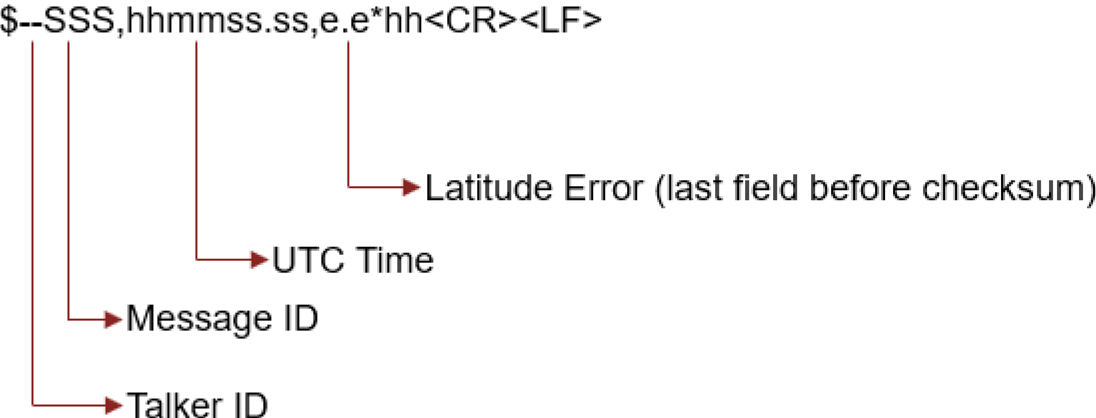
#### Extract Data Using CustomSentence Name-Value Pair

You can extract data from any NMEA sentence using the `CustomSentence` name-value pair. The NMEA data to be parsed is obtained from marine electronic devices.

#### Identify the Structure of NMEA Sentence and Create the Parser Function

You need to identify the structure of the NMEA sentence, as defined in the specification, and use that information to define the structure of output data to be used in the nmeaParser System object.

For example, let us consider an example sentence with Message ID, `SSS`.




After identifying the structure, you create a function file that defines the parser function, **fsssParser.** In the function file, you define the output data as a structure array with its fields matching the sequence as it appears in the specification.

The Navigation Toolbox™ provides an optional pre-configured function, `extractNMEASentence`, that checks if the sentence is valid and convert the fields in the sentence into string array. You can call `extractNMEASentence` inside the function file. You can also use any other function instead (which outputs a string array from unparsed data), and then call it inside the function file.

The below image shows the function file with the code, with the assumption that the fields available in `SSS` sentence are TalkerID, MessageID, UTC, and LatitudeError. Refer the additional comments for details.

fsssParser.m

```
1
2    function OutputData = fsssParser(unparsedData, MessageId)
3    % fsssParser custom function to parse SSS sentence
4
5    % Define OutputData as a structure array with fields in the same sequence as they appear in
6    % SSS sentence structure
7    OutputData = struct('TalkerID',"",'MessageID',"",'UTC',nan,'LatitudeError',nan);
8
9    % Call another function to convert the unparsed data into string array.
10   % To do this, use either extractNMEASentence function
11   % or any other function that outputs a string array.
12   [valid, splitString] = extractNMEASentence(unparsedData,MessageId);
13
14   % Map each field of the structure to the corresponding string element
15   if(valid)
16       OutputData.TalkerID = splitString(1);
17       OutputData.MessageID = splitString(2);
18       temp = char(splitString(3));
19       utcOutput = [temp(1:2), ':', temp(3:4), ':', temp(5:9)];
20       OutputData.UTC = utcOutput;
21       OutputData.LatitudeError = str2double(splitString(4));
22
23   end
24
25   end
```

In the above sample file, you define the mapping between the fields in the structure array and the elements of string array. For certain fields (for example, UTC time), you may need to define a character array to map the fields.

After you include the MATLAB code as mentioned above, save the function file (**fsssParser.m**) in the MATLAB path, so that you can call it to obtain parsed data using the `CustomSentence` name-value pair of nmeaParser System object.

To download another sample function file **parserRMB.m** that is used this example, click **Open Live Script**. This is a function file specific to the fields of an RMB sentence (mentioned in NMEA Standard, Version 4.1).

**Extract Data from RMB Sentence**

Create an nmeaParser System Object by using the CustomSentence name-value pair and specifying the message ID as "RMB" and the function as "parserRMB" (downloaded in the previous step).

```
pnmea = nmeaParser("CustomSentence",{["RMB","parserRMB"]});
```

Provide the RMB sentence obtained from the GNSS receiver as the input and extract data.

```
unparsedRMBLine='$GPRMB,A,4.08,L,EGLL,EGLM,5130.02,N,00046.34,W,004.6,213.9,122.9,A*3D';
rmbData = pnmea(unparsedRMBLine)
```

```
rmbData = struct with fields:
                        TalkerID: "GP"
```

```
                   MessageID: "RMB"
                  DataStatus: 'A'
              CrossTrackError: 4.0800
             DirectionToSteer: NaN
             OriginWaypointID: NaN
        DestinationWaypointID: NaN
  DestinationWaypointLatitude: '5130.02 N'
 DestinationWaypointLongitude: '00046.34 W'
           RangeToDestination: 4.6000
         BearingToDestination: 213.9000
   DestinationClosingVelocity: 122.9000
                ArrivalStatus: 'A'
                ModeIndicator: "NA"
                       Status: 0
```

#### Extract Data from Multiple RMB Sentences

Provide multiple RMB sentences as the input.

```
unparsedRMBLine1 = ['$GPRMB,A,0.66,L,003,004,4917.24,N,12309.57,W,001.3,052.5,000.5,V*20'];
unparsedRMBLine2 = ['$GPRMB,A,4.08,L,EGLL,EGLM,5130.02,N,00046.34,W,004.6,213.9,122.9,A*3D'];
```

Create a character array to include the two sentences

```
rawNMEAData = [unparsedRMBLine1 ,newline,  unparsedRMBLine2]
```

```
rawNMEAData = 
    '$GPRMB,A,0.66,L,003,004,4917.24,N,12309.57,W,001.3,052.5,000.5,V*20
     $GPRMB,A,4.08,L,EGLL,EGLM,5130.02,N,00046.34,W,004.6,213.9,122.9,A*3D'
```

Specify the output argument for the RMB sentence to extract the data.

```
[rmbData] =  pnmea(rawNMEAData)
```

```
rmbData=2×1 struct array with fields:
    TalkerID
    MessageID
    DataStatus
    CrossTrackError
    DirectionToSteer
    OriginWaypointID
    DestinationWaypointID
    DestinationWaypointLatitude
    DestinationWaypointLongitude
    RangeToDestination
    BearingToDestination
    DestinationClosingVelocity
    ArrivalStatus
    ModeIndicator
    Status
```

#### Extract Data from a Sentence with Built-in Support (RMC) and RMB Sentence

Create an nmeaParser System Object by using the MessageID property (to parse a sentence with built-in support - RMC) and also using the CustomSentence name-value pair (specifying the message ID as "RMB" and the function as "parserRMB" (created in a previous step)).

```
pnmea = nmeaParser("MessageID","RMC","CustomSentence",{["RMB","parserRMB"]});
```

Provide RMC and RMB sentences as the input.

```
unparsedRMCLine1 = ['$GNRMC,143909.00,A,5107.0020216,N,11402.3294835,W,0.036,348.3,210307,0.0,E,A
unparsedRMBLine2 = ['$GPRMB,A,4.08,L,EGLL,EGLM,5130.02,N,00046.34,W,004.6,213.9,122.9,A*3D'];
```

Create a string array to include the two sentences

```
rawNMEAData = [unparsedRMCLine1 ,newline,  unparsedRMBLine2]
```

```
rawNMEAData = 
    '$GNRMC,143909.00,A,5107.0020216,N,11402.3294835,W,0.036,348.3,210307,0.0,E,A*31
     $GPRMB,A,4.08,L,EGLL,EGLM,5130.02,N,00046.34,W,004.6,213.9,122.9,A*3D'
```

Specify the output argument for the RMB sentence to extract the data.

```
[rmcdata,rmbData] =  pnmea(rawNMEAData)
```

```
rmcdata = struct with fields:
             TalkerID: "GN"
            MessageID: "RMC"
            FixStatus: 'A'
             Latitude: 51.1167
            Longitude: -114.0388
          GroundSpeed: 0.0185
      TrueCourseAngle: 348.3000
          UTCDateTime: 21-Mar-2007 14:39:09.000
    MagneticVariation: 0
        ModeIndicator: 'A'
     NavigationStatus: "NA"
               Status: 0


rmbData = struct with fields:
                        TalkerID: "GP"
                       MessageID: "RMB"
                      DataStatus: 'A'
                 CrossTrackError: 4.0800
                DirectionToSteer: NaN
                OriginWaypointID: NaN
           DestinationWaypointID: NaN
     DestinationWaypointLatitude: '5130.02 N'
    DestinationWaypointLongitude: '00046.34 W'
             RangeToDestination: 4.6000
           BearingToDestination: 213.9000
      DestinationClosingVelocity: 122.9000
                   ArrivalStatus: 'A'
                   ModeIndicator: "NA"
                          Status: 0
```

### Extract Data from a Manufacturer-specific Sentence Using CustomSentence Name-Value Pair

**1 Identify Structure of Manufacturer-specific Sentence and Create Function File with Parser Function**

The structure of NMEA sentence to be parsed is available in the specification of the device from the manufacturer. You need to identify the structure and use the information to define the structure of output data to be used in the nmeaParser System object.

For example, the structure of the NMEA sentence from a hardware manufacturer may look like this:

```
$PMMCZ,hhmmss.ss,Latitude,N,Longitude,E,NavSatellite,DR*hh<CR><LF>
```

Here, P denotes that the sentence is manufacturer-specific, MMC is the manufacturer mnemonic code, and Z is the sentence type. Each field thereafter indicates a specific data (position, velocity, time, and so on). Some manufacturers use two characters for the sentence type, followed by the data fields.

After identifying the structure, create the parser function, `parserMMCZ`, using the optional `extractNMEASentence` function, as shown below (you can also use other functions to extract the unparsed data to strings, instead of `extractNMEASentence`).

```
function OutputData = parserMMCZ(unparsedData, MessageID)

  OutputData = struct("MessageID",MessageID,...
  "UTC","NA",...
  "Latitude",NaN,...
  "Longitude",NaN,...
  "NavigationSatellites",NaN,...
  "Status",uint8(1));

  [isValid, splitString] = extractNMEASentence(unparsedData, MessageID);

if(isValid)
    OutputData.MessageID = splitString(1);
    temp = char(splitString(2));
    utcOutput = [temp(1:2), ':', temp(3:4), ':', temp(5:6)];
    OutputData.UTC = utcOutput;
    OutputData.Latitude = str2double(splitString{3});
    OutputData.Longitude = str2double(splitString{5});
    OutputData.NavigationSatellites = str2double(splitString{7});
    OutputData.Status = uint8(0);
  end
end
```

Save `parserMMCZ.m` in the MATLAB path.

**2 Extract Data from Manufacturer-specific Sentence**

Create an `nmeaParser` System Object by using the `CustomSentence` name-value pair and specifying the message ID as "MMCZ" and the function as "parserMMCZ" (created in the previous step).

```
pnmea = nmeaParser("CustomSentence",{["MMCZ","parserMMCZ"]});
```

Provide an MMC sentence obtained from the device as the input and extract data:

```
unparsedMMCLine='$PMMCZ,225444,4917.24,N,00046.34,E,3,DR*7C';
mmcData = pnmea(unparsedMMCLine)

mmcData = 

  struct with fields:

                MessageID: "MMCZ"
                      UTC: '22:54:44'
                 Latitude: 4.9172e+03
                Longitude: 46.3400
    NavigationSatellites: 3
                   Status: 0
```

## More About

### Status Field

The status field displayed along with the extracted values in each output structure can be used to determine the parsing status:

- `Status: 0` — Sentence is valid (checksum validation is successful and the extracted data is as per the requested Message ID)
- `Status: 1` — Checksum of the sentence to be parsed is invalid
- `Status: 2` — The requested sentence is not found in the input data

**Note** If a value is not available in the input sentence, the corresponding output value is displayed as “NA” for string values and "NaN" for numeric values.

### RMC Sentences

| Name of field displayed in the output structure after parsing is complete | Description |
| --- | --- |
| TalkerID | Identify the type of device that transmits data. For example, for a GPS receiver, the TalkerID is `GP`<br><br>Data type: `string` |
| MessageID | Type of NMEA message – `RMC`<br><br>Data type: `string` |
| FixStatus | Possible values:<br>• `A` – Data is valid<br>• `V` – Navigation receiver warning<br><br>Data type: `string` |
| Latitude | Latitude in degrees. North is considered positive.<br><br>Data type: `double` |

| Name of field displayed in the output structure after parsing is complete | Description |
|---|---|
| Longitude | Longitude in degrees. East is considered positive.<br><br>Data type: `double` |
| GroundSpeed | Speed over ground in meters per second (m/s)<br><br>Data type: `double` |
| TrueCourseAngle | Course over ground in degrees.<br><br>Data type: `double` |
| UTCDateTime | UTC date and time<br><br>Data type: `datetime` |
| MagneticVariation | Magnetic variation value. Direction W is considered as negative<br><br>Data type: `double` |
| ModeIndicator | Possible values:<br><br>• `N` – No fix<br>• `E` – Estimated/Dead reckoning fix<br>• `A` – Autonomous GNSS fix<br>• `D` – Differential GNSS fix<br>• `F` – RTK float<br>• `M` – Manual input mode<br>• `P` – Precision mode<br><br>Data type: `string` |
| NavigationStatus | Possible values:<br><br>• `S` – Safe<br>• `C` – Caution<br>• `U` = Unsafe<br>• `V` = Navigational Status not valid<br><br>Data type: `string` |

**GGA Sentences**

| Name of field displayed in the output structure after parsing is complete | Description |
|---|---|
| TalkerID | Identify the type of device that transmits data. For example, for a GPS receiver, the TalkerID is `GP`<br><br>Data type: `string` |

| Name of field displayed in the output structure after parsing is complete | Description |
| --- | --- |
| MessageID | Type of NMEA message – `GGA`<br><br>Data type: `string` |
| UTCTime | UTC Time (`hhmmss.ss`)<br><br>Data type: `datetime` |
| Latitude | Latitude in degrees. North is considered positive.<br><br>Data type: `double` |
| Longitude | Longitude in degrees. East is considered positive.<br><br>Data type: `double` |
| QualityIndicator | Possible values:<br><br>• `0` – No fix<br>• `1` – Fix Valid<br>• `2` – Differential GPS, SPS mode fix<br>• `4` – RTK fix<br>• `5` – RTK float<br>• `6` – Estimated/Dead reckoning fix<br>• `7` – Manual input mode<br>• `8` – Simulator mode<br><br>Data type: `uint8` |
| NumSatellitesInUse | Number of satellites used. This could be different from number of satellites in view.<br><br>Data type: `uint8` |
| HDOP | Horizontal dilution of precision<br><br>Data type: `double` |
| Altitude | Altitude above mean sea level in meters<br><br>Data type: `double` |
| GeoidSeparation | Difference between ellipsoid and mean sea level in meters<br><br>Data type: `double` |
| AgeOfDifferentialData | Age of differential corrections<br><br>Data type: `double` |
| DifferentialReferenceStationID | ID of station providing differential corrections<br><br>Data type: `uint16` |

### GSA Sentences

| Name of field displayed in the output structure after parsing is complete | Description |
|---|---|
| TalkerID | Identify the type of device that transmits data. For example, for a GPS receiver, the TalkerID is `GP`<br><br>Data type: `string` |
| MessageID | Type of NMEA message – `GSA`<br><br>Data type: `string` |
| Mode | Possible values:<br>• `M` – Manually set to operate in 2-D or 3-D mode<br>• `A` – Automatic switching between 2-D or 3-D mode<br><br>Data type: `string` |
| FixType | Possible values:<br>• `1` – No fix<br>• `2` – 2-D fix<br>• `3` – 3-D fix<br><br>Data type: `uint8` |
| SatellitesIDNumber | Satellite numbers (array of 12 bytes). Empty fields will be displayed as `Nan`.<br><br>Data type: `uint8` |
| PDOP | Position dilution of precision<br><br>Data type: `double` |
| VDOP | Vertical dilution of precision<br><br>Data type: `double` |
| HDOP | Horizontal Dilution of Precision<br><br>Data type: `double` |
| SystemID | NMEA defined GNSS System ID<br><br>Data type: `uint8` |

#### GSV Sentences

| Name of field displayed in the output structure after parsing is complete | Description |
| --- | --- |
| TalkerID | Identify the type of device that transmits data. For example, for a GPS receiver, the TalkerID is `GP`<br><br>Data type: `string` |
| MessageID | Type of NMEA message – `GSV`<br><br>Data type: `string` |
| NumSentences | Total number of sentences. The complete satellite information is available in multiple GSV sentences. This field indicates the total number of `gsvData` structures containing the complete information per update.<br><br>Data type: `double` |
| SentenceNumber | Sentence number of the currently parsed GSV line<br><br>Data type: `double` |
| SatellitesInView | Total number of satellites in view<br><br>Data type: `double` |
| SatelliteID | Satellite ID numbers specified as a row vector of size 1-by-N, where N is the number of satellite information available in one sentence. The maximum allowed valued of N is 4.<br><br>Data type: `double` |
| Elevation | Elevation in degrees, specified as a row vector of size 1-by-N, where N is the number of satellite information available in one sentence. The maximum allowed valued of N is 4.<br><br>The maximum value of Elevation is 90 degrees.<br><br>Data type: `double` |
| Azimuth | Azimuth in degrees, specified as a row vector of size 1-by-N, where N is the number of satellite information available in one sentence. The maximum allowed valued of N is 4.<br><br>The range of Azimuth value is [0-359] degrees.<br><br>Data type: `double` |

| Name of field displayed in the output structure after parsing is complete | Description |
| --- | --- |
| SNR | Signal-to-noise ratio in dB-Hz, specified as a row vector of size 1-by-N, where N is the number of satellite information available in one sentence. The maximum allowed valued of N is 4.<br><br>The range of SNR value is [0,99] dB.<br><br>Data type: `double` |
| SignalID | Signal ID corresponding to the SatelliteID.<br><br>This value is displayed only if the sentences conform to NMEA 0183 Standard, Version 4.1. Otherwise, the value displayed is `NaN`.<br><br>Data type: `double` |

The possible values of SignalID and the corresponding Signal Channel are listed in this table.

| System | TalkerID displayed in the parsed data | SatelliteID | SignalID | Signal Channel |
| --- | --- | --- | --- | --- |
| GPS | GP | • 1 – 32 (for GPS)<br>• 33 – 64 (for SBAS) | 0 | All signals |
| | | | 1 | L1 C/A |
| | | | 2 | L1 P (Y) |
| | | | 3 | L1 M |
| | | | 4 | L2 P (Y) |
| | | | 5 | L2C-M |
| | | | 6 | L2C-L |
| | | | 7 | L5-I |
| | | | 8 | L5-Q |
| GLONASS | GL | • 33 – 64 (for SBAS)<br>• 65 – 99 (for GLONASS) | 0 | All signals |
| | | | 1 | G1 C/A |
| | | | 2 | G1 P |
| | | | 3 | G2 C/A |
| | | | 4 | GLONASS (M) G2 P |
| GALILEO | GA | • 1 – 36 (for Galileo satellites)<br>• 37 – 64 (for Galileo SBAS) | 0 | All signals |
| | | | 1 | E5a |
| | | | 2 | E5b |
| | | | 3 | E5a and E5b |
| | | | 4 | E6-A |
| | | | 5 | E6-BC |

| System | TalkerID displayed in the parsed data | SatelliteID | SignalID | Signal Channel |
| --- | --- | --- | --- | --- |
| | | | 6 | L1-A |
| | | | 7 | L1-BC |

**ZDA Sentences**

| Name of field displayed in the output structure after parsing is complete | Description |
| --- | --- |
| TalkerID | Identify the type of device that transmits data. For example, for a GPS receiver, the TalkerID is `GP`<br><br>Data type: `string` |
| MessageID | Type of NMEA message – `ZDA`<br><br>Data type: `string` |
| UTCTime | UTC Time<br><br>Data type: `datetime` |
| UTCDay | UTC Day<br><br>Data type: `uint8` |
| UTCMonth | UTC Month<br><br>Data type: `uint8` |
| UTCYear | UTC Year<br><br>Data type: `uint8` |
| LocalZoneHours | Local zone hours ranging from `00` to `+/-13`<br><br>Data type: `int8` |
| LocalZoneMinutes | Local zone minutes ranging from `00` to `59`<br><br>Data type: `uint8` |

**GLL Sentences**

| Name of field displayed in the output structure after parsing is complete | Description |
| --- | --- |
| TalkerID | Identify the type of device that transmits data. For example, for a GPS receiver, the TalkerID is `GP`<br><br>Data type: `string` |

| Name of field displayed in the output structure after parsing is complete | Description |
|---|---|
| MessageID | Type of NMEA message – `GLL`<br><br>Data type: `string` |
| Latitude | Latitude in degrees. North is considered positive.<br><br>Data type: `double` |
| Longitude | Longitude in degrees. East is considered positive.<br><br>Data type: `double` |
| UTCTime | UTC Time<br><br>Data type: `datetime` |
| DataValidity | Data validity status:<br><br>• `A` – Data valid<br>• `V` – Data invalid<br><br>Data type: `string` |
| PositioningMode | Possible values:<br><br>• `N` – Data not Valid<br>• `E` – Estimated/Dead reckoning mode<br>• `A` – Autonomous mode<br>• `D` – Differential mode<br>• `S` – Simulator Mode<br>• `M` – Manual input mode<br><br>Data type: `string` |

**VTG Sentences**

| Name of field displayed in the output structure after parsing is complete | Description |
|---|---|
| TalkerID | Identify the type of device that transmits data. For example, for a GPS receiver, the TalkerID is `GP`<br><br>Data type: `string` |
| MessageID | Type of NMEA message – `VTG`<br><br>Data type: `string` |
| TrueCourseAngle | Course over ground (true) in degrees<br><br>Data type: `double` |

| Name of field displayed in the output structure after parsing is complete | Description |
| --- | --- |
| MagneticCourseAngle | Course over ground (magnetic) in degrees<br><br>Data type: `double` |
| GroundSpeed | Speed over ground in meters per second (m/s)<br><br>Data type: `double` |
| ModeIndicator | Possible values:<br><br>• `N` – No fix<br>• `E` – Estimated/Dead reckoning mode<br>• `A` – Autonomous mode<br>• `D` – Differential mode<br>• `M` – Manual input mode<br>• `N` – Data not valid<br>• `P` – Precise<br>• `S` – Simulator mode<br><br>Data type: `string` |

**GST Sentences**

| Name of field displayed in the output structure after parsing is complete | Description |
| --- | --- |
| TalkerID | Identify the type of device that transmits data. For example, for a GPS receiver, the TalkerID is `GP`<br><br>Data type: `string` |
| MessageID | Type of NMEA message – `GST`<br><br>Data type: `string` |
| UTCTime | UTC Time<br><br>Data type: `datetime` |
| RMSStdDeviationOfRanges | RMS value of the standard deviation of the ranges in meters.<br><br>Data type: `double` |
| StdDeviationSemiMajorAxis | Standard deviation of semi-major axis in meters<br><br>Data type: `double` |
| StdDeviationSemiMinorAxis | Standard deviation of semi-minor axis in meters<br><br>Data type: `double` |

| Name of field displayed in the output structure after parsing is complete | Description |
| --- | --- |
| OrientationSemiMajorAxis | Orientation of semi-major axis, in degrees<br><br>Data type: `double` |
| StdDeviationLatitudeError | Standard deviation of latitude error, in meters<br><br>Data type: `double` |
| StdDeviationLongitudeError | Standard deviation of longitude error in meters<br><br>Data type: `double` |
| StdDeviationAltitudeError | Standard deviation of altitude error in meters<br><br>Data type: `double` |

**HDT Sentences**

| Name of field displayed in the output structure after parsing is complete | Description |
| --- | --- |
| TalkerID | Identify the type of device that transmits data. For example, for a GPS receiver, the TalkerID is `GP`<br><br>Data type: `string` |
| MessageID | Type of NMEA message – `HDT`<br><br>Data type: `string` |
| TrueHeadingAngle | Heading in degrees with respect to true north<br><br>Data type: `double` |

# Version History

**Introduced in R2020b**

## See Also

`skyplot` | `extractNMEASentence`

### Topics

"Plot Position of GNSS Receiver Using Live NMEA Data or NMEA Log File"

# navGraph

Create navGraph object

## Description

The navGraph object is a graph data structure for Navigation Toolbox™ that aids search-based planners.

The navGraph object enables you to create a graph and perform computations on it. The navGraph object supports functionalities that are frequently used by graph search algorithms. You can easily implement Dijkstra, A*, or variants using navGraph.

In graph theory, states represent nodes and links represent edges. The states and links are represented by their corresponding row index in the table. The navGraph is a directed graph that currently supports unique names, with no self-loops in edges.

## Creation

### Syntax

```
graph = navGraph(states,links)
graph = navGraph( ___ ,Name=Value)
graph = navGraph(digraph)
graph = navGraph(stateTable,linkTable)
graph = navGraph( ___ ,Name=Value)
```

#### Description

graph = navGraph(states,links) creates a navGraph object with nodes specified as a matrix of states and edges specified as a matrix of links (or end nodes). The states and links inputs set the values of the States and Links properties, respectively.

graph = navGraph( ___ ,Name=Value) specifies additional parameters using the Name and Weight name-value arguments in addition to the argument from the previous syntax.

graph = navGraph(digraph) creates a navGraph object from the data present in the specified digraph object.

graph = navGraph(stateTable,linkTable) creates a navGraph object with the specified state table and link table, which contain the metadata for the graph. The stateTable and linkTable inputs set the value of the States and Links properties, respectively.

graph = navGraph( ___ ,Name=Value) specifies additional parameters using the LinkWeightFcn name-value argument in addition to the arguments from the previous syntaxes.

#### Input Arguments

**states — State vectors**
matrix

State vectors, specified as a matrix in which each row represents a state vector.

Example: `[9 10 0.42; 10 10 0.92; 7 10 0.65]`

Data Types: `double`

**`links` — Link vectors**
matrix

Link vectors, specified as a matrix in which each row represents a pair of state IDs as a two-element row vector of positive integers.

Example: `[6 1; 7 7; 6 6]`

Data Types: `double`

**`digraph` — Directed graph**
`digraph` object

Directed graph, specified as a `digraph` object. The first column must be `StateVector` in the `digraph` object node table.

**`stateTable` — State table of graph nodes**
table

State table of graph nodes, specified as a table with rows containing variables describing the nodes (states) of the graph. The first column must be `StateVector`, which represents the state vectors of the environment. You can optionally include other metadata columns, such as a `Name` column representing the names of the states.

Example: `table([9 10 0.42; 10 10 0.92; 7 10 0.65],VariableNames={'StateVector'})`

Data Types: `table`

**`linkTable` — Link table of graph edges**
table

Link table of graph edges, specified as a table with rows containing variables describing edges (links) of the graph. The first column must be `EndStates`, which represents the connecting states. You can optionally include other metadata columns, such as a `Weight` column representing the costs of traversing the links.

Example: `table([6 1; 7 7; 6 6],VariableNames={'EndStates'})`

Data Types: `table`

#### Name-Value Pair Arguments

Specify optional pairs of arguments as `Name1=Value1,...,NameN=ValueN`, where `Name` is the argument name and `Value` is the corresponding value. Name-value arguments must appear after other arguments, but the order of the pairs does not matter.

Example: `LinkWeightFcn=@nav.algs.distanceManhattan`

**`Name` — State names**
column vector of characters | column vector of strings | cell array of characters

State names, specified as a column vector of characters, column vector of strings, or cell array of characters. The number of rows must be equal to the number of states, and the value of each row must be unique.

Example: `Name=['A'; 'B'; 'C']`

Example: `Name=["A"; "B"; "C"]`

Example: `Name={'A'; 'B'; 'C'}`

Data Types: `char` | `string` | `cell`

**`Weight` — Link weights**
numeric column vector

Link weights, specified as a numeric column vector. The number of rows must be equal to the number of links.

Example: `Weight=[2.22; 24.41; 42.76]`

Data Types: `single` | `double`

**`LinkWeightFcn` — Link weights function**
`@nav.algs.distanceEuclidean` (default) | `@nav.algs.distanceManhattan` | `@nav.algs.distanceEuclideanSquared` | function handle

Link weights function, specified as a function handle that computes the link weights in the absence of the `Weight` argument. The `LinkWeightFcn` argument sets the value of the LinkWeightFcn property.

The function handle must be one of these types:

1. `COST = @(STATE1,STATE2)fcn`, where `STATE1` and `STATE2` are state vectors.
2. `COST = @(STATEID1,STATEID2,GRAPHOBJ)fcn`, where `STATEID1` and `STATEID2` are state indices.

`STATE1` and `STATEID1` can have a single row or *N* rows, while `STATE2` and `STATEID2` must have *N* rows.

**Note** For best performance, vectorize the function handle.

Example: `LinkWeightFcn=@nav.algs.distanceManhattan`

Data Types: `function_handle`

## Properties

**`States` — State table of graph nodes**
table

This property is read-only.

State table of graph nodes, specified as a table with rows containing variables describing the nodes (states) of the graph. The first column must be `StateVector`, which represents the state vectors of the environment. You can optionally include other metadata columns, such as a `Name` column representing the names of the states.

Data Types: `table`

**`Links` — Link table of graph edges**
table

This property is read-only.

Link table of graph edges, specified as a table with rows containing variables describing edges (links) of the graph. The first column must be `EndStates`, which represents the connecting states. You can optionally include other metadata columns, such as a `Weight` column representing the costs of traversing the links.

Data Types: `table`

**`LinkWeightFcn` — Link weight function**
`@nav.algs.distanceEuclidean` (default) | `@nav.algs.distanceManhattan` | `@nav.algs.distanceEuclideanSquared` | function handle

Link weight function, specified as a function handle that computes the cost of traversing the link.

The function handle must be one of these types:

1. `COST = @(STATE1,STATE2)fcn`, where `STATE1` and `STATE2` are state vectors.
2. `COST = @(STATEID1,STATEID2,GRAPHOBJ)fcn`, where `STATEID1` and `STATEID2` are state indices.

`STATE1` and `STATEID1` can have a single row or *N* rows, while `STATE2` and `STATEID2` must have *N* rows.

**Note** For best performance, vectorize the function handle.

Example: `graph.LinkWeightFcn=@nav.algs.distanceManhattan`

Data Types: `function_handle`

## Object Functions

| | |
|---|---|
| findlink | Find IDs of links |
| findstate | Find IDs of states |
| index2state | Find state vectors of state indices |
| state2index | Find indices for queried state vectors |
| successors | Find successive state indices and costs |
| show | Plot graph representation |
| copy | Create deep copy of navGraph object |

## Examples

### Create `navGraph` Object with State and Link Tables

Load data for states and links.

```
load navGraphData.mat
```

Create state and link tables.

```
stateTable = table(data.states,data.names,data.numLanes, ...
    VariableNames=["StateVector","Name","Lanes"]);
linkTable = table(data.links,data.linkWt,data.curvature, ...
    VariableNames=["EndStates","Weight","Curvature"]);
```

Create a `navGraph` object from the state and link tables.

```
graphObj = navGraph(stateTable,linkTable);
```

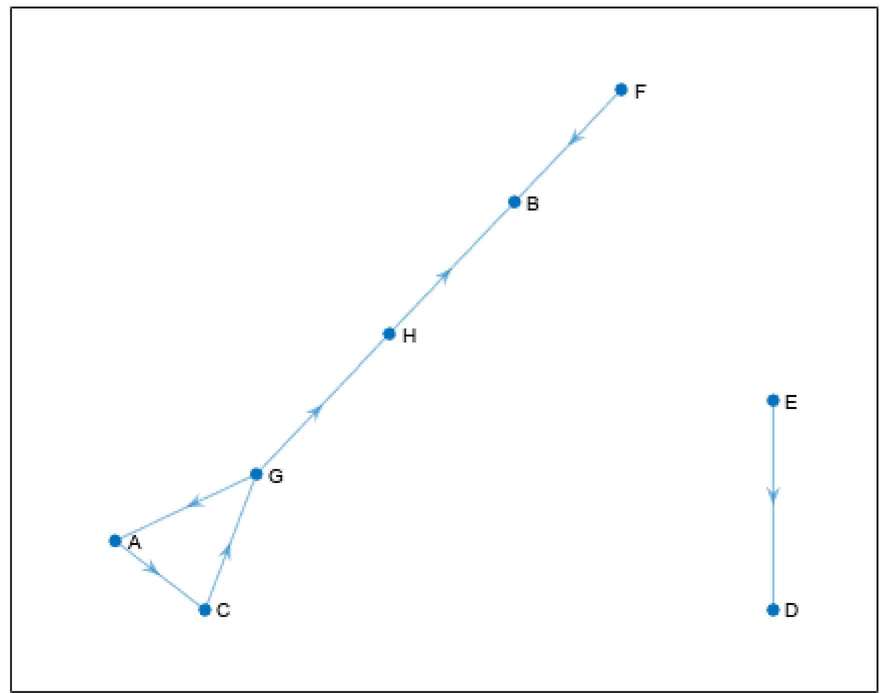
Create a deep copy of the `navGraph` object.

```
graph2 = copy(graphObj)
```

```
graph2 = 
  navGraph with properties:

           States: [8x3 table]
            Links: [7x3 table]
    LinkWeightFcn: @nav.algs.distanceEuclidean
```

Visualize the `navGraph` object.

```
show(graphObj)
```



Find the link IDs of two state pairs. The function returns the link ID for the state pair `["G","A"]`. However, it returns `0` as the link ID for the state pair `["C","D"]` as the link does not exist in the `navGraph` object.

```
linkIDS = findlink(navGraphObj,["G","A"; "C","D"])
```

```
linkIDS = 2×1

     5
     0
```

# Version History

**Introduced in R2023a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

Usage notes and limitations:

- To use LinkWeightFcn in code generation workflow, this property must be set to a function handle during object creation.
- `DynamicMemoryAllocation="off"` is not supported.

## See Also

**Objects**
`plannerAStar` | `digraph`

**Functions**
`findlink` | `findstate` | `index2state` | `state2index` | `successors` | `show` | `copy`

# navPath

Planned path

## Description

The navPath object stores paths that are typically created by geometric path planners. Path points are stored as states in an associated state space.

## Creation

### Syntax

```
path = navPath
path = navPath(space)
path = navPath(space,states)
path = navPath(space,states,maxNumStates)
```

#### Description

path = navPath creates a path object, path, using the SE(2) state space with default settings.

path = navPath(space) creates a path object with state space specified by space. The space input also sets the value of the StateSpace property.

path = navPath(space,states) allows you to initialize the path with state samples given by states. Specify states as a matrix of state samples. States that are outside of the StateBounds of the state space object are reduced to the bounds. The states input also sets the value of the States property.

path = navPath(space,states,maxNumStates) creates a path object with the specified maximum number of states allowed in path maxNumStates. The maxNumStates input also sets the value of the MaxNumStates property.

## Properties

**StateSpace — State space for path**
stateSpaceSE2 (default) | state space object

State space for the path, specified as a state space object. Each state in the path is a sample from the specified state space. You can use objects such as stateSpaceSE2, stateSpaceDubins, stateSpaceReedsShepp, or stateSpaceSE3 as a state space object. You can also customize a state space object using the nav.StateSpace object.

**States — States of path**
zeros(0,StateSpace.NumStateVariables) (default) | real-valued *M*-by-*N* matrix

States of the path, specified as a real-valued *M*-by-*N* matrix. *M* is the number of states in the path, and *N* is the dimension of each state. You can only set this property during object creation or using the `append` function.

Example: `[0 0 0; 1 1 0; 2 2 0]`

Example: `[0 0 0 1 0 0 0; 1 1 1 1 0 0 0; 2 2 1 1 0 0 0]`

Data Types: `double`

**`NumStates` — Number of state samples in path**
0 (default) | nonnegative integer

This property is read-only.

Number of state samples in the path, specified as a nonnegative integer. The number is the same as the number of rows of the state matrix specified in the States property.

Data Types: `double`

**`MaxNumStates` — Maximum number of states allowed in path**
`inf` (default) | positive scalar integer

Maximum number of states allowed in the path, specified as a positive scalar integer.

When specified as `inf`, the path is explicitly resizeable. For code generation, `DynamicMemoryAllocation` must be set to `'On'`.

When specified as a positive scalar integer, the maximum number of states in the object is limited to the specified value. Use this to create a resizeable path when enabling `DynamicMemoryAllocation` is not allowed during code generation.

Data Types: `double`

## Object Functions

| | |
|---|---|
| append | Add states to end of path |
| copy | Create copy of path object |
| interpolate | Interpolate points along path |
| pathLength | Length of path |

## Examples

### Create navPath Based on Multiple Waypoints

Create a `navPath` object based on multiple waypoints in a Dubins space.

```
dubinsSpace = stateSpaceDubins([0 25; 0 25; -pi pi])
```

```
dubinsSpace = 
  stateSpaceDubins with properties:

   SE2 Properties
                 Name: 'SE2 Dubins'
          StateBounds: [3x2 double]
    NumStateVariables: 3
```

```
   Dubins Vehicle Properties
     MinTurningRadius: 1
```

```
pathobj = navPath(dubinsSpace)
```

```
pathobj = 
  navPath with properties:

      StateSpace: [1x1 stateSpaceDubins]
          States: [0x3 double]
       NumStates: 0
    MaxNumStates: Inf
```

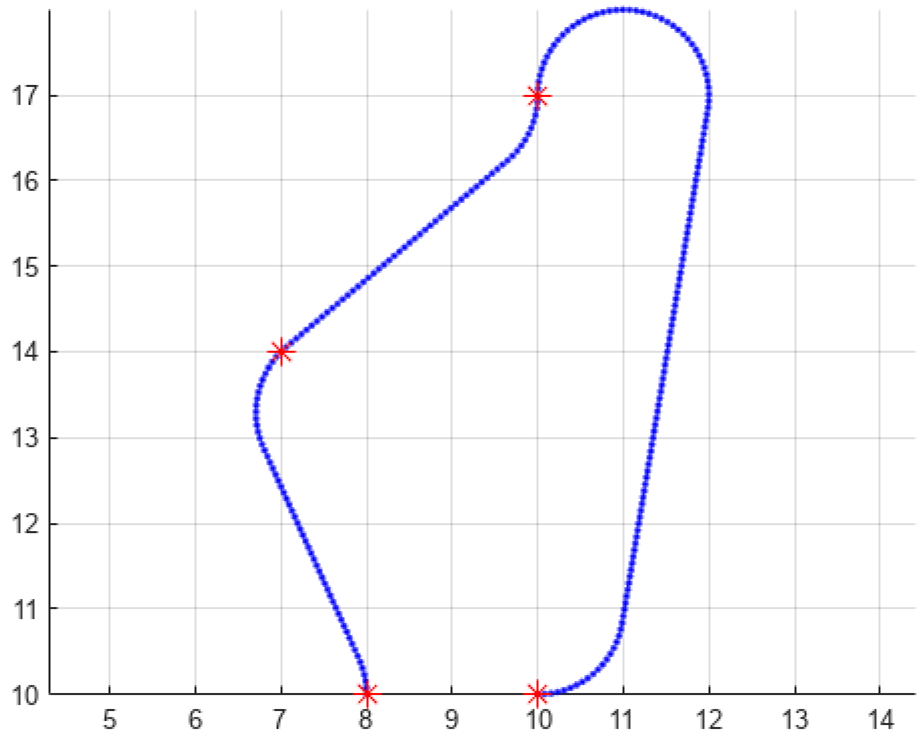
```
waypoints = [8 10 pi/2;
             7 14 pi/4;
             10 17 pi/2;
             10 10 -pi];
append(pathobj,waypoints)
```

Interpolate that path so that it contains exactly 250 points.

```
interpolate(pathobj,250)
```

Visualize the interpolated path and the original waypoints.

```
figure
grid on
axis equal
hold on
plot(pathobj.States(:,1),pathobj.States(:,2),".b")
plot(waypoints(:,1),waypoints(:,2),"*r","MarkerSize",10)
```




Calculate length of path.

```
len = pathLength(pathobj);
disp("Path length = " + num2str(len))
```

```
Path length = 19.4722
```

#### Create `navPath` Based on Multiple Waypoints in SE(3) State Space

Load a 3-D occupancy map of a city block into the workspace. Specify the threshold to consider cells as obstacle-free.

```
mapData = load("dMapCityBlock.mat");
omap = mapData.omap;
omap.FreeThreshold = 0.5;
```

Inflate the occupancy map to add a buffer zone for safe operation around the obstacles.

```
inflate(omap,1)
```

Create an SE(3) state space object with bounds for state variables.

```
ss = stateSpaceSE3([0 220;0 220;0 100;inf inf;inf inf;inf inf;inf inf]);
```

Create a `navPath` object based on multiple waypoints in an SE(3) state space.

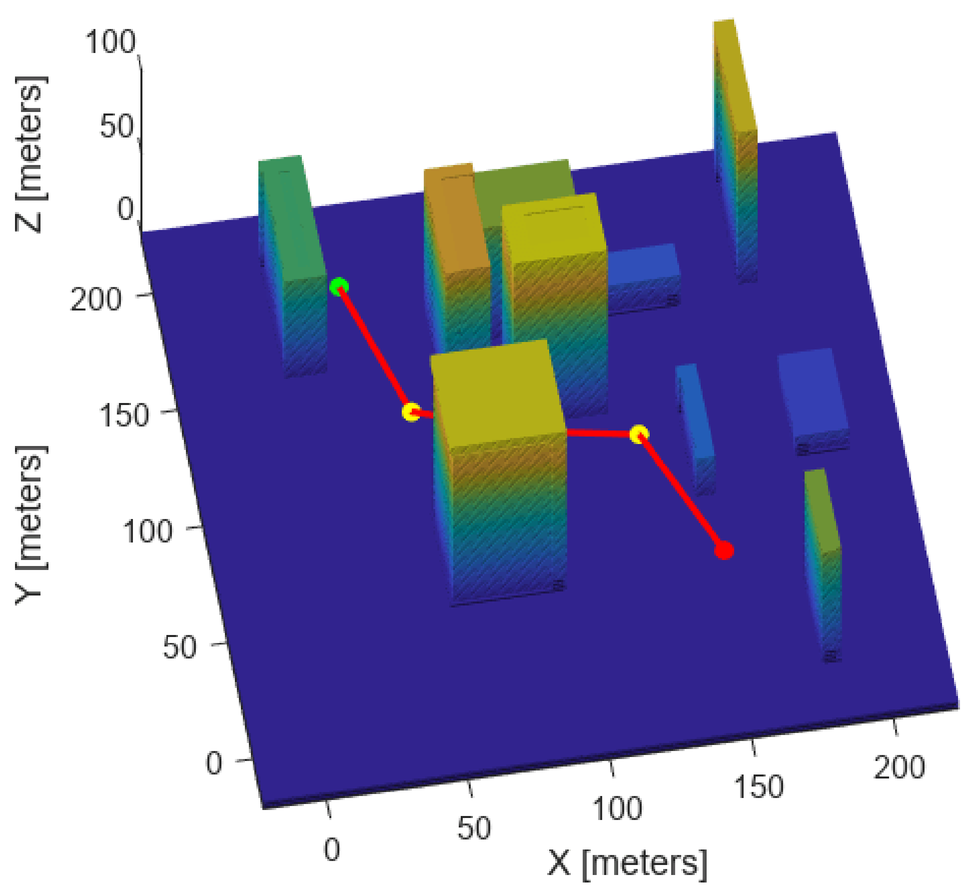
```
path = navPath(ss);
waypoints = [40 180 15 0.7 0.2 0 0.1;
             55 120 20 0.6 0.2 0 0.1;
             100 100 25 0.5 0.2 0 0.1;
             130 90 30 0.4 0 0.1 0.6;
             150 33 35 0.3 0 0.1 0.6];
append(path,waypoints)
```

Interpolate that path so that it contains exactly 250 points.

```
interpolate(path,250)
```

Visualize the interpolated path and the original waypoints.

```
show(omap)
axis equal
view([-10 55])
hold on
% Start state
scatter3(waypoints(1,1),waypoints(1,2),waypoints(1,3),"g","filled")
% Goal state
scatter3(waypoints(end,1),waypoints(end,2),waypoints(end,3),"r","filled")
% Intermediate waypoints
scatter3(waypoints(2:end-1,1),waypoints(2:end-1,2), ...
         waypoints(2:end-1,3),"y","filled")
% Path
plot3(path.States(:,1),path.States(:,2),path.States(:,3), ...
      "r-",LineWidth=2)
```




Calculate length of path.

```
len = pathLength(path);
disp("Path length = " + num2str(len))
```

```
Path length = 204.1797
```

# Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
stateSpaceSE2 | stateSpaceReedsShepp | stateSpaceDubins | stateSpaceSE3 | pathmetrics

**Classes**
nav.StateSpace

**Functions**
append | copy | interpolate | pathLength

# append

Add states to end of path

## Syntax

```
append(path,states)
```

## Description

`append(path,states)` appends the state samples, `states`, to the end of the `path`.

## Examples

### Create navPath Based on Multiple Waypoints

Create a `navPath` object based on multiple waypoints in a Dubins space.

```
dubinsSpace = stateSpaceDubins([0 25; 0 25; -pi pi])
```

```
dubinsSpace = 
  stateSpaceDubins with properties:

   SE2 Properties
                 Name: 'SE2 Dubins'
          StateBounds: [3x2 double]
    NumStateVariables: 3

   Dubins Vehicle Properties
     MinTurningRadius: 1
```

```
pathobj = navPath(dubinsSpace)
```

```
pathobj = 
  navPath with properties:

      StateSpace: [1x1 stateSpaceDubins]
          States: [0x3 double]
       NumStates: 0
    MaxNumStates: Inf
```

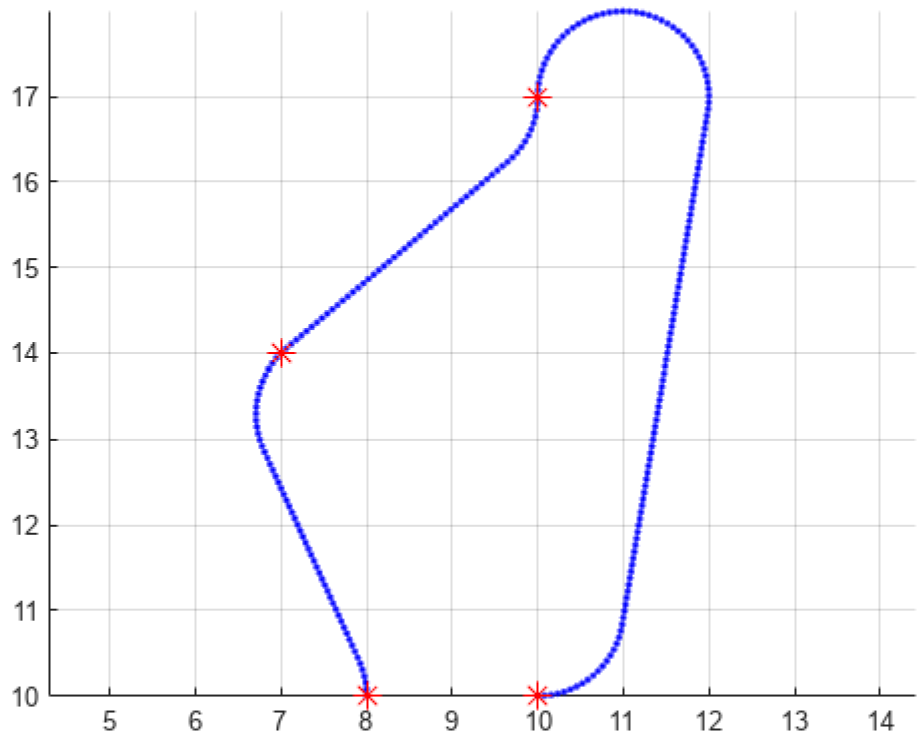
```
waypoints = [8 10 pi/2;
             7 14 pi/4;
             10 17 pi/2;
             10 10 -pi];
append(pathobj,waypoints)
```

Interpolate that path so that it contains exactly 250 points.

```
interpolate(pathobj,250)
```

Visualize the interpolated path and the original waypoints.

```
figure
grid on
axis equal
hold on
plot(pathobj.States(:,1),pathobj.States(:,2),".b")
plot(waypoints(:,1),waypoints(:,2),"*r","MarkerSize",10)
```




Calculate length of path.

```
len = pathLength(pathobj);
disp("Path length = " + num2str(len))
```

```
Path length = 19.4722
```

#### Create navPath Based on Multiple Waypoints in SE(3) State Space

Load a 3-D occupancy map of a city block into the workspace. Specify the threshold to consider cells as obstacle-free.

```
mapData = load("dMapCityBlock.mat");
omap = mapData.omap;
omap.FreeThreshold = 0.5;
```

Inflate the occupancy map to add a buffer zone for safe operation around the obstacles.

```
inflate(omap,1)
```

Create an SE(3) state space object with bounds for state variables.

```
ss = stateSpaceSE3([0 220;0 220;0 100;inf inf;inf inf;inf inf;inf inf]);
```

Create a `navPath` object based on multiple waypoints in an SE(3) state space.

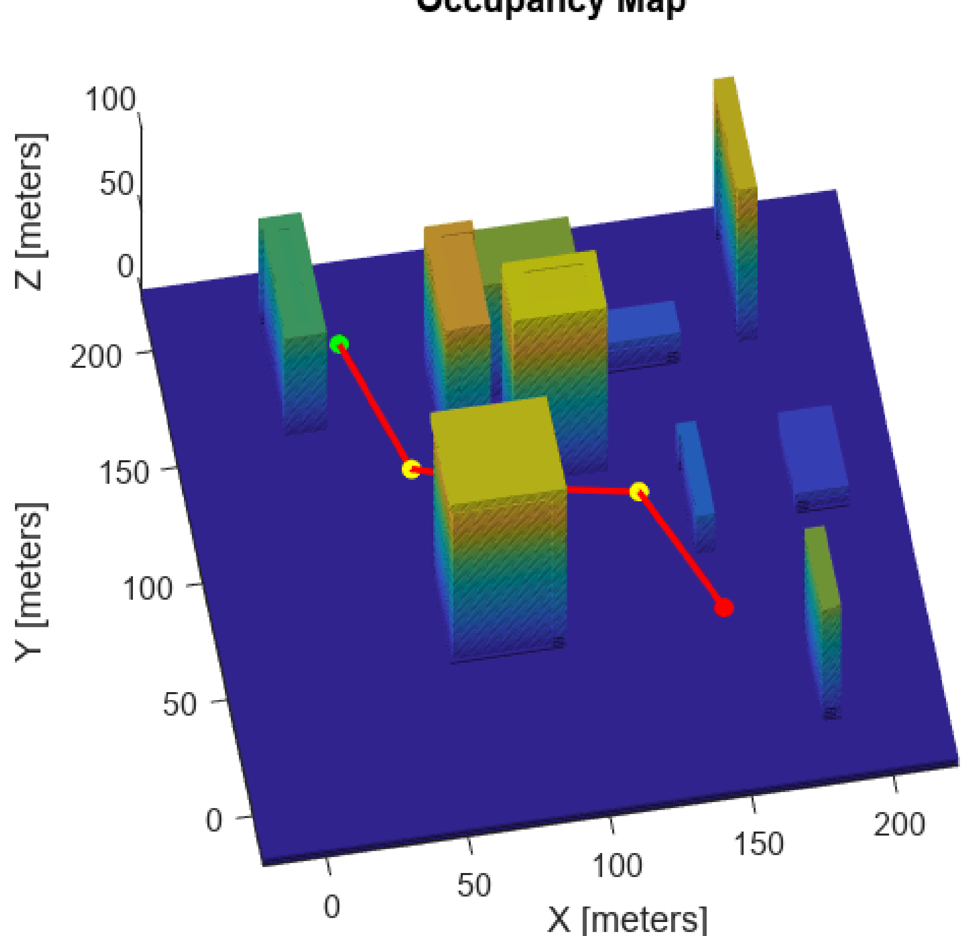
```
path = navPath(ss);
waypoints = [40 180 15 0.7 0.2 0 0.1;
             55 120 20 0.6 0.2 0 0.1;
             100 100 25 0.5 0.2 0 0.1;
             130 90 30 0.4 0 0.1 0.6;
             150 33 35 0.3 0 0.1 0.6];
append(path,waypoints)
```

Interpolate that path so that it contains exactly 250 points.

```
interpolate(path,250)
```

Visualize the interpolated path and the original waypoints.

```
show(omap)
axis equal
view([-10 55])
hold on
% Start state
scatter3(waypoints(1,1),waypoints(1,2),waypoints(1,3),"g","filled")
% Goal state
scatter3(waypoints(end,1),waypoints(end,2),waypoints(end,3),"r","filled")
% Intermediate waypoints
scatter3(waypoints(2:end-1,1),waypoints(2:end-1,2), ...
         waypoints(2:end-1,3),"y","filled")
% Path
plot3(path.States(:,1),path.States(:,2),path.States(:,3), ...
      "r-",LineWidth=2)
```




Calculate length of path.

```
len = pathLength(path);
disp("Path length = " + num2str(len))
```

```
Path length = 204.1797
```

## Input Arguments

**path — path object**
navPath object

Path object, specified as a `navPath` object.

**states — states of path**
real-valued *M*-by-*N* matrix

States of the path, specified as a real-valued *M*-by-*N* matrix. *M* is the number of states appended to the path, and *N* is the dimension of each state. The dimension of each state is governed by the state

space defined in the StateSpace property of `navPath`. States outside of the `StateBounds` of the state space of path are pruned to the bounds.

Example: `[0 0 0; 1 1 0; 2 2 0]`

Example: `[0 0 0 1 0 0 0; 1 1 1 1 0 0 0; 2 2 1 1 0 0 0]`

Data Types: `double`

# Version History

**Introduced in R2019b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
`navPath`

**Functions**
`copy` | `interpolate` | `pathLength`

# interpolate

Interpolate points along path

## Syntax

`interpolate(path,numStates)`

## Description

`interpolate(path,numStates)` inserts a number of states in the path and ensures the distribution of all the points in the path to be uniform. The function preserves all the existing states in the path. The value of `numStates` must be greater than or equal to the number of existing states in the path.

## Examples

### Create navPath Based on Multiple Waypoints

Create a `navPath` object based on multiple waypoints in a Dubins space.

```
dubinsSpace = stateSpaceDubins([0 25; 0 25; -pi pi])
```

```
dubinsSpace = 
  stateSpaceDubins with properties:

   SE2 Properties
                 Name: 'SE2 Dubins'
          StateBounds: [3x2 double]
    NumStateVariables: 3

   Dubins Vehicle Properties
     MinTurningRadius: 1
```

```
pathobj = navPath(dubinsSpace)
```

```
pathobj = 
  navPath with properties:

      StateSpace: [1x1 stateSpaceDubins]
          States: [0x3 double]
       NumStates: 0
    MaxNumStates: Inf
```

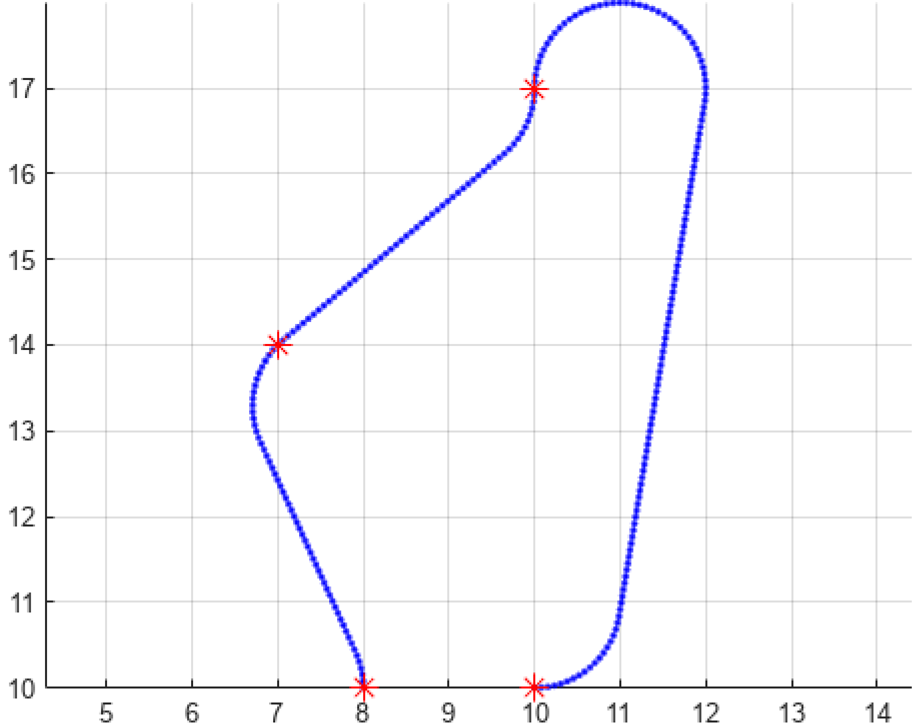
```
waypoints = [8 10 pi/2;
             7 14 pi/4;
             10 17 pi/2;
             10 10 -pi];
append(pathobj,waypoints)
```

Interpolate that path so that it contains exactly 250 points.

```
interpolate(pathobj,250)
```

Visualize the interpolated path and the original waypoints.

```
figure
grid on
axis equal
hold on
plot(pathobj.States(:,1),pathobj.States(:,2),".b")
plot(waypoints(:,1),waypoints(:,2),"*r","MarkerSize",10)
```




Calculate length of path.

```
len = pathLength(pathobj);
disp("Path length = " + num2str(len))
```

```
Path length = 19.4722
```

#### Create navPath Based on Multiple Waypoints in SE(3) State Space

Load a 3-D occupancy map of a city block into the workspace. Specify the threshold to consider cells as obstacle-free.

```
mapData = load("dMapCityBlock.mat");
omap = mapData.omap;
omap.FreeThreshold = 0.5;
```

Inflate the occupancy map to add a buffer zone for safe operation around the obstacles.

```
inflate(omap,1)
```

Create an SE(3) state space object with bounds for state variables.

```
ss = stateSpaceSE3([0 220;0 220;0 100;inf inf;inf inf;inf inf;inf inf]);
```

Create a `navPath` object based on multiple waypoints in an SE(3) state space.

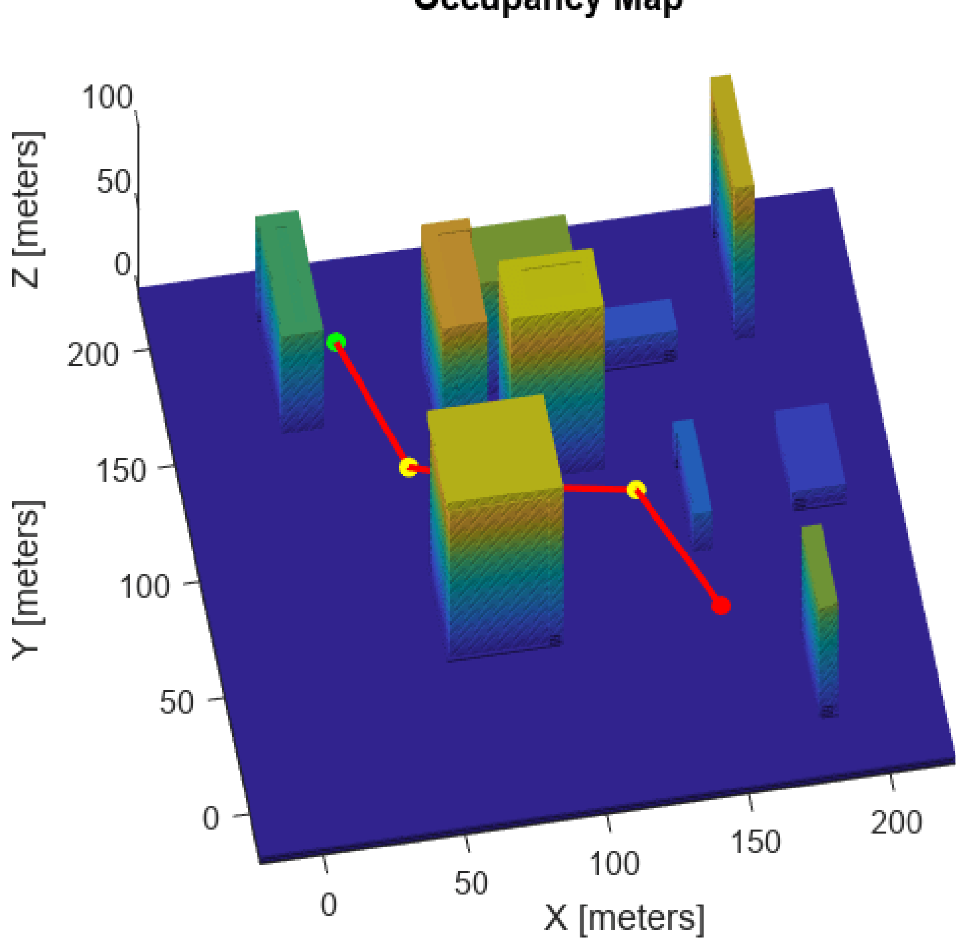
```
path = navPath(ss);
waypoints = [40 180 15 0.7 0.2 0 0.1;
             55 120 20 0.6 0.2 0 0.1;
             100 100 25 0.5 0.2 0 0.1;
             130 90 30 0.4 0 0.1 0.6;
             150 33 35 0.3 0 0.1 0.6];
append(path,waypoints)
```

Interpolate that path so that it contains exactly 250 points.

```
interpolate(path,250)
```

Visualize the interpolated path and the original waypoints.

```
show(omap)
axis equal
view([-10 55])
hold on
% Start state
scatter3(waypoints(1,1),waypoints(1,2),waypoints(1,3),"g","filled")
% Goal state
scatter3(waypoints(end,1),waypoints(end,2),waypoints(end,3),"r","filled")
% Intermediate waypoints
scatter3(waypoints(2:end-1,1),waypoints(2:end-1,2), ...
         waypoints(2:end-1,3),"y","filled")
% Path
plot3(path.States(:,1),path.States(:,2),path.States(:,3), ...
      "r-",LineWidth=2)
```




Calculate length of path.

```
len = pathLength(path);
disp("Path length = " + num2str(len))
```

```
Path length = 204.1797
```

## Input Arguments

**path — Path object**
navpath object

Path object, specified as a navPath object.

**numStates — Number of states**
nonnegative integer

Number of states inserted in the path, specified as a nonnegative integer. Its value must be greater than or equal to the number of existing states in the path.

Data Types: `double`

# Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Objects

`navPath`

### Functions

`append` | `copy` | `pathLength`

# pathLength

Length of path

## Syntax

`len = pathLength(path)`

## Description

`len = pathLength(path)` returns the total length of path by summing the distances between every sequential pair of states in the path. The function uses the state space object associated with `path` to calculate the distance between each state pair.

## Examples

### Create navPath Based on Multiple Waypoints

Create a `navPath` object based on multiple waypoints in a Dubins space.

```
dubinsSpace = stateSpaceDubins([0 25; 0 25; -pi pi])
```

```
dubinsSpace = 
  stateSpaceDubins with properties:

   SE2 Properties
                 Name: 'SE2 Dubins'
          StateBounds: [3x2 double]
    NumStateVariables: 3

   Dubins Vehicle Properties
     MinTurningRadius: 1
```

```
pathobj = navPath(dubinsSpace)
```

```
pathobj = 
  navPath with properties:

      StateSpace: [1x1 stateSpaceDubins]
          States: [0x3 double]
       NumStates: 0
    MaxNumStates: Inf
```

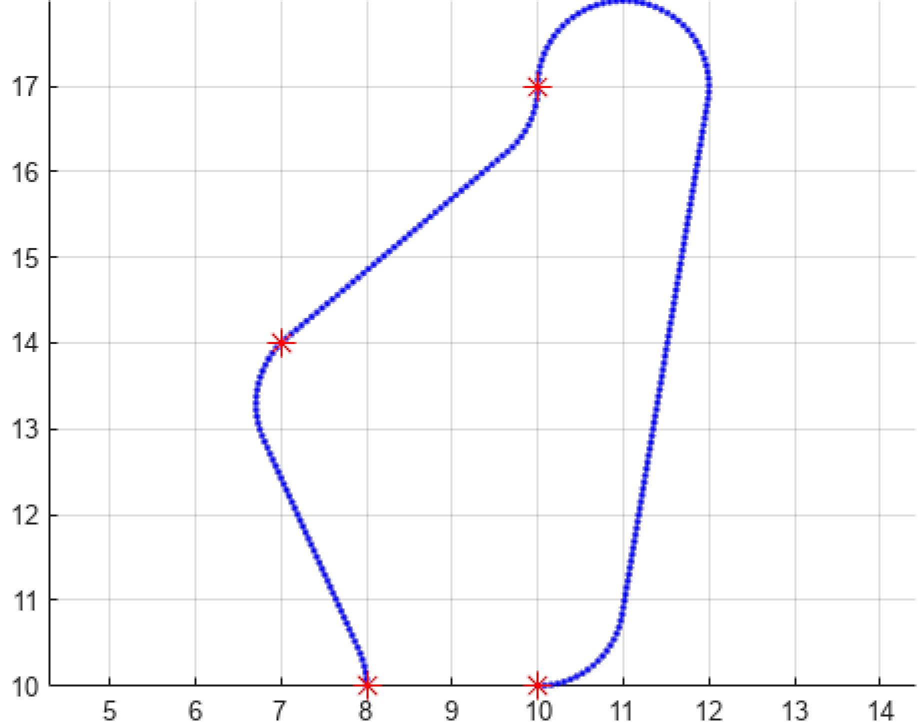
```
waypoints = [8 10 pi/2;
             7 14 pi/4;
             10 17 pi/2;
             10 10 -pi];
append(pathobj,waypoints)
```

Interpolate that path so that it contains exactly 250 points.

```
interpolate(pathobj,250)
```

Visualize the interpolated path and the original waypoints.

```
figure
grid on
axis equal
hold on
plot(pathobj.States(:,1),pathobj.States(:,2),".b")
plot(waypoints(:,1),waypoints(:,2),"*r","MarkerSize",10)
```




Calculate length of path.

```
len = pathLength(pathobj);
disp("Path length = " + num2str(len))
```

```
Path length = 19.4722
```

### Create navPath Based on Multiple Waypoints in SE(3) State Space

Load a 3-D occupancy map of a city block into the workspace. Specify the threshold to consider cells as obstacle-free.

```
mapData = load("dMapCityBlock.mat");
omap = mapData.omap;
omap.FreeThreshold = 0.5;
```

Inflate the occupancy map to add a buffer zone for safe operation around the obstacles.

```
inflate(omap,1)
```

Create an SE(3) state space object with bounds for state variables.

```
ss = stateSpaceSE3([0 220;0 220;0 100;inf inf;inf inf;inf inf;inf inf]);
```

Create a `navPath` object based on multiple waypoints in an SE(3) state space.

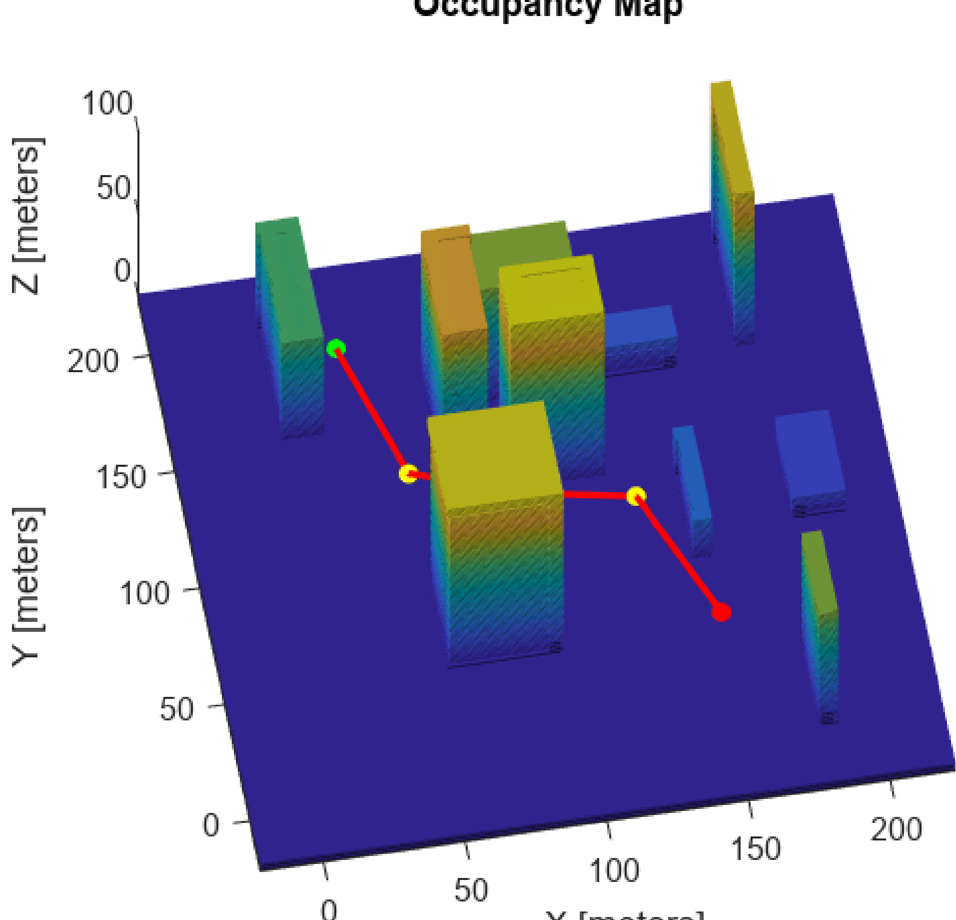
```
path = navPath(ss);
waypoints = [40 180 15 0.7 0.2 0 0.1;
             55 120 20 0.6 0.2 0 0.1;
             100 100 25 0.5 0.2 0 0.1;
             130 90 30 0.4 0 0.1 0.6;
             150 33 35 0.3 0 0.1 0.6];
append(path,waypoints)
```

Interpolate that path so that it contains exactly 250 points.

```
interpolate(path,250)
```

Visualize the interpolated path and the original waypoints.

```
show(omap)
axis equal
view([-10 55])
hold on
% Start state
scatter3(waypoints(1,1),waypoints(1,2),waypoints(1,3),"g","filled")
% Goal state
scatter3(waypoints(end,1),waypoints(end,2),waypoints(end,3),"r","filled")
% Intermediate waypoints
scatter3(waypoints(2:end-1,1),waypoints(2:end-1,2), ...
         waypoints(2:end-1,3),"y","filled")
% Path
plot3(path.States(:,1),path.States(:,2),path.States(:,3), ...
      "r-",LineWidth=2)
```




Calculate length of path.

```
len = pathLength(path);
disp("Path length = " + num2str(len))
```

```
Path length = 204.1797
```

## Input Arguments

**path — Path object**
navpath object

Path object, specified as a `navPath` object.

## Output Arguments

**len — Length of path**
nonnegative scalar

Length of the path, returned as a nonnegative scalar in meters.

Data Types: `double`

# Version History

**Introduced in R2019b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
`navPath`

**Functions**
`append` | `copy` | `interpolate`

# navPathControl

Path representing control-based kinematic trajectory

## Description

The `navPathControl` object stores paths that are typically created by control-based path planners like the `plannerControlRRT` object. The `navPathControl` object represents paths as a sequence of states, controls, durations, and targets. This object associates each path with a specific state propagator, which propagates the control commands to determine the resulting states.

This object specifies states and targets in the path in the state space of propagator. Controls are outputs from a controller that are used to update your systems state during propagation. This object applies each control for an associated duration. Controls can be reference signals or direct inputs to an integrator depending on your system design.

## Creation

### Syntax

```
pathObj = navPathControl(propagator)
pathObj = navPathControl(propagator,states,controls,targets,durations)
```

#### Description

`pathObj = navPathControl(propagator)` creates a path object with the specified state propagator. The `propagator` argument specifies the `StatePropagator`

`pathObj = navPathControl(propagator,states,controls,targets,durations)` initializes the path with a sequence of specified states, controls, targets, and durations. The input states must have one more row than the other input vectors and matrices.

### Properties

**`StatePropagator` — State propagator**
object of subclass of `nav.StatePropagator`

State propagator, specified as an object of a subclass of `nav.StatePropagator`. For example, the `mobileRobotPropagator` object represents the state space and kinematic control behavior for different mobile robot vehicle models.

Data Types: `double`

**`States` — Series of states for path**
`[]` (default) | *n*-by-*m* matrix

Series of states for the path, specified as an *n*-by-*m* matrix. *n* is the number of points in the path. *m* is the dimension of the state vector.

You can specify this property at object creation by using the `states` argument.

Data Types: `double`

**`Controls` — Control input for each state**
`[ ]` (default) | *(n–1)*-by-*m* matrix

Control input for each state, specified as an *(n–1)*-by-*m* matrix. *n* is the number of points in the path. *m* is the dimension of the state vector.

You can specify this property at object creation by using the `controls` argument.

Data Types: `double`

**`TargetStates` — Target state for each state in path**
`[ ]` (default) | *(n–1)*-by-*m* matrix

Target state for each state in the path, specified as an *(n–1)*-by-*m* matrix. *n* is the number of points in the path. *m* is the dimension of the state vector.

You can specify this property at object creation by using the `targets` argument.

Data Types: `double`

**`Durations` — Duration of each control input**
`[ ]` (default) | *(n–1)*-element vector in seconds

Duration of each control input, specified as an *(n–1)*-element vector in seconds. *n* is the number of points in the path.

You can specify this property at object creation by using the `durations` argument.

Data Types: `double`

**`NumStates` — Number of states in path**
`0` (default) | nonnegative integer

Number of states in the path, specified as a positive integer.

Data Types: `double`

**`NumSegments` — Number of segments between states**
`0` (default) | nonnegative integer

Number of segments between states in the path, specified as a positive integer, which must be one less than the number of states.

Data Types: `double`

## Object Functions

| | |
|---|---|
| append | Add states to end of path |
| interpolate | Interpolate path based on propagator step size |
| pathDuration | Total elapsed duration of control path |

## Examples

### Plan Kinodynamic Path with Controls for Mobile Robot

Plan control paths for a bicycle kinematic model with the `mobileRobotPropagator` object. Specify a map for the environment, set state bounds, and define a start and goal location. Plan a path using the control-based RRT algorithm, which uses a state propagator for planning motion and the required control commands.

#### Set State and State Propagator Parameters

Load a ternary map matrix and create an `occupancyMap` object. Create the state propagator using the map. By default, the state propagator uses a bicycle kinematic model.

```
load('exampleMaps','ternaryMap')
map = occupancyMap(ternaryMap,10);

propagator = mobileRobotPropagator(Environment=map); % Bicycle model
```

Set the state bounds on the state space based on the map world limits.

```
propagator.StateSpace.StateBounds(1:2,:) = ...
                    [map.XWorldLimits; map.YWorldLimits];
```

#### Plan Path

Create the path planner from the state propagator.

```
planner = plannerControlRRT(propagator);
```

Specify the start and goal states.

```
start = [10 15 0];
goal  = [40 30 0];
```

Plan a path between the states. For repeatable results, reset the random number generator before planning. The `plan` function outputs a `navPathControl` object, which contains the states, control commands, and durations.

```
rng("default")
path = plan(planner,start,goal)
```

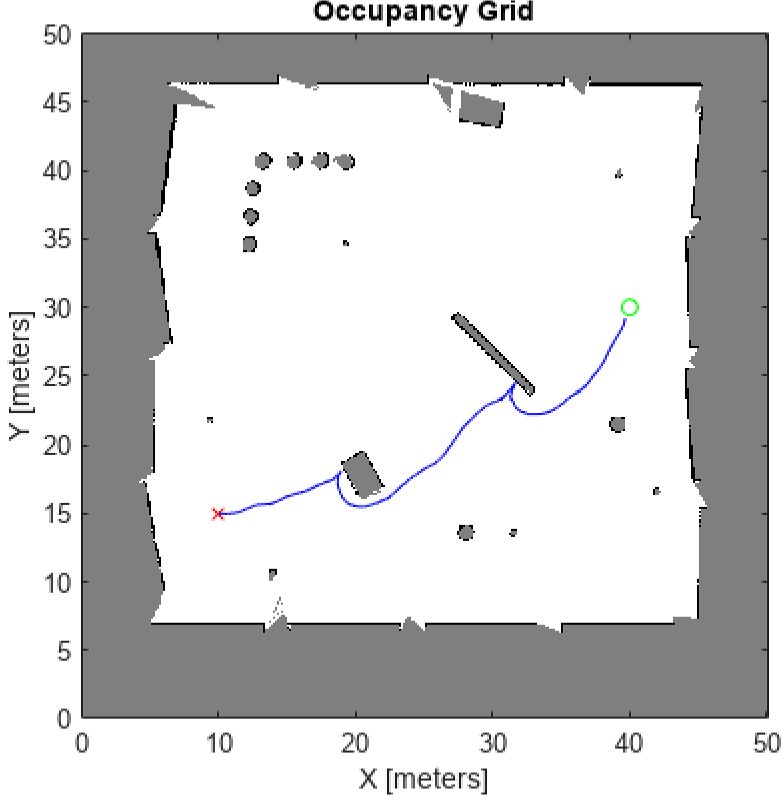
```
path = 
  navPathControl with properties:

    StatePropagator: [1x1 mobileRobotPropagator]
             States: [192x3 double]
           Controls: [191x2 double]
          Durations: [191x1 double]
       TargetStates: [191x3 double]
          NumStates: 192
        NumSegments: 191
```

#### Visualize Results

Visualize the map and plot the path states.

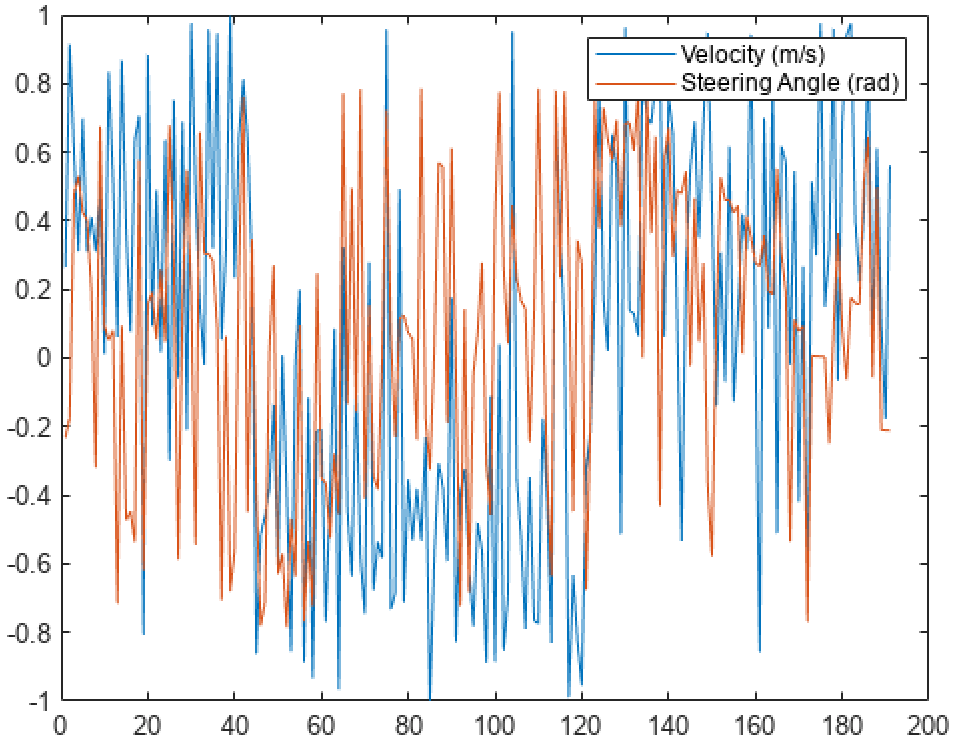
```
show(map)
hold on
```

```
plot(start(1),start(2),"rx")
plot(goal(1),goal(2),"go")
plot(path.States(:,1),path.States(:,2),"b")
hold off
```




Display the `[v psi]` control inputs of forward velocity and steering angle.

```
plot(path.Controls)
ylim([-1 1])
legend(["Velocity (m/s)","Steering Angle (rad)"])
```




# Version History

**Introduced in R2021b**

## See Also

**Objects**
`navPath` | `mobileRobotPropagator`

**Functions**
`append` | `interpolate` | `pathDuration`

# append

Add states to end of path

## Syntax

```
append(pathObj,states,controls,targets,durations)
```

## Description

`append(pathObj,states,controls,targets,durations)` adds a sequence of states `states`, controls `controls`, targets `targets`, and durations `durations`, to the end of the path. If the path is empty, the `states` input must have one more row than the other input vectors and matrices. If the path contains points already, the function applies the first control to the last state in the current path.

## Input Arguments

**`pathObj` — Control path**
`navControlPath`

Control path, specified as a `navPathControl` object.

Data Types: `double`

**`states` — Series of states for path**
*n*-by-*m* matrix

Series of states for the path, specified as an *n*-by-*m* matrix. *n* is the number of points to add to the path. *m* is the dimension of the state vector.

**Note** If the path object is empty, the `states` input should be an *(n+1)*-by-*m* matrix.

Data Types: `double`

**`controls` — Control input for each state**
*n*-by-*m* matrix

Control input for each state, specified as an *n*-by-*m* matrix. *n* is the number of points to add to the path. *m* is the dimension of the state vector.

Data Types: `double`

**`targets` — Target state for each state in path**
*n*-element vector in seconds

Target state for each state in the path,specified as an *n*-by-*m* matrix. *n* is the number of points to add to the path. *m* is the dimension of the state vector.

Data Types: `double`

**`durations` — Duration of each control input**
*n*-element vector in seconds

Duration of each control input, specified as an *n*-element vector in seconds. *n* is the number of points to add to the path.

Data Types: `double`

# Version History

**Introduced in R2021b**

## See Also

**Objects**
`navPathControl` | `navPath` | `mobileRobotPropagator`

**Functions**
`interpolate` | `pathDuration`

# interpolate

Interpolate path based on propagator step size

## Syntax

```
interpolate(pathObj)
```

## Description

`interpolate(pathObj)` evaluates the path based on the `ControlStepSize` property of `pathObj`, and adds all intermediate points to the path.

## Examples

### Create navPath Based on Multiple Waypoints

Create a `navPath` object based on multiple waypoints in a Dubins space.

```
dubinsSpace = stateSpaceDubins([0 25; 0 25; -pi pi])
```

```
dubinsSpace = 
  stateSpaceDubins with properties:

   SE2 Properties
                 Name: 'SE2 Dubins'
          StateBounds: [3x2 double]
    NumStateVariables: 3

   Dubins Vehicle Properties
     MinTurningRadius: 1
```

```
pathobj = navPath(dubinsSpace)
```

```
pathobj = 
  navPath with properties:

      StateSpace: [1x1 stateSpaceDubins]
          States: [0x3 double]
       NumStates: 0
    MaxNumStates: Inf
```

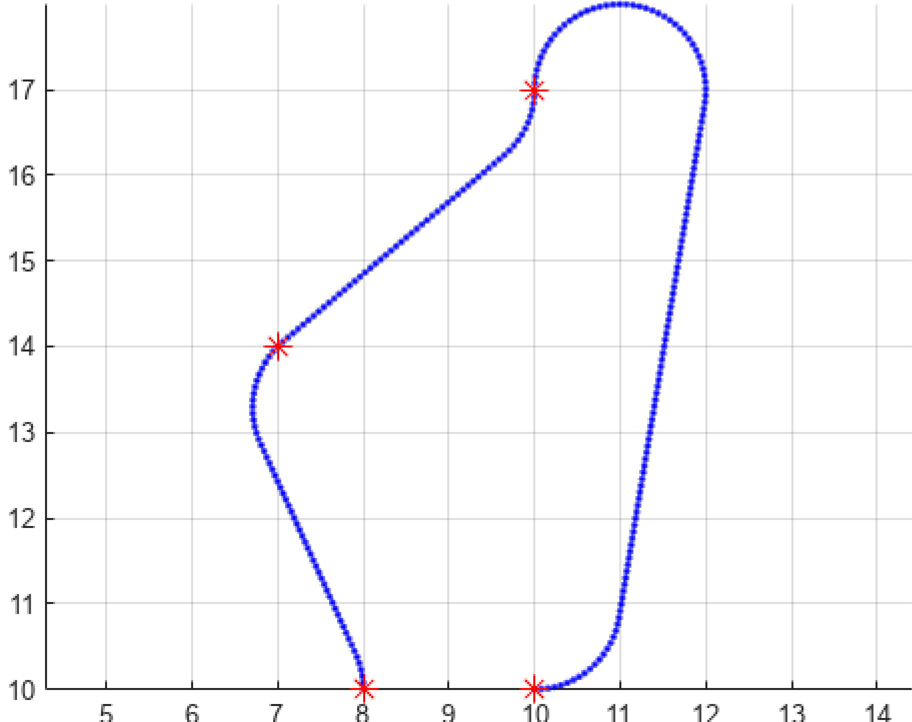
```
waypoints = [8 10 pi/2;
             7 14 pi/4;
             10 17 pi/2;
             10 10 -pi];
append(pathobj,waypoints)
```

Interpolate that path so that it contains exactly 250 points.

```
interpolate(pathobj,250)
```

Visualize the interpolated path and the original waypoints.

```
figure
grid on
axis equal
hold on
plot(pathobj.States(:,1),pathobj.States(:,2),".b")
plot(waypoints(:,1),waypoints(:,2),"*r","MarkerSize",10)
```




Calculate length of path.

```
len = pathLength(pathobj);
disp("Path length = " + num2str(len))
```

```
Path length = 19.4722
```

## Input Arguments

**pathObj — Control path object**
navControlPath object

Control path, specified as a `navPathControl` object.

Data Types: `double`

## Version History

**Introduced in R2021b**

## See Also

**Objects**

navPathControl | navPath | mobileRobotPropagator

**Functions**

append | pathDuration

# pathDuration

Total elapsed duration of control path

## Syntax

`totalTime = pathDuration(pathObj)`

## Description

`totalTime = pathDuration(pathObj)` returns the total elapsed duration of the control path.

## Input Arguments

**`pathObj` — Control path object**
`navControlPath` object

Control path, specified as a `navPathControl` object.

Data Types: `double`

## Output Arguments

**`totalTime` — Total duration of control path**
positive scalar

Total duration of the control path, returned as a positive scalar in seconds.

Data Types: `double`

# Version History

**Introduced in R2021b**

## See Also

**Objects**
`navPathControl` | `navPath` | `mobileRobotPropagator`

**Functions**
`append` | `interpolate`

# nav.StatePropagator class

**Package:** nav

State propagator for control-based planning

## Description

The nav.StatePropagator class is an interface for all state propagators used with the kinodynamic path planners derived from nav.StateSpace. Derive from this class if you are defining a propagator for your custom motion model or control system. For a concrete implementation for mobile robots, see the mobileRobotPropagator object.

This class generates controls, propagates state, and estimates cost or distance between states. Controlled systems utilize two main equations for two steps:

#### Initial Control

- [u(i),steps] = controlFcn(q(i-1),u(i-1),qTgt) generates the next control command from the previous state, control input, and target state.

#### Propagate the System

- q(i) = q(i-1) + integrate(q,u(i),steps) propagates the state q(i-1) using the generated command u(i) for the specified number of steps. The propagator uses a fixed step size, specified by the ControlStepSize property.

The propagateWhileValid method defines the integration and optionally, the control behavior, and also checks whether the generated states are valid within the state space. To skip state validation, use the propagate method.

When creating an instance of class, specify the StateSpace property, which defines the number of state variables, state bounds, and sampling behavior of the propagator. Also, specify the control limits on creation, which determines the value of the NumControlOutput property.

When you change properties, such as the state space, you may need to change the internal behavior of the propagator. To do this, implement the changes in the setup method and call setup(obj) before calling other methods again.

The nav.StatePropagator class is a handle class.

# Creation

## Syntax

```
propagatorObj = nav.StatePropagator(stateSpace,stepSize,numControlOutput)
```

#### Description

propagatorObj = nav.StatePropagator(stateSpace,stepSize,numControlOutput) creates a state propagator object for propagating a kinodynamic system.

## Properties

### Public Properties

**StateSpace — State space for sampling during planning**
object of subclass of nav.StateSpace

State space for sampling during planning, specified as an object of a subclass of `nav.StateSpace`.

The state space is responsible for representing configuration space of a system. The class should include all state information related to the propagated system. Systems employing multi-layer cascade controllers can append persistent low-level control information directly to the state vector, whereas the state propagator directly manages top-level control commands.

**ControlStepSize — Duration of each control command**
0.1 (default) | positive scalar

Duration of each control command, specified as a positive scalar.

### Protected Properties

**NumControlOutput — Number of variables in control command**
positive integer

Number of variables in the control command, specified as a positive integer.

**Attributes:**

| | |
|---|---|
| GetAccess | protected |
| SetAccess | immutable |

## Methods

### Public Methods

| | |
|---|---|
| distance | Estimate cost of propagating to target state |
| propagate | Propagate system without validation |
| propagateWhileValid | Propagate system and return valid motion |
| sampleControl | Generate control command and step count |
| setup | Estimate cost of propagating to target state |

# Version History

**Introduced in R2021b**

## See Also

### Classes
nav.StateSpace | nav.StateValidator

### Objects
stateSpaceSE2 | stateSpaceDubins | stateSpaceReedsShepp | validatorOccupancyMap | validatorVehicleCostmap

# distance

**Class:** `nav.StatePropagator`
**Package:** `nav`

Estimate cost of propagating to target state

## Syntax

```
h = distance(q1,q2)
```

## Description

`h = distance(q1,q2)` estimates the cost of propagating from an initial set of states `q1` to final states `q2`. Each row in `q1` and `q2` represents a specific state in the system and the number of columns matches the number of state variables. The function outputs an *n*-element vector `h` for each `q1`-`q2` pair.

## Input Arguments

**q1 — Initial states**
*n*-by-*s* matrix

Initial states, specified as an *n*-by-*s* matrix.

**q2 — Final states**
*n*-by-*s* matrix

Final states, specified as an *n*-by-*s* matrix.

## Output Arguments

**h — Cost values**
*n*-element vector

Cost values, returned as an *n*-element vector, where *n* is the number of `q1`-`q2` pairs.

Cost values returned by this function are typically used to find the nearest neighbor for sampled target states when planning.

## Attributes

| | |
|---|---|
| `Abstract` | `true` |

To learn about attributes of methods, see Method Attributes.

# Version History

**Introduced in R2021b**

## See Also

**Classes**
nav.StatePropagator | nav.StateSpace | nav.StateValidator

**Functions**
propagate | propagateWhileValid | sampleControl | setup

# propagate

**Class:** `nav.StatePropagator`
**Package:** `nav`

Propagate system without validation

## Syntax

`[q,u,steps] = propagate(spObj,q0,u0,qTgt,maxSteps)`

## Description

`[q,u,steps] = propagate(spObj,q0,u0,qTgt,maxSteps)` iteratively propagates the system from the current state `q0` towards a target state `qTgt` with an initial control input `u0`for a maximum number of steps `maxSteps`. All propagations are validated and the function returns system information between `q0` and the last valid state.

At the end of each propagation step *i*, the system returns:

- `q(i,:)` — Current state of the system
- `u(i,:)` — Control input for step *i+1*
- `steps(i)` — Number of steps between *i-1* and *i*

## Input Arguments

**`spObj` — State propagator object**
handle from child class of `nav.StatePropagator`

State propagator object, specified as a handle from a child class of `nav.StatePropagator`.

**`q0` — Initial state**
*s*-element vector

Initial state of the system, specified as an *s*-element vector, where *s* is the number of state variables in the state space.

**`u0` — Initial control on the initial state**
*c*-element vector

Initial control input, specified as an *c*-element vector, where *c* is the number of control inputs.

**`qTgt` — Target state**
*s*-element vector

Target state of the system, specified as an *s*-element vector, where *s* is the number of state variables in the state space.

**`maxSteps` — Maximum number of steps**
positive scalar

Maximum number of steps, specified as a positive scalar.

## Output Arguments

**q — Propagated states**
*n*-by-*s* matrix

Initial state of the system, specified as an *s*-element vector, where *s* is the number of state variables in the state space.

**u — Control inputs for propagating states**
*n*-by-*c* matrix

Control inputs for propagating states, specified as an *s*-element vector, where *c* is the number of control inputs.

**`steps` — Number of steps between each state and control input**
*n*-element vector of positive integers

Number of steps between each state and control input, specified as an *n*-element vector of positive integers.

## Attributes

| | |
|---|---|
| `Abstract` | `true` |

To learn about attributes of methods, see Method Attributes.

# Version History

**Introduced in R2021b**

## See Also

**Classes**
`nav.StatePropagator` | `nav.StateSpace` | `nav.StateValidator`

**Functions**
`distance` | `propagateWhileValid` | `sampleControl` | `setup`

# propagateWhileValid

**Class:** `nav.StatePropagator`
**Package:** `nav`

Propagate system and return valid motion

## Syntax

`[q,u,steps] = propagateWhileValid(spObj,q0,u0,qTgt,maxSteps)`

## Description

`[q,u,steps] = propagateWhileValid(spObj,q0,u0,qTgt,maxSteps)` iteratively propagates the system from the current state `q0` towards a target state `qTgt` with an initial control input `u0`for a maximum number of steps `maxSteps`. All propagations are validated and the function returns system information between `q0` and the last valid state.

At the end of each propagation step *i*, the system returns:

- `q(i,:)` — Current state of the system
- `u(i,:)` — Control input for step *i+1*
- `steps(i)` — Number of steps between *i-1* and *i*

## Input Arguments

**`spObj` — State propagator object**
handle from child class of `nav.StatePropagator`

State propagator object, specified as a handle from a child class of `nav.StatePropagator`.

**`q0` — Initial state**
*s*-element vector

Initial state of the system, specified as an *s*-element vector, where *s* is the number of state variables in the state space.

**`u0` — Initial control on the initial state**
*c*-element vector

Initial control input, specified as an *c*-element vector, where *c* is the number of control inputs.

**`qTgt` — Target state**
*s*-element vector

Target state of the system, specified as an *s*-element vector, where *s* is the number of state variables in the state space.

**`maxSteps` — Maximum number of steps**
positive scalar

Maximum number of steps, specified as a positive scalar.

## Output Arguments

**q — Propagated states**
*n*-by-*s* matrix

Initial state of the system, specified as an *s*-element vector, where *s* is the number of state variables in the state space.

**u — Control inputs for propagating states**
*n*-by-*c* matrix

Control inputs for propagating states, specified as an *s*-element vector, where *c* is the number of control inputs.

**`steps` — Number of steps between each state and control input**
*n*-element vector of positive integers

Number of steps between each state and control input, specified as an *n*-element vector of positive integers.

## Attributes

| | |
|---|---|
| `Abstract` | `true` |

To learn about attributes of methods, see Method Attributes.

# Version History

**Introduced in R2021b**

## See Also

**Classes**
`nav.StatePropagator` | `nav.StateSpace` | `nav.StateValidator`

**Functions**
`distance` | `propagate` | `sampleControl` | `setup`

# sampleControl

**Class:** `nav.StatePropagator`
**Package:** `nav`

Generate control command and step count

## Syntax

`[u,steps] = sampleControl(spObj,q0,u0,qTgt)`

## Description

`[u,steps] = sampleControl(spObj,q0,u0,qTgt)` generates a series of control commands and number of steps to move from the current state `q0` with control command `u0` towards the target state `qTgt`

## Input Arguments

### `spObj` — State propagator object
handle from child class of `nav.StatePropagator`

State propagator object, specified as a handle from a child class of `nav.StatePropagator`.

### `q0` — Initial state
*s*-element vector

Initial state of the system, specified as an *s*-element vector, where *s* is the number of state variables in the state space.

### `u0` — Initial control on the initial state
*c*-element vector

Initial control input, specified as an *c*-element vector, where *c* is the number of control inputs.

### `qTgt` — Target state
*s*-element vector

Target state of the system, specified as an *s*-element vector, where *s* is the number of state variables in the state space.

## Output Arguments

### `u` — Control inputs for propagating states
*n*-by-*c* matrix

Control inputs for propagating states, specified as an *s*-element vector, where *c* is the number of control inputs.

### `steps` — Number of steps between each state and control input
*n*-element vector of positive integers

Number of steps between each state and control input, specified as an *n*-element vector of positive integers.

## Attributes

| Abstract | true |
| --- | --- |

To learn about attributes of methods, see Method Attributes.

# Version History

**Introduced in R2021b**

## See Also

**Classes**
nav.StatePropagator | nav.StateSpace | nav.StateValidator

**Functions**
distance | propagate | propagateWhileValid | setup

# setup

**Class:** nav.StatePropagator
**Package:** nav

Estimate cost of propagating to target state

## Syntax

```
setup(mobileProp)
```

## Description

setup(mobileProp) sets up the nav.StatePropagator object based on the specified parameters. If you change properties on the object, call this method before you sample controls, propagate the system, or calculate distances.

## Input Arguments

**spObj — State propagator object**
handle from child class of nav.StatePropagator

State propagator object, specified as a handle from a child class of nav.StatePropagator.

# Version History

**Introduced in R2021b**

## See Also

**Classes**
nav.StatePropagator | nav.StateSpace | nav.StateValidator

**Functions**
distance | propagate | propagateWhileValid | sampleControl

# nav.StateSpace class

**Package:** nav

Create state space for path planning

## Description

The nav.StateSpace class is an interface for state spaces used for path planning. Derive from this class if you want to define your own state space. This representation allows for sampling, interpolation, and calculating distances between spaces in the state space.

To create a sample template for generating your own state space class, call `createPlanningTemplate`. For specific implementations of the state validator class for general application, see **State Spaces** in “Motion Planning”.

The `nav.StateSpace` class is a `handle` class.

### Class Attributes

| | |
|---|---|
| `Abstract` | `true` |

For information on class attributes, see “Class Attributes”.

# Creation

## Syntax

`ssObj = nav.StateSpace(Name,NumStateVariables,StateBounds)`

### Description

`ssObj = nav.StateSpace(Name,NumStateVariables,StateBounds)` creates a state space object with a given name, number of state variables, and state bounds. This constructor can only be called from a derived class. Create your own class definition using `createPlanningTemplate`.

## Properties

### Public Properties

**`NumStateVariables` — Number of variables in state space**
positive numeric scalar

Number of variables in the state space, specified as a positive numeric scalar. This property is the dimension of the state space.

Example: 3

**Attributes:**

| | |
|---|---|
| SetAccess | immutable |

**StateBounds — Minimum and maximum bounds of state variables**
[min max] | *n*-by-2 matrix

Minimum and maximum bounds of state variables, specified as a [min max] *n*-by-2 matrix. This property depends on NumStateVariables, where *n* is the number of state variables. When specifying on construction, use the Bounds input.

Example: [-10 10; -10 10; -pi pi]

**Attributes:**

| | |
|---|---|
| GetAccess | public |
| SetAccess | protected |
| Dependent | true |

Data Types: double

**Protected Properties**

**Name — Name of state space object**
string scalar | character vector

Name of the state space object, specified as a string scalar or character vector.

Example: "customSE2StateSpace"

**Attributes:**

| | |
|---|---|
| GetAccess | protected |
| SetAccess | protected |

## Methods

**Public Methods**

| | |
|---|---|
| copy | Copy array of handle objects |
| distance | Distance between two states |
| enforceStateBounds | Limit state to state bounds |
| interpolate | Interpolate between states |
| sampleGaussian | Sample state using Gaussian distribution |
| sampleUniform | Sample state using uniform distribution |

## Examples

### Create Custom State Space for Path Planning

This example shows how to use the createPlanningTemplate function to generate a template for customizing your own state space definition and sampler to use with path planning algorithms. A simple implementation is provided with the template.

Call the create template function. This function generates a class definition file for you to modify for your own implementation.

```
createPlanningTemplate
```

### Class and Property Definition

The first part of the template specifies the class definition and any properties for the class. Derive from the `nav.StateSpace` class. For this example, create a property for the uniform and normal distributions. You can specify any additional user-defined properties here.

```
classdef MyCustomStateSpace < nav.StateSpace & ...
        matlabshared.planning.internal.EnforceScalarHandle
     properties
        UniformDistribution
        NormalDistribution
        % Specify additional properties here
end
```

Save your custom state space class and ensure your file name matches the class name.

### Class Constructor

Use the constructor to set the name of the state space, the number of state variables, and define its boundaries. Alternatively, you can add input arguments to the function and pass the variables in when you create an object.

- For each state variable, define the `[min max]` values for the state bounds.
- Call the constructor of the base class.
- For this example, you specify the normal and uniform distribution property values using predefined `NormalDistribution` and `UniformDistribution` classes.
- Specify any other user-defined property values here.

```
methods
    function obj = MyCustomStateSpace
        spaceName = "MyCustomStateSpace";
        numStateVariables = 3;
        stateBounds = [-100 100;  % [min max]
                       -100 100;
                       -100 100];

        obj@nav.StateSpace(spaceName, numStateVariables, stateBounds);

        obj.NormalDistribution = matlabshared.tracking.internal.NormalDistribution(numStateVarial
        obj.UniformDistribution = matlabshared.tracking.internal.UniformDistribution(numStateVar
        % User-defined property values here
    end
```

### Copy Semantics

Specify the `copy` method definition. Copy all the values of your user-defined variables into a new object, so `copyObj` is a deep copy. The default behavior given in this example creates a new copy of the object with the same name, state bounds, and distributions.

```
function copyObj = copy(obj)
    copyObj = feval(class(obj));
    copyObj.StateBounds = obj.StateBounds;
    copyObj.UniformDistribution = obj.UniformDistribution.copy;
    copyObj.NormalDistribution = obj.NormalDistribution.copy;
end
```

#### Enforce State Bounds

Specify how to ensure states are always within the state bounds. For this example, the state values get saturated at the minimum or maximum values for the state bounds.

```
function boundedState = enforceStateBounds(obj, state)
    nav.internal.validation.validateStateMatrix(state, nan, obj.NumStateVariables, "enforceStateB
    boundedState = state;
    boundedState = min(max(boundedState, obj.StateBounds(:,1)'), ...
        obj.StateBounds(:,2)');

end
```

#### Sample Uniformly

Specify the behavior for sampling across a uniform distribution. support multiple syntaxes to constrain the uniform distribution to a nearby state within a certain distance and sample multiple states.

```
STATE = sampleUniform(OBJ)
STATE = sampleUniform(OBJ,NUMSAMPLES)
STATE = sampleUniform(OBJ,NEARSTATE,DIST)
STATE = sampleUniform(OBJ,NEARSTATE,DIST,NUMSAMPLES)
```

For this example, use a validation function to process a `varargin` input that handles the varying input arguments.

```
 function state = sampleUniform(obj, varargin)
    narginchk(1,4);
    [numSamples, stateBounds] = obj.validateSampleUniformInput(varargin{:});

    obj.UniformDistribution.RandomVariableLimits = stateBounds;
    state = obj.UniformDistribution.sample(numSamples);
 end
```

#### Sample from Gaussian Distribution

Specify the behavior for sampling across a Gaussian distribution. Support multiple syntaxes for sampling a single state or multiple states.

```
STATE = sampleGaussian(OBJ, MEANSTATE, STDDEV)
STATE = sampleGaussian(OBJ, MEANSTATE, STDDEV, NUMSAMPLES)


function state = sampleGaussian(obj, meanState, stdDev, varargin)
    narginchk(3,4);

    [meanState, stdDev, numSamples] = obj.validateSampleGaussianInput(meanState, stdDev, varargin

    obj.NormalDistribution.Mean = meanState;
    obj.NormalDistribution.Covariance = diag(stdDev.^2);

    state = obj.NormalDistribution.sample(numSamples);
    state = obj.enforceStateBounds(state);

end
```

#### Interpolate Between States

Define how to interpolate between two states in your state space. Use an input, `fraction`, to determine how to sample along the path between two states. For this example, define a basic linear interpolation method using the difference between states.

```
function interpState = interpolate(obj, state1, state2, fraction)
    narginchk(4,4);
    [state1, state2, fraction] = obj.validateInterpolateInput(state1, state2, fraction);

    stateDiff = state2 - state1;
    interpState = state1 + fraction' * stateDiff;
end
```

#### Calculate Distance Between States

Specify how to calculate the distance between two states in your state space. Use the `state1` and `state2` inputs to define the start and end positions. Both inputs can be a single state (row vector) or multiple states (matrix of row vectors). For this example, calculate the distance based on the Euclidean distance between each pair of state positions.

```
function dist = distance(obj, state1, state2)

    narginchk(3,3);

    nav.internal.validation.validateStateMatrix(state1, nan, obj.NumStateVariables, "distance", "
    nav.internal.validation.validateStateMatrix(state2, size(state1,1), obj.NumStateVariables, "d

    stateDiff = bsxfun(@minus, state2, state1);
    dist = sqrt( sum( stateDiff.^2, 2 ) );
end
```

Terminate the methods and class sections.

```
    end
end
```

Save your state space class definition. You can now use the class constructor to create an object for your state space.

## Version History

**Introduced in R2019b**

## Extended Capabilities

#### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`nav.StateValidator` | `stateSpaceSE2` | `stateSpaceDubins` | `stateSpaceReedsShepp`

# distance

**Class:** `nav.StateSpace`
**Package:** `nav`

Distance between two states

## Syntax

```
dist = distance(ssObj,state1,state2)
```

## Description

`dist = distance(ssObj,state1,state2)` calculates the distance between two states.

## Input Arguments

**`ssObj` — State space object**
object of a subclass of `nav.StateSpace`

State space object, specified as an object of a subclass of `nav.StateSpace`.

**`state1` — Initial state position**
*n*-element vector | *m*-by-*n* matrix of row vectors

Initial state position, specified as a *n*-element vector or *m*-by-*n* matrix of row vectors. *n* is the dimension of the state space specified in the `NumStateVariables` property of `ssObj`. *m* is the number of state positions provided.

If specified as a matrix, `state1` and `state2` should have the same dimensions.

**`state2` — Final state position**
*n*-element vector | *m*-by-*n* matrix of row vectors

Final state position, specified as a *n*-element vector or *m*-by-*n* matrix of row vectors. *n* is the dimension of the state space specified in the `NumStateVariables` property of `ssObj`. *m* is the number of state positions provided.

If specified as a matrix, `state1` and `state2` should have the same dimensions.

## Output Arguments

**`dist` — Distance between two states**
numeric scalar | *m*-element vector

Distance between two states, returned as a numeric scalar or *m*-element vector. This distance calculation is the main component of evaluating costs of paths.

## Examples

### Create Custom State Space for Path Planning

This example shows how to use the `createPlanningTemplate` function to generate a template for customizing your own state space definition and sampler to use with path planning algorithms. A simple implementation is provided with the template.

Call the create template function. This function generates a class definition file for you to modify for your own implementation.

```
createPlanningTemplate
```

#### Class and Property Definition

The first part of the template specifies the class definition and any properties for the class. Derive from the `nav.StateSpace` class. For this example, create a property for the uniform and normal distributions. You can specify any additional user-defined properties here.

```
classdef MyCustomStateSpace < nav.StateSpace & ...
        matlabshared.planning.internal.EnforceScalarHandle
     properties
        UniformDistribution
        NormalDistribution
        % Specify additional properties here
end
```

Save your custom state space class and ensure your file name matches the class name.

#### Class Constructor

Use the constructor to set the name of the state space, the number of state variables, and define its boundaries. Alternatively, you can add input arguments to the function and pass the variables in when you create an object.

- For each state variable, define the `[min max]` values for the state bounds.
- Call the constructor of the base class.
- For this example, you specify the normal and uniform distribution property values using predefined `NormalDistribution` and `UniformDistribution` classes.
- Specify any other user-defined property values here.

```
methods
    function obj = MyCustomStateSpace
        spaceName = "MyCustomStateSpace";
        numStateVariables = 3;
        stateBounds = [-100 100;  % [min max]
                       -100 100;
                       -100 100];

        obj@nav.StateSpace(spaceName, numStateVariables, stateBounds);

        obj.NormalDistribution = matlabshared.tracking.internal.NormalDistribution(numStateVarial
        obj.UniformDistribution = matlabshared.tracking.internal.UniformDistribution(numStateVar
        % User-defined property values here
    end
```

### Copy Semantics

Specify the `copy` method definition. Copy all the values of your user-defined variables into a new object, so `copyObj` is a deep copy. The default behavior given in this example creates a new copy of the object with the same name, state bounds, and distributions.

```
function copyObj = copy(obj)
    copyObj = feval(class(obj));
    copyObj.StateBounds = obj.StateBounds;
    copyObj.UniformDistribution = obj.UniformDistribution.copy;
    copyObj.NormalDistribution = obj.NormalDistribution.copy;
end
```

### Enforce State Bounds

Specify how to ensure states are always within the state bounds. For this example, the state values get saturated at the minimum or maximum values for the state bounds.

```
function boundedState = enforceStateBounds(obj, state)
    nav.internal.validation.validateStateMatrix(state, nan, obj.NumStateVariables, "enforceStateB
    boundedState = state;
    boundedState = min(max(boundedState, obj.StateBounds(:,1)'), ...
        obj.StateBounds(:,2)');

end
```

### Sample Uniformly

Specify the behavior for sampling across a uniform distribution. support multiple syntaxes to constrain the uniform distribution to a nearby state within a certain distance and sample multiple states.

```
STATE = sampleUniform(OBJ)
STATE = sampleUniform(OBJ,NUMSAMPLES)
STATE = sampleUniform(OBJ,NEARSTATE,DIST)
STATE = sampleUniform(OBJ,NEARSTATE,DIST,NUMSAMPLES)
```

For this example, use a validation function to process a `varargin` input that handles the varying input arguments.

```
 function state = sampleUniform(obj, varargin)
    narginchk(1,4);
    [numSamples, stateBounds] = obj.validateSampleUniformInput(varargin{:});

    obj.UniformDistribution.RandomVariableLimits = stateBounds;
    state = obj.UniformDistribution.sample(numSamples);
 end
```

### Sample from Gaussian Distribution

Specify the behavior for sampling across a Gaussian distribution. Support multiple syntaxes for sampling a single state or multiple states.

```
STATE = sampleGaussian(OBJ, MEANSTATE, STDDEV)
STATE = sampleGaussian(OBJ, MEANSTATE, STDDEV, NUMSAMPLES)


function state = sampleGaussian(obj, meanState, stdDev, varargin)
    narginchk(3,4);
```

```
    [meanState, stdDev, numSamples] = obj.validateSampleGaussianInput(meanState, stdDev, varargi

    obj.NormalDistribution.Mean = meanState;
    obj.NormalDistribution.Covariance = diag(stdDev.^2);

    state = obj.NormalDistribution.sample(numSamples);
    state = obj.enforceStateBounds(state);

end
```

#### Interpolate Between States

Define how to interpolate between two states in your state space. Use an input, `fraction`, to determine how to sample along the path between two states. For this example, define a basic linear interpolation method using the difference between states.

```
function interpState = interpolate(obj, state1, state2, fraction)
    narginchk(4,4);
    [state1, state2, fraction] = obj.validateInterpolateInput(state1, state2, fraction);

    stateDiff = state2 - state1;
    interpState = state1 + fraction' * stateDiff;
end
```

#### Calculate Distance Between States

Specify how to calculate the distance between two states in your state space. Use the `state1` and `state2` inputs to define the start and end positions. Both inputs can be a single state (row vector) or multiple states (matrix of row vectors). For this example, calculate the distance based on the Euclidean distance between each pair of state positions.

```
function dist = distance(obj, state1, state2)

    narginchk(3,3);

    nav.internal.validation.validateStateMatrix(state1, nan, obj.NumStateVariables, "distance", '
    nav.internal.validation.validateStateMatrix(state2, size(state1,1), obj.NumStateVariables, "c

    stateDiff = bsxfun(@minus, state2, state1);
    dist = sqrt( sum( stateDiff.^2, 2 ) );
end
```

Terminate the methods and class sections.

```
    end
end
```

Save your state space class definition. You can now use the class constructor to create an object for your state space.

## Version History

**Introduced in R2019b**

## See Also

`nav.StateSpace` | `nav.StateValidator` | `stateSpaceSE2` | `stateSpaceDubins` | `stateSpaceReedsShepp`

# enforceStateBounds

**Class:** `nav.StateSpace`
**Package:** `nav`

Limit state to state bounds

## Syntax

`boundedState = enforceStateBounds(ssObj,state)`

## Description

`boundedState = enforceStateBounds(ssObj,state)` returns a bounded state that lies inside the state bounds based on the given `state`. Use this method to define specific bounding behavior like wrapping angular states. The bounds are specified in the `StateBounds` property of `ssObj`.

## Input Arguments

**`ssObj` — State space object**
object of a subclass of `nav.StateSpace`

State space object, specified as an object of a subclass of `nav.StateSpace`.

**`state` — State position**
*n*-element vector | *m*-by-*n* matrix of row vectors

State position, specified as a *n*-element vector or an *m*-by-*n* matrix of row vectors. *n* is the dimension of the state space specified in the `NumStateVariables` property of `ssObj`.

## Output Arguments

**`boundedState` — State position with enforced state bounds**
*n*-element vector | *m*-by-*n* matrix of row vectors

State position with enforced state bounds, specified as a *n*-element vector or *m*-by-*n* matrix of row vectors. *n* is the dimension of the state space specified in the `NumStateVariables` property of `ssObj`.

## Examples

### Create Custom State Space for Path Planning

This example shows how to use the `createPlanningTemplate` function to generate a template for customizing your own state space definition and sampler to use with path planning algorithms. A simple implementation is provided with the template.

Call the create template function. This function generates a class definition file for you to modify for your own implementation.

```
createPlanningTemplate
```

### Class and Property Definition

The first part of the template specifies the class definition and any properties for the class. Derive from the `nav.StateSpace` class. For this example, create a property for the uniform and normal distributions. You can specify any additional user-defined properties here.

```
classdef MyCustomStateSpace < nav.StateSpace & ...
        matlabshared.planning.internal.EnforceScalarHandle
     properties
        UniformDistribution
        NormalDistribution
        % Specify additional properties here
end
```

Save your custom state space class and ensure your file name matches the class name.

### Class Constructor

Use the constructor to set the name of the state space, the number of state variables, and define its boundaries. Alternatively, you can add input arguments to the function and pass the variables in when you create an object.

- For each state variable, define the `[min max]` values for the state bounds.
- Call the constructor of the base class.
- For this example, you specify the normal and uniform distribution property values using predefined `NormalDistribution` and `UniformDistribution` classes.
- Specify any other user-defined property values here.

```
methods
    function obj = MyCustomStateSpace
        spaceName = "MyCustomStateSpace";
        numStateVariables = 3;
        stateBounds = [-100 100;  % [min max]
                       -100 100;
                       -100 100];

        obj@nav.StateSpace(spaceName, numStateVariables, stateBounds);

        obj.NormalDistribution = matlabshared.tracking.internal.NormalDistribution(numStateVarial
        obj.UniformDistribution = matlabshared.tracking.internal.UniformDistribution(numStateVar:
        % User-defined property values here
    end
```

### Copy Semantics

Specify the `copy` method definition. Copy all the values of your user-defined variables into a new object, so `copyObj` is a deep copy. The default behavior given in this example creates a new copy of the object with the same name, state bounds, and distributions.

```
function copyObj = copy(obj)
    copyObj = feval(class(obj));
    copyObj.StateBounds = obj.StateBounds;
    copyObj.UniformDistribution = obj.UniformDistribution.copy;
    copyObj.NormalDistribution = obj.NormalDistribution.copy;
end
```

#### Enforce State Bounds

Specify how to ensure states are always within the state bounds. For this example, the state values get saturated at the minimum or maximum values for the state bounds.

```
function boundedState = enforceStateBounds(obj, state)
    nav.internal.validation.validateStateMatrix(state, nan, obj.NumStateVariables, "enforceStateB
    boundedState = state;
    boundedState = min(max(boundedState, obj.StateBounds(:,1)'), ...
        obj.StateBounds(:,2)');

end
```

#### Sample Uniformly

Specify the behavior for sampling across a uniform distribution. support multiple syntaxes to constrain the uniform distribution to a nearby state within a certain distance and sample multiple states.

```
STATE = sampleUniform(OBJ)
STATE = sampleUniform(OBJ,NUMSAMPLES)
STATE = sampleUniform(OBJ,NEARSTATE,DIST)
STATE = sampleUniform(OBJ,NEARSTATE,DIST,NUMSAMPLES)
```

For this example, use a validation function to process a `varargin` input that handles the varying input arguments.

```
 function state = sampleUniform(obj, varargin)
    narginchk(1,4);
    [numSamples, stateBounds] = obj.validateSampleUniformInput(varargin{:});

    obj.UniformDistribution.RandomVariableLimits = stateBounds;
    state = obj.UniformDistribution.sample(numSamples);
 end
```

#### Sample from Gaussian Distribution

Specify the behavior for sampling across a Gaussian distribution. Support multiple syntaxes for sampling a single state or multiple states.

```
STATE = sampleGaussian(OBJ, MEANSTATE, STDDEV)
STATE = sampleGaussian(OBJ, MEANSTATE, STDDEV, NUMSAMPLES)
```

```
function state = sampleGaussian(obj, meanState, stdDev, varargin)
    narginchk(3,4);

    [meanState, stdDev, numSamples] = obj.validateSampleGaussianInput(meanState, stdDev, varargin

    obj.NormalDistribution.Mean = meanState;
    obj.NormalDistribution.Covariance = diag(stdDev.^2);

    state = obj.NormalDistribution.sample(numSamples);
    state = obj.enforceStateBounds(state);

end
```

#### Interpolate Between States

Define how to interpolate between two states in your state space. Use an input, `fraction`, to determine how to sample along the path between two states. For this example, define a basic linear interpolation method using the difference between states.

```
function interpState = interpolate(obj, state1, state2, fraction)
    narginchk(4,4);
    [state1, state2, fraction] = obj.validateInterpolateInput(state1, state2, fraction);

    stateDiff = state2 - state1;
    interpState = state1 + fraction' * stateDiff;
end
```

#### Calculate Distance Between States

Specify how to calculate the distance between two states in your state space. Use the `state1` and `state2` inputs to define the start and end positions. Both inputs can be a single state (row vector) or multiple states (matrix of row vectors). For this example, calculate the distance based on the Euclidean distance between each pair of state positions.

```
function dist = distance(obj, state1, state2)

    narginchk(3,3);

    nav.internal.validation.validateStateMatrix(state1, nan, obj.NumStateVariables, "distance", "
    nav.internal.validation.validateStateMatrix(state2, size(state1,1), obj.NumStateVariables, "d

    stateDiff = bsxfun(@minus, state2, state1);
    dist = sqrt( sum( stateDiff.^2, 2 ) );
end
```

Terminate the methods and class sections.

```
    end
end
```

Save your state space class definition. You can now use the class constructor to create an object for your state space.

## Version History

**Introduced in R2019b**

## See Also

`nav.StateSpace` | `nav.StateValidator` | `stateSpaceSE2` | `stateSpaceDubins` | `stateSpaceReedsShepp`

# interpolate

**Class:** `nav.StateSpace`
**Package:** `nav`

Interpolate between states

## Syntax

`interpStates = interpolate(ssObj,state1,state2,ratios)`

## Description

`interpStates = interpolate(ssObj,state1,state2,ratios)` interpolates between two states in your state space based on the given `ratios`.

## Input Arguments

**`ssObj` — State space object**
object of a subclass of `nav.StateSpace`

State space object, specified as an object of a subclass of `nav.StateSpace`.

**`state1` — Initial state position**
*n*-element vector

Initial state position, specified as a *n*-element vector. *n* is the dimension of the state space specified in the `NumStateVariables` property of `ssObj`.

**`state2` — Final state position**
*n*-element vector | *m*-by-*n* matrix of row vectors

Final state position, specified as a *n*-element vector. *n* is the dimension of the state space specified in the `NumStateVariables` property of `ssObj`.

**`ratios` — Ratio values for interpolating along path**
*m*-element vector

Ratio values for interpolating along path, specified as an *m*-element vector. These ratios determine how to sample between the two states.

## Output Arguments

**`interpStates` — Interpolated states**
*m*-by-*n* matrix of row vectors

Interpolated states, returned as an *m*-by-*n* matrix of row vectors. *m* is the length of `ratios` and *n* is the dimension of the state space specified in the `NumStateVariables` property of `ssObj`.

## Examples

### Create Custom State Space for Path Planning

This example shows how to use the `createPlanningTemplate` function to generate a template for customizing your own state space definition and sampler to use with path planning algorithms. A simple implementation is provided with the template.

Call the create template function. This function generates a class definition file for you to modify for your own implementation.

```
createPlanningTemplate
```

#### Class and Property Definition

The first part of the template specifies the class definition and any properties for the class. Derive from the `nav.StateSpace` class. For this example, create a property for the uniform and normal distributions. You can specify any additional user-defined properties here.

```
classdef MyCustomStateSpace < nav.StateSpace & ...
        matlabshared.planning.internal.EnforceScalarHandle
     properties
        UniformDistribution
        NormalDistribution
        % Specify additional properties here
end
```

Save your custom state space class and ensure your file name matches the class name.

#### Class Constructor

Use the constructor to set the name of the state space, the number of state variables, and define its boundaries. Alternatively, you can add input arguments to the function and pass the variables in when you create an object.

- For each state variable, define the `[min max]` values for the state bounds.
- Call the constructor of the base class.
- For this example, you specify the normal and uniform distribution property values using predefined `NormalDistribution` and `UniformDistribution` classes.
- Specify any other user-defined property values here.

```
methods
    function obj = MyCustomStateSpace
        spaceName = "MyCustomStateSpace";
        numStateVariables = 3;
        stateBounds = [-100 100;  % [min max]
                       -100 100;
                       -100 100];

        obj@nav.StateSpace(spaceName, numStateVariables, stateBounds);

        obj.NormalDistribution = matlabshared.tracking.internal.NormalDistribution(numStateVarial
        obj.UniformDistribution = matlabshared.tracking.internal.UniformDistribution(numStateVar:
        % User-defined property values here
    end
```

### Copy Semantics

Specify the `copy` method definition. Copy all the values of your user-defined variables into a new object, so `copyObj` is a deep copy. The default behavior given in this example creates a new copy of the object with the same name, state bounds, and distributions.

```
function copyObj = copy(obj)
    copyObj = feval(class(obj));
    copyObj.StateBounds = obj.StateBounds;
    copyObj.UniformDistribution = obj.UniformDistribution.copy;
    copyObj.NormalDistribution = obj.NormalDistribution.copy;
end
```

### Enforce State Bounds

Specify how to ensure states are always within the state bounds. For this example, the state values get saturated at the minimum or maximum values for the state bounds.

```
function boundedState = enforceStateBounds(obj, state)
    nav.internal.validation.validateStateMatrix(state, nan, obj.NumStateVariables, "enforceStateB
    boundedState = state;
    boundedState = min(max(boundedState, obj.StateBounds(:,1)'), ...
        obj.StateBounds(:,2)');

end
```

### Sample Uniformly

Specify the behavior for sampling across a uniform distribution. support multiple syntaxes to constrain the uniform distribution to a nearby state within a certain distance and sample multiple states.

```
STATE = sampleUniform(OBJ)
STATE = sampleUniform(OBJ,NUMSAMPLES)
STATE = sampleUniform(OBJ,NEARSTATE,DIST)
STATE = sampleUniform(OBJ,NEARSTATE,DIST,NUMSAMPLES)
```

For this example, use a validation function to process a `varargin` input that handles the varying input arguments.

```
 function state = sampleUniform(obj, varargin)
    narginchk(1,4);
    [numSamples, stateBounds] = obj.validateSampleUniformInput(varargin{:});

    obj.UniformDistribution.RandomVariableLimits = stateBounds;
    state = obj.UniformDistribution.sample(numSamples);
 end
```

### Sample from Gaussian Distribution

Specify the behavior for sampling across a Gaussian distribution. Support multiple syntaxes for sampling a single state or multiple states.

```
STATE = sampleGaussian(OBJ, MEANSTATE, STDDEV)
STATE = sampleGaussian(OBJ, MEANSTATE, STDDEV, NUMSAMPLES)
```

```
function state = sampleGaussian(obj, meanState, stdDev, varargin)
    narginchk(3,4);
```

```
    [meanState, stdDev, numSamples] = obj.validateSampleGaussianInput(meanState, stdDev, varargi

    obj.NormalDistribution.Mean = meanState;
    obj.NormalDistribution.Covariance = diag(stdDev.^2);

    state = obj.NormalDistribution.sample(numSamples);
    state = obj.enforceStateBounds(state);

end
```

#### Interpolate Between States

Define how to interpolate between two states in your state space. Use an input, `fraction`, to determine how to sample along the path between two states. For this example, define a basic linear interpolation method using the difference between states.

```
function interpState = interpolate(obj, state1, state2, fraction)
    narginchk(4,4);
    [state1, state2, fraction] = obj.validateInterpolateInput(state1, state2, fraction);

    stateDiff = state2 - state1;
    interpState = state1 + fraction' * stateDiff;
end
```

#### Calculate Distance Between States

Specify how to calculate the distance between two states in your state space. Use the `state1` and `state2` inputs to define the start and end positions. Both inputs can be a single state (row vector) or multiple states (matrix of row vectors). For this example, calculate the distance based on the Euclidean distance between each pair of state positions.

```
function dist = distance(obj, state1, state2)

    narginchk(3,3);

    nav.internal.validation.validateStateMatrix(state1, nan, obj.NumStateVariables, "distance", 
    nav.internal.validation.validateStateMatrix(state2, size(state1,1), obj.NumStateVariables, "

    stateDiff = bsxfun(@minus, state2, state1);
    dist = sqrt( sum( stateDiff.^2, 2 ) );
end
```

Terminate the methods and class sections.

```
    end
end
```

Save your state space class definition. You can now use the class constructor to create an object for your state space.

## Version History

**Introduced in R2019b**

## See Also

nav.StateSpace | nav.StateValidator | stateSpaceSE2 | stateSpaceDubins | stateSpaceReedsShepp

# sampleGaussian

**Class:** nav.StateSpace
**Package:** nav

Sample state using Gaussian distribution

## Syntax

```
states = sampleGaussian(ssObj,meanState,stdDev)
states = sampleGaussian(ssObj,meanState,stdDev,numSamples)
```

## Description

states = sampleGaussian(ssObj,meanState,stdDev) samples a single state in your state space from a Gaussian distribution centered on meanState with specified standard deviation.

states = sampleGaussian(ssObj,meanState,stdDev,numSamples) samples multiple states based on numSamples.

## Input Arguments

**ssObj — State space object**
object of a subclass of nav.StateSpace

State space object, specified as an object of a subclass of nav.StateSpace.

**meanState — Mean state position**
*n*-element vector | *m*-by-*n* matrix of row vectors

Mean state position, specified as a *n*-element vector or *m*-by-*n* matrix of row vectors, where *n* is the dimension of the state space specified in the NumStateVariables property of ssObj. *m* is the number of samples specified in numSamples.

**stdDev — Standard deviation around mean state**
*n*-element vector | *m*-by-*n* matrix of row vectors

Standard deviation around mean state, specified as an *n*-element vector or *m*-by-*n* matrix of row vectors, where each element corresponds to an element in meanState.

**numSamples — Number of samples**
positive integer

Number of samples, specified as a positive integer. By default, the function assumes numSamples is 1.

## Output Arguments

**states — Sampled states from state space**
*n*-element vector | *m*-by-*n* matrix of row vectors

Sampled states from state space, specified as a *n*-element vector or *m*-by-*n* matrix of row vectors. *n* is the dimension of the state space specified in the `NumStateVariables` property of `ssObj`. *m* is the number of samples specified in `numSamples`. All states are sampled within the `StateBounds` property of `ssObj`.

## Examples

### Create Custom State Space for Path Planning

This example shows how to use the `createPlanningTemplate` function to generate a template for customizing your own state space definition and sampler to use with path planning algorithms. A simple implementation is provided with the template.

Call the create template function. This function generates a class definition file for you to modify for your own implementation.

```
createPlanningTemplate
```

#### Class and Property Definition

The first part of the template specifies the class definition and any properties for the class. Derive from the `nav.StateSpace` class. For this example, create a property for the uniform and normal distributions. You can specify any additional user-defined properties here.

```
classdef MyCustomStateSpace < nav.StateSpace & ...
        matlabshared.planning.internal.EnforceScalarHandle
     properties
        UniformDistribution
        NormalDistribution
        % Specify additional properties here
end
```

Save your custom state space class and ensure your file name matches the class name.

#### Class Constructor

Use the constructor to set the name of the state space, the number of state variables, and define its boundaries. Alternatively, you can add input arguments to the function and pass the variables in when you create an object.

- For each state variable, define the `[min max]` values for the state bounds.
- Call the constructor of the base class.
- For this example, you specify the normal and uniform distribution property values using predefined `NormalDistribution` and `UniformDistribution` classes.
- Specify any other user-defined property values here.

```
methods
    function obj = MyCustomStateSpace
        spaceName = "MyCustomStateSpace";
        numStateVariables = 3;
        stateBounds = [-100 100;  % [min max]
                       -100 100;
                       -100 100];
```

```
        obj@nav.StateSpace(spaceName, numStateVariables, stateBounds);

        obj.NormalDistribution = matlabshared.tracking.internal.NormalDistribution(numStateVarial
        obj.UniformDistribution = matlabshared.tracking.internal.UniformDistribution(numStateVar:
        % User-defined property values here
    end
```

#### Copy Semantics

Specify the `copy` method definition. Copy all the values of your user-defined variables into a new object, so `copyObj` is a deep copy. The default behavior given in this example creates a new copy of the object with the same name, state bounds, and distributions.

```
function copyObj = copy(obj)
    copyObj = feval(class(obj));
    copyObj.StateBounds = obj.StateBounds;
    copyObj.UniformDistribution = obj.UniformDistribution.copy;
    copyObj.NormalDistribution = obj.NormalDistribution.copy;
end
```

#### Enforce State Bounds

Specify how to ensure states are always within the state bounds. For this example, the state values get saturated at the minimum or maximum values for the state bounds.

```
function boundedState = enforceStateBounds(obj, state)
    nav.internal.validation.validateStateMatrix(state, nan, obj.NumStateVariables, "enforceState
    boundedState = state;
    boundedState = min(max(boundedState, obj.StateBounds(:,1)'), ...
        obj.StateBounds(:,2)');

end
```

#### Sample Uniformly

Specify the behavior for sampling across a uniform distribution. support multiple syntaxes to constrain the uniform distribution to a nearby state within a certain distance and sample multiple states.

```
STATE = sampleUniform(OBJ)
STATE = sampleUniform(OBJ,NUMSAMPLES)
STATE = sampleUniform(OBJ,NEARSTATE,DIST)
STATE = sampleUniform(OBJ,NEARSTATE,DIST,NUMSAMPLES)
```

For this example, use a validation function to process a `varargin` input that handles the varying input arguments.

```
 function state = sampleUniform(obj, varargin)
    narginchk(1,4);
    [numSamples, stateBounds] = obj.validateSampleUniformInput(varargin{:});

    obj.UniformDistribution.RandomVariableLimits = stateBounds;
    state = obj.UniformDistribution.sample(numSamples);
 end
```

#### Sample from Gaussian Distribution

Specify the behavior for sampling across a Gaussian distribution. Support multiple syntaxes for sampling a single state or multiple states.

```
STATE = sampleGaussian(OBJ, MEANSTATE, STDDEV)
STATE = sampleGaussian(OBJ, MEANSTATE, STDDEV, NUMSAMPLES)


function state = sampleGaussian(obj, meanState, stdDev, varargin)
    narginchk(3,4);

    [meanState, stdDev, numSamples] = obj.validateSampleGaussianInput(meanState, stdDev, varargi

    obj.NormalDistribution.Mean = meanState;
    obj.NormalDistribution.Covariance = diag(stdDev.^2);

    state = obj.NormalDistribution.sample(numSamples);
    state = obj.enforceStateBounds(state);

end
```

#### Interpolate Between States

Define how to interpolate between two states in your state space. Use an input, `fraction`, to determine how to sample along the path between two states. For this example, define a basic linear interpolation method using the difference between states.

```
function interpState = interpolate(obj, state1, state2, fraction)
    narginchk(4,4);
    [state1, state2, fraction] = obj.validateInterpolateInput(state1, state2, fraction);

    stateDiff = state2 - state1;
    interpState = state1 + fraction' * stateDiff;
end
```

#### Calculate Distance Between States

Specify how to calculate the distance between two states in your state space. Use the `state1` and `state2` inputs to define the start and end positions. Both inputs can be a single state (row vector) or multiple states (matrix of row vectors). For this example, calculate the distance based on the Euclidean distance between each pair of state positions.

```
function dist = distance(obj, state1, state2)

    narginchk(3,3);

    nav.internal.validation.validateStateMatrix(state1, nan, obj.NumStateVariables, "distance", '
    nav.internal.validation.validateStateMatrix(state2, size(state1,1), obj.NumStateVariables, "

    stateDiff = bsxfun(@minus, state2, state1);
    dist = sqrt( sum( stateDiff.^2, 2 ) );
end
```

Terminate the methods and class sections.

```
    end
end
```

Save your state space class definition. You can now use the class constructor to create an object for your state space.

## Version History

**Introduced in R2019b**

### See Also

`nav.StateSpace` | `nav.StateValidator` | `stateSpaceSE2` | `stateSpaceDubins` | `stateSpaceReedsShepp`

# sampleUniform

**Class:** `nav.StateSpace`
**Package:** `nav`

Sample state using uniform distribution

## Syntax

```
states = sampleUniform(ssObj)
states = sampleUniform(ssObj,numSamples)
states = sampleUniform(ssObj,meanState,distance)
states = sampleUniform(ssObj,meanState,distance,numSamples)
```

## Description

`states = sampleUniform(ssObj)` samples throughout your entire state space using a uniform distribution.

`states = sampleUniform(ssObj,numSamples)` samples multiple states based on `numSamples`.

`states = sampleUniform(ssObj,meanState,distance)` samples near a given mean state within a certain distance.

`states = sampleUniform(ssObj,meanState,distance,numSamples)` samples multiple states near a given mean state based on `numSamples`.

## Input Arguments

**`ssObj` — State space object**
object of a subclass of `nav.StateSpace`

State space object, specified as an object of a subclass of `nav.StateSpace`.

**`meanState` — Mean state position**
*n*-element vector

Mean state position for sampling near, specified as a *n*-element vector, where *n* is the dimension of the state space specified in the `NumStateVariables` property of `ssObj`. *m* is the number of samples specified in `numSamples`.

**`distance` — Max distance from mean state position**
*n*-element vector

Max distance from mean state position, `nearState`, specified as a *n*-element vector, where `nearState` defines the center of the sampled region and `distance` is the maximum distance from `nearState` allowed in each dimension.

**`numSamples` — Number of samples**
positive integer

Number of samples, specified as a positive integer.

## Output Arguments

**states — Sampled states from state space**
*n*-element vector | *m*-by-*n* matrix of row vectors

Sampled states from state space, specified as a *n*-element vector or *m*-by-*n* matrix of row vectors. *n* is the dimension of the state space specified in the `NumStateVariables` property of `ssObj`. *m* is the number of samples specified in `numSamples`. All states are sampled within the `StateBounds` property of `ssObj`.

## Examples

### Create Custom State Space for Path Planning

This example shows how to use the `createPlanningTemplate` function to generate a template for customizing your own state space definition and sampler to use with path planning algorithms. A simple implementation is provided with the template.

Call the create template function. This function generates a class definition file for you to modify for your own implementation.

```
createPlanningTemplate
```

**Class and Property Definition**

The first part of the template specifies the class definition and any properties for the class. Derive from the `nav.StateSpace` class. For this example, create a property for the uniform and normal distributions. You can specify any additional user-defined properties here.

```
classdef MyCustomStateSpace < nav.StateSpace & ...
        matlabshared.planning.internal.EnforceScalarHandle
     properties
        UniformDistribution
        NormalDistribution
        % Specify additional properties here
end
```

Save your custom state space class and ensure your file name matches the class name.

**Class Constructor**

Use the constructor to set the name of the state space, the number of state variables, and define its boundaries. Alternatively, you can add input arguments to the function and pass the variables in when you create an object.

- For each state variable, define the `[min max]` values for the state bounds.
- Call the constructor of the base class.
- For this example, you specify the normal and uniform distribution property values using predefined `NormalDistribution` and `UniformDistribution` classes.
- Specify any other user-defined property values here.

```
methods
    function obj = MyCustomStateSpace
```

```
        spaceName = "MyCustomStateSpace";
        numStateVariables = 3;
        stateBounds = [-100 100;  % [min max]
                       -100 100;
                       -100 100];

        obj@nav.StateSpace(spaceName, numStateVariables, stateBounds);

        obj.NormalDistribution = matlabshared.tracking.internal.NormalDistribution(numStateVariab
        obj.UniformDistribution = matlabshared.tracking.internal.UniformDistribution(numStateVari
        % User-defined property values here
    end
```

**Copy Semantics**

Specify the `copy` method definition. Copy all the values of your user-defined variables into a new object, so `copyObj` is a deep copy. The default behavior given in this example creates a new copy of the object with the same name, state bounds, and distributions.

```
function copyObj = copy(obj)
    copyObj = feval(class(obj));
    copyObj.StateBounds = obj.StateBounds;
    copyObj.UniformDistribution = obj.UniformDistribution.copy;
    copyObj.NormalDistribution = obj.NormalDistribution.copy;
end
```

**Enforce State Bounds**

Specify how to ensure states are always within the state bounds. For this example, the state values get saturated at the minimum or maximum values for the state bounds.

```
function boundedState = enforceStateBounds(obj, state)
    nav.internal.validation.validateStateMatrix(state, nan, obj.NumStateVariables, "enforceStateB
    boundedState = state;
    boundedState = min(max(boundedState, obj.StateBounds(:,1)'), ...
        obj.StateBounds(:,2)');

end
```

**Sample Uniformly**

Specify the behavior for sampling across a uniform distribution. support multiple syntaxes to constrain the uniform distribution to a nearby state within a certain distance and sample multiple states.

```
STATE = sampleUniform(OBJ)
STATE = sampleUniform(OBJ,NUMSAMPLES)
STATE = sampleUniform(OBJ,NEARSTATE,DIST)
STATE = sampleUniform(OBJ,NEARSTATE,DIST,NUMSAMPLES)
```

For this example, use a validation function to process a `varargin` input that handles the varying input arguments.

```
 function state = sampleUniform(obj, varargin)
    narginchk(1,4);
    [numSamples, stateBounds] = obj.validateSampleUniformInput(varargin{:});

    obj.UniformDistribution.RandomVariableLimits = stateBounds;
```

```
    state = obj.UniformDistribution.sample(numSamples);
 end
```

### Sample from Gaussian Distribution

Specify the behavior for sampling across a Gaussian distribution. Support multiple syntaxes for sampling a single state or multiple states.

```
STATE = sampleGaussian(OBJ, MEANSTATE, STDDEV)
STATE = sampleGaussian(OBJ, MEANSTATE, STDDEV, NUMSAMPLES)


function state = sampleGaussian(obj, meanState, stdDev, varargin)
    narginchk(3,4);

    [meanState, stdDev, numSamples] = obj.validateSampleGaussianInput(meanState, stdDev, varargi

    obj.NormalDistribution.Mean = meanState;
    obj.NormalDistribution.Covariance = diag(stdDev.^2);

    state = obj.NormalDistribution.sample(numSamples);
    state = obj.enforceStateBounds(state);

end
```

### Interpolate Between States

Define how to interpolate between two states in your state space. Use an input, `fraction`, to determine how to sample along the path between two states. For this example, define a basic linear interpolation method using the difference between states.

```
function interpState = interpolate(obj, state1, state2, fraction)
    narginchk(4,4);
    [state1, state2, fraction] = obj.validateInterpolateInput(state1, state2, fraction);

    stateDiff = state2 - state1;
    interpState = state1 + fraction' * stateDiff;
end
```

### Calculate Distance Between States

Specify how to calculate the distance between two states in your state space. Use the `state1` and `state2` inputs to define the start and end positions. Both inputs can be a single state (row vector) or multiple states (matrix of row vectors). For this example, calculate the distance based on the Euclidean distance between each pair of state positions.

```
function dist = distance(obj, state1, state2)

    narginchk(3,3);

    nav.internal.validation.validateStateMatrix(state1, nan, obj.NumStateVariables, "distance", "
    nav.internal.validation.validateStateMatrix(state2, size(state1,1), obj.NumStateVariables, "d

    stateDiff = bsxfun(@minus, state2, state1);
    dist = sqrt( sum( stateDiff.^2, 2 ) );
end
```

Terminate the methods and class sections.

```
    end
end
```

Save your state space class definition. You can now use the class constructor to create an object for your state space.

# Version History

**Introduced in R2019b**

## See Also

`nav.StateSpace` | `nav.StateValidator` | `stateSpaceSE2` | `stateSpaceDubins` | `stateSpaceReedsShepp`

# nav.StateValidator class

**Package:** `nav`

Create state validator for path planning

## Description

`nav.StateValidator` is an interface for all state validators used for path planning. Derive from this class if you want to define your own state validator. This representation allows for state and motion validation.

To create a sample template for generating your own state space class, call `createPlanningTemplate("StateValidator")`. For specific implementations of the state validator class for general application, see **State Validation** in "Motion Planning".

The `nav.StateValidator` class is a `handle` class.

### Class Attributes

| | |
|---|---|
| `Abstract` | `true` |

For information on class attributes, see "Class Attributes".

# Creation

## Syntax

`ssObj = nav.StateValidator(stateSpace)`

### Description

`ssObj = nav.StateValidator(stateSpace)` creates a state validator object that validates states in the given state space. This constructor can only be called from a derived class. Create your own class definition using `createPlanningTemplate`.

## Properties

**`StateSpace` — State space definition**
object of a subclass from `nav.StateSpace`

State space definition, specified as an object of a subclass from `nav.StateSpace`. Specify this property using the `stateSpace` input on construction. You can also specify any of our predefined objects in the **State Validation** section from "Motion Planning".

Example: `stateSpaceSE2`

**Attributes:**

| | |
|---|---|
| GetAccess | public |
| SetAccess | immutable |

## Methods

### Public Methods

| | |
|---|---|
| copy | Copy array of handle objects |
| isMotionValid | Check if path between states is valid |
| isStateValid | Check if state is valid |

## Examples

### Create Custom State Space Validator for Path Planning

This example shows how to use the `createPlanningTemplate` function to generate a template for customizing your own state validation class. State validation is used with path planning algorithms to ensure valid paths. The template function provides a basic implementation for example purposes.

Call the create template function. This function generates a class definition file for you to modify for your own implementation. Save this file.

```
createPlanningTemplate("StateValidator")
```

#### Class and Property Definition

The first part of the template specifies the class definition and any properties for the class. Derive from the `nav.StateValidator` class. You can specify any additional user-defined properties here.

```
classdef MyCustomStateValidator < nav.StateValidator & ...
        matlabshared.planning.internal.EnforceScalarHandle
    properties
       % User-defined properties
    end
```

Save your custom state validator class and ensure your file name matches the class name.

#### Class Constructor

Use the constructor to set the name of the state space validator and specify the state space object. Set a default value for the state space if one is not provided. Call the constructor of the base class. Initialize any other user-defined properties. This example uses a default of `MyCustomStateSpace`, which was illustrated in the previous example.

```
methods
        function obj = MyCustomStateValidator(space)
            narginchk(0,1)

            if nargin == 0
                space = MyCustomStateSpace;
            end

            obj@nav.StateValidator(space);
```

```
            % Initialize user-defined properties
        end
```

#### Copy Semantics

Specify the `copy` method definition. Copy all the values of your user-defined variables into a new object, so `copyObj` is a deep copy. The default behavior given in this example creates a new copy of the object with the same type.

```
        function copyObj = copy(obj)
            copyObj = feval(class(obj), obj.StateSpace);
        end
```

#### Check State Validity

Define how a given state is validated. The `state` input can either be a single row vector, or a matrix of row vectors for multiple states. Customize this function for any special validation behavior for your state space like collision checking against obstacles.

```
        function isValid = isStateValid(obj, state)
            narginchk(2,2);
            nav.internal.validation.validateStateMatrix(state, nan, obj.StateSpace.NumStateVarial
                "isStateValid", "state");

            bounds = obj.StateSpace.StateBounds';
            inBounds = state >= bounds(1,:) & state <= bounds(2,:);
            isValid = all(inBounds, 2);

        end
```

#### Check Motion Validity

Define how to generate the motion between states and determine if it is valid. For this example, use `linspace` to evenly interpolate between states and check if these states are valid using `isStateValid`. Customize this function to sample between states or consider other analytical methods for determining if a vehicle can move between given states.

```
        function [isValid, lastValid] = isMotionValid(obj, state1, state2)
            narginchk(3,3);
            state1 = nav.internal.validation.validateStateVector(state1, ...
                obj.StateSpace.NumStateVariables, "isMotionValid", "state1");
            state2 = nav.internal.validation.validateStateVector(state2, ...
                obj.StateSpace.NumStateVariables, "isMotionValid", "state2");

            if (~obj.isStateValid(state1))
                error("statevalidator:StartStateInvalid", "The start state of the motion is inval
            end

            % Interpolate at a fixed interval between states and check state validity
            numInterpPoints = 100;
            interpStates = obj.StateSpace.interpolate(state1, state2, linspace(0,1,numInterpPoint
            interpValid = obj.isStateValid(interpStates);

            % Look for invalid states. Set lastValid state to index-1.
            firstInvalidIdx = find(~interpValid, 1);
            if isempty(firstInvalidIdx)
                isValid = true;
```

```
                lastValid = state2;
            else
                isValid = false;
                lastValid = interpStates(firstInvalidIdx-1,:);
            end

        end
```

Terminate the methods and class sections.

```
    end
end
```

Save your state space validator class definition. You can now use the class constructor to create an object for validation of states for a given state space.

# Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`nav.StateSpace` | `validatorOccupancyMap` | `validatorVehicleCostmap`

# isMotionValid

**Class:** `nav.StateValidator`
**Package:** `nav`

Check if path between states is valid

## Syntax

```
[isValid,lastValid] = isMotionValid(validatorObj,state1,state2)
```

## Description

`[isValid,lastValid] = isMotionValid(validatorObj,state1,state2)` determines if the motion between two states is valid by interpolating between states. The function also returns the last valid state along the path.

A default implementation for this method is provided when you call `createPlanningTemplate`.

## Input Arguments

### `validatorObj` — State validator object

object from a subclass of `nav.StateValidator`

State validator object, specified as an object from a subclass of `nav.StateValidator`. For provided state validator objects, see `validatorOccupancyMap` or `validatorVehicleCostmap`.

### `state1` — Initial state position

*n*-element vector | *m*-by-*n* matrix of row vectors

Initial state position, specified as a *n*-element vector or *m*-by-*n* matrix of row vectors. *n* is the dimension of the state space specified in the state space property in `validatorObj`.

### `state2` — Final state position

*n*-element vector | *m*-by-*n* matrix of row vectors

Final state position, specified as a *n*-element vector or *m*-by-*n* matrix of row vectors. *n* is the dimension of the state space specified in the state space property in `validatorObj`.

## Output Arguments

### `isValid` — Valid states

*m*-element vector of `1`s and `0`s

Valid states, specified as a *m*-element vector of `1`s and `0`s.

Data Types: `logical`

### `lastValid` — Final valid state along path

*n*-element vector

Final valid state along path, specified as a *n*-element vector. *n* is the dimension of the state space specified in the state space property in `validatorObj`.

## Examples

### Create Custom State Space Validator for Path Planning

This example shows how to use the `createPlanningTemplate` function to generate a template for customizing your own state validation class. State validation is used with path planning algorithms to ensure valid paths. The template function provides a basic implementation for example purposes.

Call the create template function. This function generates a class definition file for you to modify for your own implementation. Save this file.

```
createPlanningTemplate("StateValidator")
```

**Class and Property Definition**

The first part of the template specifies the class definition and any properties for the class. Derive from the `nav.StateValidator` class. You can specify any additional user-defined properties here.

```
classdef MyCustomStateValidator < nav.StateValidator & ...
        matlabshared.planning.internal.EnforceScalarHandle
    properties
       % User-defined properties
    end
```

Save your custom state validator class and ensure your file name matches the class name.

**Class Constructor**

Use the constructor to set the name of the state space validator and specify the state space object. Set a default value for the state space if one is not provided. Call the constructor of the base class. Initialize any other user-defined properties. This example uses a default of `MyCustomStateSpace`, which was illustrated in the previous example.

```
methods
        function obj = MyCustomStateValidator(space)
            narginchk(0,1)

            if nargin == 0
                space = MyCustomStateSpace;
            end

            obj@nav.StateValidator(space);

           % Initialize user-defined properties
        end
```

**Copy Semantics**

Specify the `copy` method definition. Copy all the values of your user-defined variables into a new object, so `copyObj` is a deep copy. The default behavior given in this example creates a new copy of the object with the same type.

```
        function copyObj = copy(obj)
            copyObj = feval(class(obj), obj.StateSpace);
        end
```

#### Check State Validity

Define how a given state is validated. The `state` input can either be a single row vector, or a matrix of row vectors for multiple states. Customize this function for any special validation behavior for your state space like collision checking against obstacles.

```
        function isValid = isStateValid(obj, state)
            narginchk(2,2);
            nav.internal.validation.validateStateMatrix(state, nan, obj.StateSpace.NumStateVarial
                "isStateValid", "state");

            bounds = obj.StateSpace.StateBounds';
            inBounds = state >= bounds(1,:) & state <= bounds(2,:);
            isValid = all(inBounds, 2);

        end
```

#### Check Motion Validity

Define how to generate the motion between states and determine if it is valid. For this example, use `linspace` to evenly interpolate between states and check if these states are valid using `isStateValid`. Customize this function to sample between states or consider other analytical methods for determining if a vehicle can move between given states.

```
        function [isValid, lastValid] = isMotionValid(obj, state1, state2)
            narginchk(3,3);
            state1 = nav.internal.validation.validateStateVector(state1, ...
                obj.StateSpace.NumStateVariables, "isMotionValid", "state1");
            state2 = nav.internal.validation.validateStateVector(state2, ...
                obj.StateSpace.NumStateVariables, "isMotionValid", "state2");

            if (~obj.isStateValid(state1))
                error("statevalidator:StartStateInvalid", "The start state of the motion is inva
            end

            % Interpolate at a fixed interval between states and check state validity
            numInterpPoints = 100;
            interpStates = obj.StateSpace.interpolate(state1, state2, linspace(0,1,numInterpPoin
            interpValid = obj.isStateValid(interpStates);

            % Look for invalid states. Set lastValid state to index-1.
            firstInvalidIdx = find(~interpValid, 1);
            if isempty(firstInvalidIdx)
                isValid = true;
                lastValid = state2;
            else
                isValid = false;
                lastValid = interpStates(firstInvalidIdx-1,:);
            end

        end
```

Terminate the methods and class sections.

```
    end
end
```

Save your state space validator class definition. You can now use the class constructor to create an object for validation of states for a given state space.

# Version History

**Introduced in R2019b**

## See Also

`nav.StateValidator` | `nav.StateSpace` | `validatorOccupancyMap` | `validatorVehicleCostmap`

# isStateValid

**Class:** `nav.StateValidator`
**Package:** `nav`

Check if state is valid

## Syntax

`isValid = isStateValid(validatorObj,states)`

## Description

`isValid = isStateValid(validatorObj,states)` determines if the `states` are valid.

## Input Arguments

**`validatorObj` — State validator object**
object from a subclass of `nav.StateValidator`

State validator object, specified as an object from a subclass of `nav.StateValidator`. For provided state validator objects, see `validatorOccupancyMap` or `validatorVehicleCostmap`.

**`states` — State positions**
*n*-element vector | *m*-by-*n* matrix of row vectors

Initial state position, specified as a *n*-element vector or *m*-by-*n* matrix of row vectors. *n* is the dimension of the state space specified in `validatorObj`. *m* is the number of states to validate.

## Output Arguments

**`isValid` — Valid states**
*m*-element vector of `1`s and `0`s

Valid states, specified as a *m*-element vector of `1`s and `0`s.

## Examples

### Create Custom State Space Validator for Path Planning

This example shows how to use the `createPlanningTemplate` function to generate a template for customizing your own state validation class. State validation is used with path planning algorithms to ensure valid paths. The template function provides a basic implementation for example purposes.

Call the create template function. This function generates a class definition file for you to modify for your own implementation. Save this file.

```
createPlanningTemplate("StateValidator")
```

### Class and Property Definition

The first part of the template specifies the class definition and any properties for the class. Derive from the `nav.StateValidator` class. You can specify any additional user-defined properties here.

```
classdef MyCustomStateValidator < nav.StateValidator & ...
        matlabshared.planning.internal.EnforceScalarHandle
    properties
       % User-defined properties
    end
```

Save your custom state validator class and ensure your file name matches the class name.

### Class Constructor

Use the constructor to set the name of the state space validator and specify the state space object. Set a default value for the state space if one is not provided. Call the constructor of the base class. Initialize any other user-defined properties. This example uses a default of `MyCustomStateSpace`, which was illustrated in the previous example.

```
methods
        function obj = MyCustomStateValidator(space)
            narginchk(0,1)

            if nargin == 0
                space = MyCustomStateSpace;
            end

            obj@nav.StateValidator(space);

           % Initialize user-defined properties
        end
```

### Copy Semantics

Specify the `copy` method definition. Copy all the values of your user-defined variables into a new object, so `copyObj` is a deep copy. The default behavior given in this example creates a new copy of the object with the same type.

```
        function copyObj = copy(obj)
            copyObj = feval(class(obj), obj.StateSpace);
        end
```

### Check State Validity

Define how a given state is validated. The `state` input can either be a single row vector, or a matrix of row vectors for multiple states. Customize this function for any special validation behavior for your state space like collision checking against obstacles.

```
        function isValid = isStateValid(obj, state)
            narginchk(2,2);
            nav.internal.validation.validateStateMatrix(state, nan, obj.StateSpace.NumStateVarial
                "isStateValid", "state");

            bounds = obj.StateSpace.StateBounds';
            inBounds = state >= bounds(1,:) & state <= bounds(2,:);
            isValid = all(inBounds, 2);
```

```
        end
```

#### Check Motion Validity

Define how to generate the motion between states and determine if it is valid. For this example, use `linspace` to evenly interpolate between states and check if these states are valid using `isStateValid`. Customize this function to sample between states or consider other analytical methods for determining if a vehicle can move between given states.

```
        function [isValid, lastValid] = isMotionValid(obj, state1, state2)
            narginchk(3,3);
            state1 = nav.internal.validation.validateStateVector(state1, ...
                obj.StateSpace.NumStateVariables, "isMotionValid", "state1");
            state2 = nav.internal.validation.validateStateVector(state2, ...
                obj.StateSpace.NumStateVariables, "isMotionValid", "state2");

            if (~obj.isStateValid(state1))
                error("statevalidator:StartStateInvalid", "The start state of the motion is inva
            end

            % Interpolate at a fixed interval between states and check state validity
            numInterpPoints = 100;
            interpStates = obj.StateSpace.interpolate(state1, state2, linspace(0,1,numInterpPoin
            interpValid = obj.isStateValid(interpStates);

            % Look for invalid states. Set lastValid state to index-1.
            firstInvalidIdx = find(~interpValid, 1);
            if isempty(firstInvalidIdx)
                isValid = true;
                lastValid = state2;
            else
                isValid = false;
                lastValid = interpStates(firstInvalidIdx-1,:);
            end

        end
```

Terminate the methods and class sections.

```
    end
end
```

Save your state space validator class definition. You can now use the class constructor to create an object for validation of states for a given state space.

## Version History

**Introduced in R2019b**

## See Also

`nav.StateValidator` | `nav.StateSpace` | `validatorOccupancyMap` | `validatorVehicleCostmap`

# insfilterNonholonomic

Estimate pose with nonholonomic constraints

## Description

The `insfilterNonholonomic` object implements sensor fusion of inertial measurement unit (IMU) and GPS data to estimate pose in the NED (or ENU) reference frame. IMU data is derived from gyroscope and accelerometer data. The filter uses a 16-element state vector to track the orientation quaternion, velocity, position, and IMU sensor biases. The `insfilterNonholonomic` object uses an extended Kalman filter to estimate these quantities.

## Creation

### Syntax

```
filter = insfilterNonholonomic
filter = insfilterNonholonomic('ReferenceFrame',RF)
filter = insfilterNonholonomic( ___ ,Name,Value)
```

#### Description

`filter = insfilterNonholonomic` creates an `insfilterErrorState` object with default property values.

`filter = insfilterNonholonomic('ReferenceFrame',RF)` allows you to specify the reference frame, `RF`, of the `filter`. Specify `RF` as `'NED'` (North-East-Down) or `'ENU'` (East-North-Up). The default value is `'NED'`.

`filter = insfilterNonholonomic( ___ ,Name,Value)` also allows you set properties of the created `filter` using one or more name-value pairs. Enclose each property name in single quotes.

### Properties

**`IMUSampleRate` — Sample rate of the IMU (Hz)**
`100` (default) | positive scalar

Sample rate of the IMU in Hz, specified as a positive scalar.

Data Types: `single` | `double`

**`ReferenceLocation` — Reference location (deg, deg, meters)**
`[0 0 0]` (default) | 3-element positive row vector

Reference location, specified as a 3-element row vector in geodetic coordinates (latitude, longitude, and altitude). Altitude is the height above the reference ellipsoid model, WGS84. The reference location units are [degrees degrees meters].

Data Types: `single` | `double`

### `DecimationFactor` — Decimation factor for kinematic constraint correction
2 (default) | positive integer scalar

Decimation factor for kinematic constraint correction, specified as a positive integer scalar.

Data Types: `single` | `double`

### `GyroscopeNoise` — Multiplicative process noise variance from gyroscope $(rad/s)^2$
`[4.8e-6 4.8e-6 4.8e-6]` (default) | scalar | 3-element row vector

Multiplicative process noise variance from the gyroscope in $(rad/s)^2$, specified as a scalar or 3-element row vector of positive real finite numbers.

- If `GyroscopeNoise` is specified as a row vector, the elements correspond to the noise in the *x*, *y*, and *z* axes of the gyroscope, respectively.
- If `GyroscopeNoise` is specified as a scalar, the single element is applied to the *x*, *y*, and *z* axes of the gyroscope.

Data Types: `single` | `double`

### `GyroscopeBiasNoise` — Multiplicative process noise variance from gyroscope bias $(rad/s)^2$
`[4e-14 4e-14 4e-14]` (default) | scalar | 3-element row vector

Multiplicative process noise variance from the gyroscope bias in $(rad/s)^2$, specified as a scalar or 3-element row vector of positive real finite numbers. Gyroscope bias is modeled as a lowpass filtered white noise process.

- If `GyroscopeBiasNoise` is specified as a row vector, the elements correspond to the noise in the *x*, *y*, and *z* axes of the gyroscope, respectively.
- If `GyroscopeBiasNoise` is specified as a scalar, the single element is applied to the *x*, *y*, and *z* axes of the gyroscope.

Data Types: `single` | `double`

### `GyroscopeBiasDecayFactor` — Decay factor for gyroscope bias
`0.999` (default) | scalar in the range [0,1]

Decay factor for gyroscope bias, specified as a scalar in the range [0,1]. A decay factor of `0` models gyroscope bias as a white noise process. A decay factor of `1` models the gyroscope bias as a random walk process.

Data Types: `single` | `double`

### `AccelerometerNoise` — Multiplicative process noise variance from accelerometer $(m/s^2)^2$
`[4.8e-2 4.8e-2 4.8e-2]` (default) | scalar | 3-element row vector

Multiplicative process noise variance from the accelerometer in $(m/s^2)^2$, specified as a scalar or 3-element row vector of positive real finite numbers.

- If `AccelerometerNoise` is specified as a row vector, the elements correspond to the noise in the *x*, *y*, and *z* axes of the accelerometer, respectively.
- If `AccelerometerNoise` is specified as a scalar, the single element is applied to each axis.

Data Types: `single` | `double`

**`AccelerometerBiasNoise` — Multiplicative process noise variance from accelerometer bias $(m/s^2)^2$**

`[4e-14 4e-14 4e-14]` (default) | positive scalar | 3-element row vector

Multiplicative process noise variance from the accelerometer bias in $(m/s^2)^2$, specified as a scalar or 3-element row vector of positive real numbers. Accelerometer bias is modeled as a lowpass filtered white noise process.

- If `AccelerometerBiasNoise` is specified as a row vector, the elements correspond to the noise in the *x*, *y*, and *z* axes of the accelerometer, respectively.
- If `AccelerometerBiasNoise` is specified as a scalar, the single element is applied to each axis.

**`AccelerometerBiasDecayFactor` — Decay factor for accelerometer bias**

`0.9999` (default) | scalar in the range [0,1]

Decay factor for accelerometer bias, specified as a scalar in the range [0,1]. A decay factor of `0` models accelerometer bias as a white noise process. A decay factor of `1` models the accelerometer bias as a random walk process.

Data Types: `single` | `double`

**`State` — State vector of extended Kalman filter**

`[1;zeros(15,1)]` | 16-element column vector

State vector of the extended Kalman filter. The state values represent:

| State | Units | Index |
|---|---|---|
| Orientation (quaternion parts) | N/A | 1:4 |
| Gyroscope Bias (XYZ) | rad/s | 5:7 |
| Position (NED or ENU) | m | 8:10 |
| Velocity (NED or ENU) | m/s | 11:13 |
| Accelerometer Bias (XYZ) | $m/s^2$ | 14:16 |

Data Types: `single` | `double`

**`StateCovariance` — State error covariance for extended Kalman filter**

`eye(16)` (default) | 16-by-16 matrix

State error covariance for the extended Kalman filter, specified as a 16-by-16-element matrix, or real numbers.

Data Types: `single` | `double`

**`ZeroVelocityConstraintNoise` — Velocity constraints noise $(m/s)^2$**

`1e-2` (default) | nonnegative scalar

Velocity constraints noise in $(m/s)^2$, specified as a nonnegative scalar.

Data Types: `single` | `double`

## Object Functions

| | |
|---|---|
| correct | Correct states using direct state measurements for insfilterNonholonomic |

| | |
|---|---|
| residual | Residuals and residual covariances from direct state measurements for insfilterNonholonomic |
| fusegps | Correct states using GPS data for insfilterNonholonomic |
| residualgps | Residuals and residual covariance from GPS measurements for insfilterNonholonomic |
| pose | Current orientation and position estimate for insfilterNonholonomic |
| predict | Update states using accelerometer and gyroscope data for insfilterNonholonomic |
| reset | Reset internal states for insfilterNonholonomic |
| stateinfo | Display state vector information for insfilterNonholonomic |
| tune | Tune insfilterNonholonomic parameters to reduce estimation error |
| copy | Create copy of insfitlerNonholonomic |

## Examples

### Estimate Pose of Ground Vehicle

This example shows how to estimate the pose of a ground vehicle from logged IMU and GPS sensor measurements and ground truth orientation and position.

Load the logged data of a ground vehicle following a circular trajectory.

```
load('loggedGroundVehicleCircle.mat','imuFs','localOrigin','initialState','initialStateCovariance
      'gyroData','gpsFs','gpsLLA','Rpos','gpsVel','Rvel','trueOrient','truePos');
```

Initialize the `insfilterNonholonomic` object.

```
filt = insfilterNonholonomic;
filt.IMUSampleRate = imuFs;
filt.ReferenceLocation = localOrigin;
filt.State = initialState;
filt.StateCovariance = initialStateCovariance;

imuSamplesPerGPS = imuFs/gpsFs;
```

Log data for final metric computation. Use the `predict` object function to estimate filter state based on accelerometer and gyroscope data. Then correct the filter state according to GPS data.

```
numIMUSamples = size(accelData,1);
estOrient = quaternion.ones(numIMUSamples,1);
estPos = zeros(numIMUSamples,3);

gpsIdx = 1;

for idx = 1:numIMUSamples
    predict(filt,accelData(idx,:),gyroData(idx,:));       %Predict filter state

    if (mod(idx,imuSamplesPerGPS) == 0)                   %Correct filter state
        fusegps(filt,gpsLLA(gpsIdx,:),Rpos,gpsVel(gpsIdx,:),Rvel);
        gpsIdx = gpsIdx + 1;
    end

    [estPos(idx,:),estOrient(idx,:)] = pose(filt);        %Log estimated pose
end
```

Calculate and display RMS errors.

```
posd = estPos - truePos;
quatd = rad2deg(dist(estOrient,trueOrient));
msep = sqrt(mean(posd.^2));

fprintf('Position RMS Error\n\tX: %.2f, Y: %.2f, Z: %.2f (meters)\n\n',msep(1),msep(2),msep(3));

Position RMS Error
    X: 0.15, Y: 0.11, Z: 0.01 (meters)


fprintf('Quaternion Distance RMS Error\n\t%.2f (degrees)\n\n',sqrt(mean(quatd.^2)));

Quaternion Distance RMS Error
    0.26 (degrees)
```

## Algorithms

*Note: The following algorithm only applies to an NED reference frame.*

`insfilterNonholonomic` uses a 16-axis error state Kalman filter structure to estimate pose in the NED reference frame. The state is defined as:

$$x = \begin{bmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \\ gyrobias_X \\ gyrobias_Y \\ gyrobias_Z \\ position_N \\ position_E \\ position_D \\ v_N \\ v_E \\ v_D \\ accelbias_X \\ accelbias_Y \\ accelbias_Z \end{bmatrix}$$

where

- $q_0$, $q_1$, $q_2$, $q_3$ -- Parts of orientation quaternion. The orientation quaternion represents a frame rotation from the platform's current orientation to the local NED coordinate system.
- $gyrobias_X$, $gyrobias_Y$, $gyrobias_Z$ -- Bias in the gyroscope reading.
- $position_N$, $position_E$, $position_D$ -- Position of the platform in the local NED coordinate system.
- $\nu_N$, $\nu_E$, $\nu_D$ -- Velocity of the platform in the local NED coordinate system.

- *accelbias*$_X$, *accelbias*$_Y$, *accelbias*$_Z$ –– Bias in the accelerometer reading.

Given the conventional formulation of the state transition function,

$$x_{k|k-1} = f(\hat{x}_{k-1|k-1})$$

the predicted state estimate is:

$$x_{k|k-1} =$$

$$\left[\begin{array}{c}
q_0 + \Delta t * q_1(gyrobias_X/2 - gyro_X/2) + \Delta t * q_2 * (gyrobias_Y/2 - gyro_Y/2) + \Delta t * q_3 * (gyrobias_Z/2 - gyro_Z/2) \\
q_1 - \Delta t * q_0(gyrobias_X/2 - gyro_X/2) + \Delta t * q_3 * (gyrobias_Y/2 - gyro_Y/2) - \Delta t * q_2 * (gyrobias_Z/2 - gyro_Z/2) \\
q_2 - \Delta t * q_3(gyrobias_X/2 - gyro_X/2) - \Delta t * q_0 * (gyrobias_Y/2 - gyro_Y/2) + \Delta t * q_1 * (gyrobias_Z/2 - gyro_Z/2) \\
q_3 + \Delta t * q_2(gyrobias_X/2 - gyro_X/2) - \Delta t * q_1 * (gyrobias_Y/2 - gyro_Y/2) - \Delta t * q_0 * (gyrobias_Z/2 - gyro_Z/2) \\
-gryobias_X * (\Delta t * \lambda_{gyro} - 1) \\
-gryobias_Y * (\Delta t * \lambda_{gyro} - 1) \\
-gryobias_Z * (\Delta t * \lambda_{gyro} - 1) \\
position_N + \Delta t * v_N \\
position_E + \Delta t * v_E \\
position_D + \Delta t * v_D \\
v_N + \Delta t * \left\{\begin{array}{l}
q_0 * (q_0 * (accelbias_X - accel_X) - q_3 * (accelbias_Y - accel_Y) + q_2 * (accelbias_Z - accel_Z)) - g_N + \\
q_2 * (q_1 * (accelbias_Y - accel_Y) - q_2 * (accelbias_X - accel_X) + q_0 * (accelbias_Z - accel_Z)) + \\
q_1 * (q_1 * (accelbias_X - accel_X) + q_2 * (accelbias_Y - accel_Y) + q_3 * (accelbias_Z - accel_Z)) - \\
q_3 * (q_3 * (accelbias_X - accel_X) + q_0 * (accelbias_Y - accel_Y) - q_1 * (accelbias_Z - accel_Z))
\end{array}\right\} \\
v_E + \Delta t * \left\{\begin{array}{l}
q_0 * (q_3 * (accelbias_X - accel_X) + q_0 * (accelbias_Y - accel_Y) - q_1 * (accelbias_Z - accel_Z)) - g_E - \\
q_1 * (q_1 * (accelbias_Y - accel_Y) - q_2 * (accelbias_X - accel_X) + q_0 * (accelbias_Z - accel_Z)) + \\
q_2 * (q_1 * (accelbias_X - accel_X) + q_2 * (accelbias_Y - accel_Y) + q_3 * (accelbias_Z - accel_Z)) +
\end{array}\right.
\end{array}\right.$$

where

- $\Delta t$ –– IMU sample time.
- $g_{\mathrm{N}}$, $g_{\mathrm{E}}$, $g_{\mathrm{D}}$ –– Constant gravity vector in the NED frame.
- $accel_{\mathrm{X}}$, $accel_{\mathrm{Y}}$, $accel_{\mathrm{Z}}$ –– Acceleration vector in the body frame.
- $\lambda_{accel}$ –– Accelerometer bias decay factor.
- $\lambda_{gyro}$ –– Gyroscope bias decay factor.

# Version History

**Introduced in R2018b**

## References

[1] Munguía, R. "A GPS-Aided Inertial Navigation System in Direct Configuration." *Journal of applied research and technology.* Vol. 12, Number 4, 2014, pp. 803 – 814.

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`insfilterMARG` | `insfilterErrorState` | `insfilterAsync`

# correct

Correct states using direct state measurements for `insfilterNonholonomic`

## Syntax

`correct(FUSE,idx,measurement,measurementCovariance)`

## Description

`correct(FUSE,idx,measurement,measurementCovariance)` corrects the state and state estimation error covariance based on the measurement and measurement covariance. The measurement maps directly to the state specified by the indices `idx`.

## Input Arguments

**`FUSE` — `insfilterNonholonomic` object**
object

`insfilterNonholonomic`, specified as an object.

**`idx` — State vector Index of measurement to correct**
*N*-element vector of increasing integers in the range [1,16]

State vector index of measurement to correct, specified as an *N*-element vector of increasing integers in the range [1,16].

The state values represent:

| State | Units | Index |
| --- | --- | --- |
| Orientation (quaternion parts) | | 1:4 |
| Gyroscope bias (XYZ) | rad/s | 5:7 |
| Position (NED) | m | 8:10 |
| Velocity (NED) | m/s | 11:13 |
| Accelerometer Bias (XYZ) | $m/s^2$ | 14:16 |

Data Types: `single` | `double`

**`measurement` — Direct measurement of state**
*N*-element vector

Direct measurement of state, specified as a *N*-element vector. *N* is the number of elements of the index argument, idx.

Data Types: `single` | `double`

**`measurementCovariance` — Covariance of measurement**
scalar | *N*-element vector | *N*-by-*N* matrix

Covariance of measurement, specified as a scalar, *N*-element vector, or *N*-by-*N* matrix. *N* is the number of elements of the index argument, idx.

Data Types: `single` | `double`

# Version History

**Introduced in R2018b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`insfilter` | `insfilterNonholonomic`

# copy

Create copy of `insfitlerNonholonomic`

## Syntax

```
newFilter = copy(filter)
```

## Description

`newFilter = copy(filter)` returns a copy of the `insfilterNonholonomic`, `filter`, with the exactly same property values.

## Input Arguments

**`filter` — Filter to be copied**
`insfitlerNonholonomic`

Filter to be copied, specified as an `insfilterNonholonomic` object.

## Output Arguments

**`newFilter` — New copied filter**
`insfitlerNonholonomic`

New copied filter, returned as an `insfilterNonholonomic` object.

# Version History

**Introduced in R2020b**

## See Also

`insfilterNonholonomic`

# fusegps

Correct states using GPS data for `insfilterNonholonomic`

## Syntax

```
[res,resCov] = fusegps(FUSE,position,positionCovariance)
[res,resCov] = fusegps(FUSE,position,positionCovariance,velocity,
velocityCovariance)
```

## Description

`[res,resCov] = fusegps(FUSE,position,positionCovariance)` fuses GPS position data to correct the state estimate.

`[res,resCov] = fusegps(FUSE,position,positionCovariance,velocity, velocityCovariance)` fuses GPS position and velocity data to correct the state estimate.

## Input Arguments

**FUSE — `insfilterNonholonomic` object**
object

`insfilterNonholonomic`, specified as an object.

**`position` — Position of GPS receiver (LLA)**
3-element row vector

Position of GPS receiver in geodetic latitude, longitude, and altitude (LLA) specified as a real finite 3-element row vector. Latitude and longitude are in degrees with north and east being positive. Altitude is in meters.

Data Types: `single` | `double`

**`positionCovariance` — Position measurement covariance of GPS receiver ($m^2$)**
3-by-3 matrix

Position measurement covariance of GPS receiver in $m^2$, specified as a 3-by-3 matrix.

Data Types: `single` | `double`

**`velocity` — Velocity of GPS receiver in local NED coordinate system (m/s)**
3-element row vector

Velocity of the GPS receiver in the local NED coordinate system in m/s, specified as a 3-element row vector.

Data Types: `single` | `double`

**`velocityCovariance` — Velocity measurement covariance of GPS receiver ($m/s^2$)**
3-by-3 matrix

Velocity measurement covariance of the GPS receiver in the local NED coordinate system in $m/s^2$, specified as a 3-by-3 matrix.

Data Types: `single` | `double`

### Output Arguments

**`res` — Position and course residual**
1-by-4 vector of real values

Position and course residual, returned as a 1-by-6 vector of real values in m and rad/s, respectively.

**`resCov` — Residual covariance**
4-by-4 matrix of real values

Residual covariance, returned as a 4-by-4 matrix of real values.

## Version History

**Introduced in R2018b**

### Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

### See Also

`insfilter` | `insfilterNonholonomic`

# pose

Current orientation and position estimate for `insfilterNonholonomic`

## Syntax

```
[position,orientation,velocity] = pose(FUSE)
[position,orientation,velocity] = pose(FUSE,format)
```

## Description

`[position,orientation,velocity] = pose(FUSE)` returns the current estimate of the pose.

`[position,orientation,velocity] = pose(FUSE,format)`returns the current estimate of the pose with orientation in the specified orientation format.

## Input Arguments

**`FUSE` — `NHConstrainedIMUGPSFuser` object**
object

`insfilterNonholonomic`, specified as an object.

**`format` — Output orientation format**
`'quaternion'` (default) | `'rotmat'`

Output orientation format, specified as either `'quaternion'` for a quaternion or `'rotmat'` for a rotation matrix.

Data Types: `char` | `string`

## Output Arguments

**`position` — Position estimate expressed in the local coordinate system (m)**
three-element row vector

Position estimate expressed in the local coordinate system of the filter in meters, returned as a three-element row vector.

Data Types: `single` | `double`

**`orientation` — Orientation estimate expressed in the local coordinate system**
quaternion (default) | 3-by-3 rotation matrix

Orientation estimate expressed in the local coordinate system of the filter, returned as a scalar quaternion or 3-by-3 rotation matrix. The quaternion or rotation matrix represents a frame rotation from the local reference frame of the filter to the body reference frame.

Data Types: `single` | `double` | `quaternion`

**`velocity` — Velocity estimate expressed in local coordinate system (m/s)**
3-element row vector

Velocity estimate expressed in the local coordinate system of the filter in m/s, returned as a 3-element row vector.

Data Types: `single` | `double`

## Version History

**Introduced in R2018b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`insfilter` | `insfilterNonholonomic`

# predict

Update states using accelerometer and gyroscope data for `insfilterNonholonomic`

## Syntax

```
predict(FUSE,accelReadings,gyroReadings)
```

## Description

`predict(FUSE,accelReadings,gyroReadings)` fuses accelerometer and gyroscope data to update the state estimate.

## Input Arguments

**`FUSE` — `insfilterNonholonomic` object**
object

`insfilterNonholonomic`, specified as an object.

**`accelReadings` — Accelerometer readings in local sensor body coordinate system (m/s$^2$)**
3-element row vector

Accelerometer readings in m/s$^2$, specified as a 3-element row vector.

Data Types: `single` | `double`

**`gyroReadings` — Gyroscope readings in local sensor body coordinate system (rad/s)**
3-element row vector

Gyroscope readings in rad/s, specified as a 3-element row vector.

Data Types: `single` | `double`

# Version History

**Introduced in R2018b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

`insfilter` | `insfilterNonholonomic`

# reset

Reset internal states for `insfilterNonholonomic`

## Syntax

`reset(FUSE)`

## Description

`reset(FUSE)` resets the State, StateCovariance, and internal integrators to their default values.

## Input Arguments

**FUSE — `insfilterNonholonomic` object**
object

`insfilterNonholonomic`, specified as an object.

# Version History

**Introduced in R2018b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

`insfilter` | `insfilterNonholonomic`

# residual

Residuals and residual covariances from direct state measurements for `insfilterNonholonomic`

## Syntax

```
[res, resCov]= residual(FUSE,idx,measurement,measurementCovariance)
```

## Description

`[res, resCov]= residual(FUSE,idx,measurement,measurementCovariance)` computes the residual, `res`, and the residual covariance, `resCov`, based on the direct state measurement and measurement covariance. The `measurement` maps directly to the states specified by indices, `idx`.

## Input Arguments

**`FUSE` — `insfilterNonholonomic` object**
object

`insfilterNonholonomic`, specified as an object.

**`idx` — State vector Index of measurement to correct**
*N*-element vector of increasing integers in the range [1,16]

State vector index of measurement to correct, specified as an *N*-element vector of increasing integers in the range [1,16].

The state values represent:

| State | Units | Index |
| --- | --- | --- |
| Orientation (quaternion parts) | | 1:4 |
| Gyroscope bias (XYZ) | rad/s | 5:7 |
| Position (NED) | m | 8:10 |
| Velocity (NED) | m/s | 11:13 |
| Accelerometer Bias (XYZ) | $m/s^2$ | 14:16 |

Data Types: `single` | `double`

**`measurement` — Direct measurement of state**
*N*-element vector

Direct measurement of state, specified as a *N*-element vector. *N* is the number of elements of the index argument, `idx`.

**`measurementCovariance` — Covariance of measurement**
*N*-by-*N* matrix

Covariance of measurement, specified as an *N*-by-*N* matrix. *N* is the number of elements of the index argument, `idx`.

## Output Arguments

**`res` — Measurement residual**
1-by-*N* vector of real values

Measurement residual, returned as a 1-by-*N* vector of real values.

**`resCov` — Residual covariance**
*N*-by-*N* matrix of real values

Residual covariance, returned as a *N*-by-*N* matrix of real values.

# Version History

**Introduced in R2020a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

`insfilter` | `insfilterNonholonomic`

# residualgps

Residuals and residual covariance from GPS measurements for `insfilterNonholonomic`

## Syntax

```
[res,resCov] = residualgps(FUSE,position,positionCovariance)
[res,resCov] = residualgps(FUSE,position,positionCovariance,velocity,
velocityCovariance)
```

## Description

`[res,resCov] = residualgps(FUSE,position,positionCovariance)` computes the residual, `res`, and the residual covariance, `resCov`, based on the GPS position measurement and covariance.

`[res,resCov] = residualgps(FUSE,position,positionCovariance,velocity, velocityCovariance)` computes the residual, `res`, and the residual covariance, `resCov`, based on the GPS position measurement and covariance.

## Input Arguments

**FUSE — `insfilterNonholonomic` object**
object

`insfilterNonholonomic`, specified as an object.

**position — Position of GPS receiver (LLA)**
3-element row vector

Position of GPS receiver in geodetic latitude, longitude, and altitude (LLA) specified as a real finite 3-element row vector. Latitude and longitude are in degrees with north and east being positive. Altitude is in meters.

Data Types: `single` | `double`

**positionCovariance — Position measurement covariance of GPS receiver ($m^2$)**
3-by-3 matrix

Position measurement covariance of GPS receiver in $m^2$, specified as a 3-by-3 matrix.

Data Types: `single` | `double`

**velocity — Velocity of GPS receiver in local NED coordinate system (m/s)**
3-element row vector

Velocity of the GPS receiver in the local NED coordinate system in m/s, specified as a 3-element row vector.

Data Types: `single` | `double`

**velocityCovariance — Velocity measurement covariance of GPS receiver ($m/s^2$)**
3-by-3 matrix

Velocity measurement covariance of the GPS receiver in the local NED coordinate system in m/s$^2$, specified as a 3-by-3 matrix.

Data Types: `single` | `double`

## Output Arguments

**`res` — Position and course residual**
1-by-3 vector of real values | 1-by-4 vector of real values

Position and course residual, returned as a 1-by-3 vector of real values the inputs only contain position information, and returned as a 1-by-4 vector of real values if the inputs also contain velocity information.

**`resCov` — Residual covariance**
3-by-3 matrix of real values | 4-by-4 matrix of real values

Residual covariance, returned as a 3-by-3 matrix of real values if the inputs only contain position information, and a 4-by-4 vector of real values if the inputs also contain velocity information.

# Version History

**Introduced in R2020a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

`insfilterNonholonomic`

# stateinfo

Display state vector information for `insfilterNonholonomic`

## Syntax

```
stateinfo(FUSE)
info = stateinfo(FUSE)
```

## Description

`stateinfo(FUSE)` displays the meaning of each index of the State property and the associated units.

`info = stateinfo(FUSE)` returns a structure with fields containing descriptions of the elements of the state vector of the filter, `FUSE`.

## Examples

### State information of `insfilterNonholonomic`

Create an `insfilterNonholonomic` object.

```
filter = insfilterErrorState;
```

Display the state information of the created filter.

```
stateinfo(filter)
```

```
States                            Units    Index
Orientation (quaternion parts)             1:4
Position (NAV)                    m        5:7
Velocity (NAV)                    m/s      8:10
Gyroscope Bias (XYZ)              rad/s    11:13
Accelerometer Bias (XYZ)          m/s²     14:16
Visual Odometry Scale                      17
```

Output the state information of the filter as a structure.

```
info = stateinfo(filter)
```

```
info = struct with fields:
            Orientation: [1 2 3 4]
               Position: [5 6 7]
               Velocity: [8 9 10]
          GyroscopeBias: [11 12 13]
      AccelerometerBias: [14 15 16]
    VisualOdometryScale: 17
```

## Input Arguments

### FUSE — `insfilterNonholonomic` object

object

`insfilterNonholonomic`, specified as an object.

## Output Arguments

### `info` — State information

structure

State information, returned as a structure. The field names of the structure are names of the elements of the state vector in the filter. The values of each field are the corresponding indices of the state vector.

# Version History

**Introduced in R2018b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`insfilter` | `insfilterNonholonomic`

# tune

Tune `insfilterNonholonomic` parameters to reduce estimation error

## Syntax

```
tunedMeasureNoise = tune(filter,measureNoise,sensorData,groundTruth)
tunedMeasureNoise = tune( ___ ,config)
```

## Description

`tunedMeasureNoise = tune(filter,measureNoise,sensorData,groundTruth)` adjusts the properties of the `insfilterNonholonomic` filter object, `filter`, and measurement noises to reduce the root-mean-squared (RMS) state estimation error between the fused sensor data and the ground truth. The function also returns the tuned measurement noise, `tunedMeasureNoise`. The function uses the property values in the filter and the measurement noise provided in the `measureNoise` structure as the initial estimate for the optimization algorithm.

`tunedMeasureNoise = tune( ___ ,config)` specifies the tuning configuration based on a `tunerconfig` object, `config`.

## Examples

### Tune `insfilterNonholonomic` to Optimize Pose Estimate

Load the recorded sensor data and ground truth data.

```
load('insfilterNonholonomicTuneData.mat');
```

Create tables for the sensor data and the truth data.

```
sensorData = table(Accelerometer, Gyroscope, ...
        GPSPosition, GPSVelocity);
groundTruth = table(Orientation, Position);
```

Create an `insfilterNonholonimic` filter object.

```
filter = insfilterNonholonomic('State', initialState, ...
        'StateCovariance', initialStateCovariance, ...
        'DecimationFactor', 1);
```

Create a tuner configuration object for the filter. Set the maximum number of iterations to 30.

```
config = tunerconfig('insfilterNonholonomic','MaxIterations',30);
```

Use the `tunernoise` function to obtain a set of initial sensor noises used in the filter.

```
measNoise = tunernoise('insfilterNonholonomic')
```

```
measNoise = struct with fields:
    GPSPositionNoise: 1
```

```
    GPSVelocityNoise: 1
```

Tune the filter and obtain the tuned measurement noise.

```
tunedNoise = tune(filter,measNoise,sensorData,groundTruth,config);

    Iteration    Parameter                        Metric
    _________    _________                        ______
    1            GyroscopeNoise                   3.4877
    1            AccelerometerNoise               3.3961
    1            GyroscopeBiasNoise               3.3961
    1            GyroscopeBiasDecayFactor         3.3961
    1            AccelerometerBiasNoise           3.3961
    1            AccelerometerBiasDecayFactor     3.3961
    1            ZeroVelocityConstraintNoise      3.3935
    1            GPSPositionNoise                 3.2848
    1            GPSVelocityNoise                 3.2798
    2            GyroscopeNoise                   3.2641
    2            AccelerometerNoise               3.1715
    2            GyroscopeBiasNoise               3.1715
    2            GyroscopeBiasDecayFactor         2.9661
    2            AccelerometerBiasNoise           2.9661
    2            AccelerometerBiasDecayFactor     2.9661
    2            ZeroVelocityConstraintNoise      2.9617
    2            GPSPositionNoise                 2.8438
    2            GPSVelocityNoise                 2.8384
    3            GyroscopeNoise                   2.8373
    3            AccelerometerNoise               2.7382
    3            GyroscopeBiasNoise               2.7382
    3            GyroscopeBiasDecayFactor         2.7382
    3            AccelerometerBiasNoise           2.7382
    3            AccelerometerBiasDecayFactor     2.7382
    3            ZeroVelocityConstraintNoise      2.7335
    3            GPSPositionNoise                 2.6105
    3            GPSVelocityNoise                 2.6045
    4            GyroscopeNoise                   2.6023
    4            AccelerometerNoise               2.5001
    4            GyroscopeBiasNoise               2.5001
    4            GyroscopeBiasDecayFactor         2.5001
    4            AccelerometerBiasNoise           2.5001
    4            AccelerometerBiasDecayFactor     2.5001
    4            ZeroVelocityConstraintNoise      2.4953
    4            GPSPositionNoise                 2.3692
    4            GPSVelocityNoise                 2.3626
    5            GyroscopeNoise                   2.3595
    5            AccelerometerNoise               2.2561
    5            GyroscopeBiasNoise               2.2561
    5            GyroscopeBiasDecayFactor         2.2508
    5            AccelerometerBiasNoise           2.2508
    5            AccelerometerBiasDecayFactor     2.2508
    5            ZeroVelocityConstraintNoise      2.2469
    5            GPSPositionNoise                 2.1265
    5            GPSVelocityNoise                 2.1191
    6            GyroscopeNoise                   2.1148
    6            AccelerometerNoise               2.0150
    6            GyroscopeBiasNoise               2.0150
    6            GyroscopeBiasDecayFactor         2.0150
```

```
6             AccelerometerBiasNoise         2.0150
6             AccelerometerBiasDecayFactor   2.0150
6             ZeroVelocityConstraintNoise    2.0116
6             GPSPositionNoise               1.8970
6             GPSVelocityNoise               1.8888
7             GyroscopeNoise                 1.8847
7             AccelerometerNoise             1.7921
7             GyroscopeBiasNoise             1.7921
7             GyroscopeBiasDecayFactor       1.7845
7             AccelerometerBiasNoise         1.7845
7             AccelerometerBiasDecayFactor   1.7845
7             ZeroVelocityConstraintNoise    1.7815
7             GPSPositionNoise               1.6794
7             GPSVelocityNoise               1.6708
8             GyroscopeNoise                 1.6679
8             AccelerometerNoise             1.5886
8             GyroscopeBiasNoise             1.5886
8             GyroscopeBiasDecayFactor       1.5866
8             AccelerometerBiasNoise         1.5866
8             AccelerometerBiasDecayFactor   1.5866
8             ZeroVelocityConstraintNoise    1.5850
8             GPSPositionNoise               1.5057
8             GPSVelocityNoise               1.4965
9             GyroscopeNoise                 1.4950
9             AccelerometerNoise             1.4364
9             GyroscopeBiasNoise             1.4364
9             GyroscopeBiasDecayFactor       1.4364
9             AccelerometerBiasNoise         1.4364
9             AccelerometerBiasDecayFactor   1.4364
9             ZeroVelocityConstraintNoise    1.4355
9             GPSPositionNoise               1.3894
9             GPSVelocityNoise               1.3790
10            GyroscopeNoise                 1.3773
10            AccelerometerNoise             1.3422
10            GyroscopeBiasNoise             1.3422
10            GyroscopeBiasDecayFactor       1.3421
10            AccelerometerBiasNoise         1.3421
10            AccelerometerBiasDecayFactor   1.3421
10            ZeroVelocityConstraintNoise    1.3399
10            GPSPositionNoise               1.3319
10            GPSVelocityNoise               1.3190
11            GyroscopeNoise                 1.3159
11            AccelerometerNoise             1.3102
11            GyroscopeBiasNoise             1.3102
11            GyroscopeBiasDecayFactor       1.3100
11            AccelerometerBiasNoise         1.3100
11            AccelerometerBiasDecayFactor   1.3100
11            ZeroVelocityConstraintNoise    1.3069
11            GPSPositionNoise               1.2964
11            GPSVelocityNoise               1.2762
12            GyroscopeNoise                 1.2740
12            AccelerometerNoise             1.2655
12            GyroscopeBiasNoise             1.2655
12            GyroscopeBiasDecayFactor       1.2641
12            AccelerometerBiasNoise         1.2641
12            AccelerometerBiasDecayFactor   1.2641
12            ZeroVelocityConstraintNoise    1.2631
12            GPSPositionNoise               1.2511
```

```
    12            GPSVelocityNoise                1.2198
    13            GyroscopeNoise                  1.2184
    13            AccelerometerNoise              1.2058
    13            GyroscopeBiasNoise              1.2058
    13            GyroscopeBiasDecayFactor        1.2029
    13            AccelerometerBiasNoise          1.2029
    13            AccelerometerBiasDecayFactor    1.2029
    13            ZeroVelocityConstraintNoise     1.2029
    13            GPSPositionNoise                1.1874
    13            GPSVelocityNoise                1.1408
    14            GyroscopeNoise                  1.1403
    14            AccelerometerNoise              1.1236
    14            GyroscopeBiasNoise              1.1236
    14            GyroscopeBiasDecayFactor        1.1186
    14            AccelerometerBiasNoise          1.1186
    14            AccelerometerBiasDecayFactor    1.1186
    14            ZeroVelocityConstraintNoise     1.1183
    14            GPSPositionNoise                1.0975
    14            GPSVelocityNoise                1.0348
    15            GyroscopeNoise                  1.0347
    15            AccelerometerNoise              1.0155
    15            GyroscopeBiasNoise              1.0155
    15            GyroscopeBiasDecayFactor        1.0081
    15            AccelerometerBiasNoise          1.0081
    15            AccelerometerBiasDecayFactor    1.0081
    15            ZeroVelocityConstraintNoise     1.0076
    15            GPSPositionNoise                0.9813
    15            GPSVelocityNoise                0.9078
    16            GyroscopeNoise                  0.9074
    16            AccelerometerNoise              0.8926
    16            GyroscopeBiasNoise              0.8926
    16            GyroscopeBiasDecayFactor        0.8823
    16            AccelerometerBiasNoise          0.8823
    16            AccelerometerBiasDecayFactor    0.8823
    16            ZeroVelocityConstraintNoise     0.8815
    16            GPSPositionNoise                0.8526
    16            GPSVelocityNoise                0.7926
    17            GyroscopeNoise                  0.7920
    17            AccelerometerNoise              0.7870
    17            GyroscopeBiasNoise              0.7870
    17            GyroscopeBiasDecayFactor        0.7742
    17            AccelerometerBiasNoise          0.7742
    17            AccelerometerBiasDecayFactor    0.7742
    17            ZeroVelocityConstraintNoise     0.7730
    17            GPSPositionNoise                0.7665
    17            GPSVelocityNoise                0.7665
    18            GyroscopeNoise                  0.7662
    18            AccelerometerNoise              0.7638
    18            GyroscopeBiasNoise              0.7638
    18            GyroscopeBiasDecayFactor        0.7495
    18            AccelerometerBiasNoise          0.7495
    18            AccelerometerBiasDecayFactor    0.7495
    18            ZeroVelocityConstraintNoise     0.7482
    18            GPSPositionNoise                0.7482
    18            GPSVelocityNoise                0.7475
    19            GyroscopeNoise                  0.7474
    19            AccelerometerNoise              0.7474
    19            GyroscopeBiasNoise              0.7474
```

```
19          GyroscopeBiasDecayFactor        0.7474
19          AccelerometerBiasNoise          0.7474
19          AccelerometerBiasDecayFactor    0.7474
19          ZeroVelocityConstraintNoise     0.7453
19          GPSPositionNoise                0.7416
19          GPSVelocityNoise                0.7382
20          GyroscopeNoise                  0.7378
20          AccelerometerNoise              0.7370
20          GyroscopeBiasNoise              0.7370
20          GyroscopeBiasDecayFactor        0.7370
20          AccelerometerBiasNoise          0.7370
20          AccelerometerBiasDecayFactor    0.7370
20          ZeroVelocityConstraintNoise     0.7345
20          GPSPositionNoise                0.7345
20          GPSVelocityNoise                0.7345
21          GyroscopeNoise                  0.7334
21          AccelerometerNoise              0.7334
21          GyroscopeBiasNoise              0.7334
21          GyroscopeBiasDecayFactor        0.7334
21          AccelerometerBiasNoise          0.7334
21          AccelerometerBiasDecayFactor    0.7334
21          ZeroVelocityConstraintNoise     0.7306
21          GPSPositionNoise                0.7279
21          GPSVelocityNoise                0.7268
22          GyroscopeNoise                  0.7248
22          AccelerometerNoise              0.7247
22          GyroscopeBiasNoise              0.7247
22          GyroscopeBiasDecayFactor        0.7234
22          AccelerometerBiasNoise          0.7234
22          AccelerometerBiasDecayFactor    0.7234
22          ZeroVelocityConstraintNoise     0.7207
22          GPSPositionNoise                0.7206
22          GPSVelocityNoise                0.7170
23          GyroscopeNoise                  0.7138
23          AccelerometerNoise              0.7134
23          GyroscopeBiasNoise              0.7134
23          GyroscopeBiasDecayFactor        0.7134
23          AccelerometerBiasNoise          0.7134
23          AccelerometerBiasDecayFactor    0.7134
23          ZeroVelocityConstraintNoise     0.7122
23          GPSPositionNoise                0.7122
23          GPSVelocityNoise                0.7122
24          GyroscopeNoise                  0.7081
24          AccelerometerNoise              0.7080
24          GyroscopeBiasNoise              0.7080
24          GyroscopeBiasDecayFactor        0.7080
24          AccelerometerBiasNoise          0.7080
24          AccelerometerBiasDecayFactor    0.7080
24          ZeroVelocityConstraintNoise     0.7080
24          GPSPositionNoise                0.7080
24          GPSVelocityNoise                0.7072
25          GyroscopeNoise                  0.7009
25          AccelerometerNoise              0.7009
25          GyroscopeBiasNoise              0.7009
25          GyroscopeBiasDecayFactor        0.7007
25          AccelerometerBiasNoise          0.7007
25          AccelerometerBiasDecayFactor    0.7007
25          ZeroVelocityConstraintNoise     0.7005
```

```
    25          GPSPositionNoise               0.6997
    25          GPSVelocityNoise               0.6997
    26          GyroscopeNoise                 0.6912
    26          AccelerometerNoise             0.6906
    26          GyroscopeBiasNoise             0.6906
    26          GyroscopeBiasDecayFactor       0.6906
    26          AccelerometerBiasNoise         0.6906
    26          AccelerometerBiasDecayFactor   0.6906
    26          ZeroVelocityConstraintNoise    0.6896
    26          GPSPositionNoise               0.6896
    26          GPSVelocityNoise               0.6896
    27          GyroscopeNoise                 0.6840
    27          AccelerometerNoise             0.6831
    27          GyroscopeBiasNoise             0.6831
    27          GyroscopeBiasDecayFactor       0.6831
    27          AccelerometerBiasNoise         0.6831
    27          AccelerometerBiasDecayFactor   0.6831
    27          ZeroVelocityConstraintNoise    0.6818
    27          GPSPositionNoise               0.6816
    27          GPSVelocityNoise               0.6816
    28          GyroscopeNoise                 0.6816
    28          AccelerometerNoise             0.6809
    28          GyroscopeBiasNoise             0.6809
    28          GyroscopeBiasDecayFactor       0.6809
    28          AccelerometerBiasNoise         0.6809
    28          AccelerometerBiasDecayFactor   0.6809
    28          ZeroVelocityConstraintNoise    0.6804
    28          GPSPositionNoise               0.6802
    28          GPSVelocityNoise               0.6802
    29          GyroscopeNoise                 0.6793
    29          AccelerometerNoise             0.6785
    29          GyroscopeBiasNoise             0.6785
    29          GyroscopeBiasDecayFactor       0.6785
    29          AccelerometerBiasNoise         0.6785
    29          AccelerometerBiasDecayFactor   0.6785
    29          ZeroVelocityConstraintNoise    0.6778
    29          GPSPositionNoise               0.6773
    29          GPSVelocityNoise               0.6773
    30          GyroscopeNoise                 0.6773
    30          AccelerometerNoise             0.6769
    30          GyroscopeBiasNoise             0.6769
    30          GyroscopeBiasDecayFactor       0.6769
    30          AccelerometerBiasNoise         0.6769
    30          AccelerometerBiasDecayFactor   0.6769
    30          ZeroVelocityConstraintNoise    0.6769
    30          GPSPositionNoise               0.6769
    30          GPSVelocityNoise               0.6769
```

Fuse the sensor data using the tuned filter. Obtain estimated pose and orientation.

```
N = size(sensorData,1);
qEstTuned = quaternion.zeros(N,1);
posEstTuned = zeros(N,3);
for ii=1:N
    predict(filter,Accelerometer(ii,:),Gyroscope(ii,:));
    if all(~isnan(GPSPosition(ii,1)))
        fusegps(filter, GPSPosition(ii,:), ...
            tunedNoise.GPSPositionNoise,GPSVelocity(ii,:), ...
```

```
            tunedNoise.GPSVelocityNoise);
    end
    [posEstTuned(ii,:),qEstTuned(ii,:)] = pose(filter);
end
```

Compute the RMS errors.

```
orientationErrorTuned = rad2deg(dist(qEstTuned,Orientation));
rmsOrientationErrorTuned = sqrt(mean(orientationErrorTuned.^2))
```

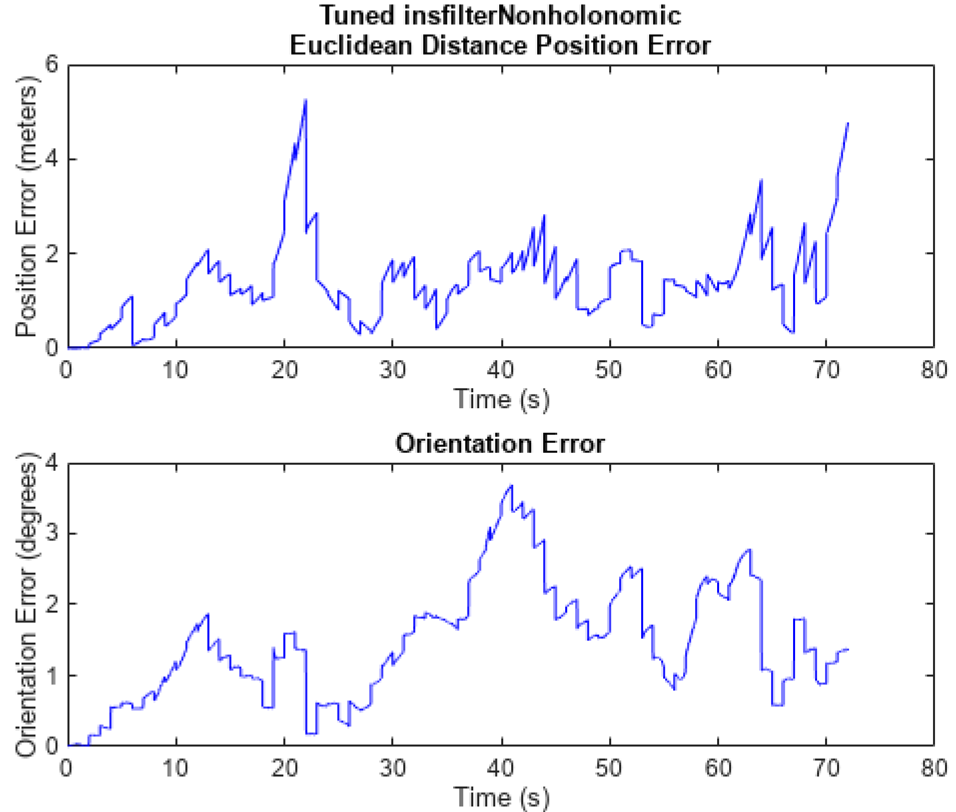
```
rmsOrientationErrorTuned = 1.6857
```

```
positionErrorTuned = sqrt(sum((posEstTuned-Position).^2,2));
rmsPositionErrorTuned = sqrt(mean(positionErrorTuned.^2))
```

```
rmsPositionErrorTuned = 1.6667
```

Visualize the results.

```
figure;
t = (0:N-1)./filter.IMUSampleRate;
subplot(2,1,1)
plot(t,positionErrorTuned,'b');
title("Tuned insfilterNonholonomic" + newline + ...
    "Euclidean Distance Position Error")
xlabel('Time (s)');
ylabel('Position Error (meters)')
subplot(2,1,2)
plot(t,orientationErrorTuned,'b');
title("Orientation Error")
xlabel('Time (s)');
ylabel('Orientation Error (degrees)');
```




## Input Arguments

**`filter` — Filter object**
`infilterAsync` object

Filter object, specified as an `insfilterNonholonomic` object.

**`measureNoise` — Measurement noise**
structure

Measurement noise, specified as a structure. The function uses the measurement noise input as the initial guess for tuning the measurement noise. The structure must contain these fields:

| Field name | Description |
| --- | --- |
| `GPSPositionNoise` | Variance of GPS position noise, specified as a scalar in $m^2$ |
| `GPSVelocityNoise` | Variance of GPS velocity noise, specified as a scalar in $(m/s)^2$ |

Data Types: `struct`

**`sensorData` — Sensor data**
`table`

Sensor data, specified as a `table`. In each row, the sensor data is specified as:

- `Accelerometer` — Accelerometer data, specified as a 1-by-3 vector of scalars in $m^2/s$.
- `Gyroscope` — Gyroscope data, specified as a 1-by-3 vector of scalars in rad/s.
- `GPSPosition` — GPS position data, specified as a 1-by-3 vector of latitude in degrees, longitude in degrees, and altitude in meters.
- `GPSVelocity` — GPS velocity data, specified as a 1-by-3 vector of scalars in m/s.

If the GPS sensor does not produce complete measurements, specify the corresponding entry for `GPSPosition` and/or `GPSVelocity` as `NaN`. If you set the `Cost` property of the tuner configuration input, `config`, to `Custom`, then you can use other data types for the `sensorData` input based on your choice.

Data Types: `table`

**`groundTruth` — Ground truth data**
`table`

Ground truth data, specified as a table. In each row, the table can optionally contain any of these variables:

- `Orientation` — Orientation from the navigation frame to the body frame, specified as a `quaternion` or a 3-by-3 rotation matrix.
- `Position` — Position in navigation frame, specified as a 1-by-3 vector of scalars in meters.
- `Velocity` — Velocity in navigation frame, specified as a 1-by-3 vector of scalars in m/s.
- `GyroscopeBias` — Gyroscope delta angle bias in body frame, specified as a 1-by-3 vector of scalars in rad/s.
- `AccelerometerBias` — Accelerometer delta angle bias in body frame, specified as a 1-by-3 vector of scalars in $m^2/s$.

The function processes each row of the `sensorData` and `groundTruth` tables sequentially to calculate the state estimate and RMS error from the ground truth. State variables not present in `groundTruth` input are ignored for the comparison. The `sensorData` and the `groundTruth` tables must have the same number of rows.

If you set the `Cost` property of the tuner configuration input, `config`, to `Custom`, then you can use other data types for the `groundTruth` input based on your choice.

Data Types: `table`

**`config` — Tuner configuration**
`tunerconfig` object

Tuner configuration, specified as a `tunerconfig` object.

## Output Arguments

**`tunedMeasureNoise` — Tuned measurement noise**
structure

Tuned measurement noise, returned as a structure. The structure contains these fields.

| Field name | Description |
| --- | --- |
| GPSPositionNoise | Variance of GPS position noise, specified as a scalar in $m^2$ |
| GPSVelocityNoise | Variance of GPS velocity noise, specified as a scalar in $(m/s)^2$ |

Data Types: struct

# Version History

**Introduced in R2020b**

## References

[1] Abbeel, Pieter, et al. “Discriminative Training of Kalman Filters.” Robotics: Science and Systems I, Robotics: Science and Systems Foundation, 2005. DOI.org (Crossref), doi:10.15607/RSS.2005.I.038.

## See Also

tunerconfig | tunernoise | insfilterNonholonomic

# occupancyMap

Create 2-D occupancy map

## Description

occupancyMap creates a 2-D occupancy grid map object. Each cell in the occupancy grid has a value representing the probability of the occupancy of that cell. Values close to 1 represent a high probability that the cell contains an obstacle. Values close to 0 represent a high probability that the cell is not occupied and obstacle free.

Occupancy maps are used in navigation algorithms such as path planning (see plannerRRT). They are also used in mapping applications for finding collision-free paths, performing collision avoidance, and calculating localization (see monteCarloLocalization). You can modify your occupancy map to fit your specific application.

The occupancyMap objects support local coordinates, world coordinates, and grid indices. The first grid location with index (1,1) begins in the top-left corner of the grid.

Use the occupancyMap class to create 2-D maps of an environment with probability values representing different obstacles in your world. You can specify exact probability values of cells or include observations from sensors such as laser scanners.

Probability values are stored using a binary Bayes filter to estimate the occupancy of each grid cell. A log-odds representation is used, with values stored as int16 to reduce the map storage size and allow for real-time applications.

## Creation

### Syntax

```
map = occupancyMap(width,height)
map = occupancyMap(width,height,resolution)
map = occupancyMap(rows,cols,resolution,'grid')
map = occupancyMap(p)
map = occupancyMap(p,resolution)
map = occupancyMap(sourcemap)
map = occupancyMap(sourcemap,resolution)
```

#### Description

map = occupancyMap(width,height) creates a 2-D occupancy map object representing a world space of width and height in meters. The default grid resolution is 1 cell per meter.

map = occupancyMap(width,height,resolution) creates an occupancy map with a specified grid resolution in cells per meter. resolution sets the “Resolution” on page 2-0 property.

`map = occupancyMap(rows,cols,resolution,'grid')` creates an occupancy map with the specified number of rows and columns and with the resolution in cells per meter. The values of `rows` and `cols` sets the "GridSize" on page 2-0 property.

`map = occupancyMap(p)` creates an occupancy map from the values in matrix `p`. The grid size matches the size of the matrix, with each cell probability value interpreted from the matrix location.

`map = occupancyMap(p,resolution)` creates an occupancy map from the specified matrix and resolution in cells per meter.

`map = occupancyMap(sourcemap)` creates an object using values from another `occupancyMap` object.

`map = occupancyMap(sourcemap,resolution)` creates an object using values from another `occupancyMap` object, but resamples the matrix to have the specified resolution.

### Input Arguments

#### `width` — Map width
scalar

Map width, specified as a scalar in meters.

#### `height` — Map height
scalar

Map height, specified as a scalar in meters.

#### `resolution` — Grid resolution
`1` (default) | scalar

Grid resolution, specified as a scalar in cells per meter.

#### `rows` — Number of rows in grid
positive scalar integer

Number of rows in grid, specified as a positive scalar integer.

#### `cols` — Number of columns in grid
positive scalar integer

Number of columns in grid, specified as a positive scalar integer.

#### `p` — Input occupancy grid
matrix of probability values from `0` to `1`

Input occupancy grid, specified as a matrix of probability values from `0` to `1`. The size of the grid matches the size of the matrix. Each matrix element corresponds to the probability of the grid cell location being occupied. Values close to `1` represent a high certainty that the cell contains an obstacle. Values close to `0` represent certainty that the cell is not occupied and obstacle free.

#### `sourcemap` — Occupancy map object
`occupancyMap` object

Occupancy map object, specified as a `occupancyMap` object.

## Properties

**`FreeThreshold` — Threshold below which cells are considered obstacle-free**
scalar between `0` and `1`

Threshold below which cells are considered obstacle-free, specified as a scalar between `0` and `1` inclusive. Cells with probability values below this threshold are considered obstacle free. This property also defines the free locations for path planning when using objects like `plannerRRT`.

Data Types: `double`

**`OccupiedThreshold` — Threshold above which cells are considered occupied**
scalar

Threshold above which cells are considered occupied, specified as a scalar. Cells with probability values above this threshold are considered occupied.

Data Types: `double`

**`ProbabilitySaturation` — Saturation limits for probability**
`[0.001 0.999]` (default) | two-element real-valued vector

Saturation limits for probability, specified as a 1-by-2 real-valued vector of the form `[min max]`. The probability values below *min* value will be saturated to *min* and the probability values above *max* value will be saturated to *max*. This property reduces oversaturating of cells when incorporating multiple observations.

Data Types: `double`

**`GridSize` — Number of rows and columns in grid**
two-element integer-valued vector

This property is read-only.

Number of rows and columns in grid, stored as a 1-by-2 real-valued vector representing the number of rows and columns, in that order.

Data Types: `double`

**`Resolution` — Grid resolution**
`1` (default) | scalar

This property is read-only.

Grid resolution, stored as a scalar in cells per meter representing the number and size of grid locations.

Data Types: `double`

**`XLocalLimits` — Minimum and maximum values of *x*-coordinates in local frame**
two-element vector

This property is read-only.

Minimum and maximum values of *x*-coordinates in local frame, stored as a two-element horizontal vector of the form `[min max]`. Local frame is defined by `LocalOriginInWorld` property.

Data Types: `double`

**`YLocalLimits` — Minimum and maximum values of *y*-coordinates in local frame**
two-element vector

This property is read-only.

Minimum and maximum values of *y*-coordinates in local frame, stored as a two-element horizontal vector of the form `[min max]`. Local frame is defined by `LocalOriginInWorld` property.

Data Types: `double`

**`XWorldLimits` — Minimum and maximum world range values of *x*-coordinates**
two-element vector

This property is read-only.

Minimum and maximum world range values of *x*-coordinates, stored as a 1-by-2 vector representing the minimum and maximum values, in that order.

Data Types: `double`

**`YWorldLimits` — Minimum and maximum world range values of *y*-coordinates**
two-element vector

This property is read-only.

Minimum and maximum world range values of *y*-coordinates, stored as a 1-by-2 vector representing the minimum and maximum values, in that order.

Data Types: `double`

**`GridLocationInWorld` — `[x y]` world coordinates of grid**
`[0 0]` (default) | two-element vector

[*x*,*y*] world coordinates of the bottom-left corner of the grid, specified as a 1-by-2 vector.

Data Types: `double`

**`LocalOriginInWorld` — Location of the local frame in world coordinates**
`[0 0]` (default) | two-element vector | `[xWorld yWorld]`

Location of the origin of the local frame in world coordinates, specified as a two-element vector, `[xLocal yLocal]`. Use the `move` function to shift the local frame as your vehicle moves.

Data Types: `double`

**`GridOriginInLocal` — Location of the grid in local coordinates**
`[0 0]` (default) | two-element vector | `[xLocal yLocal]`

Location of the bottom-left corner of the grid in local coordinates, specified as a two-element vector, `[xLocal yLocal]`.

Data Types: `double`

**`DefaultValue` — Default value for unspecified map locations**
`0.5` (default) | scalar between `0` and `1`

Default value for unspecified map locations including areas outside the map, specified as a scalar between `0` and `1` inclusive.

Data Types: `double`

## Object Functions

| | |
|---|---|
| checkOccupancy | Check if locations are free or occupied |
| copy | Create copy of 2-D occupancy map |
| getOccupancy | Get occupancy probability of locations |
| grid2local | Convert grid indices to local coordinates |
| grid2world | Convert grid indices to world coordinates |
| inflate | Inflate each occupied location |
| insertRay | Insert ray from laser scan observation |
| local2grid | Convert local coordinates to grid indices |
| local2world | Convert local coordinates to world coordinates |
| move | Move map in world frame |
| occupancyMatrix | Convert occupancy map to matrix |
| raycast | Compute cell indices along a ray |
| rayIntersection | Find intersection points of rays and occupied map cells |
| setOccupancy | Set occupancy probability of locations |
| show | Display 2-D occupancy map |
| syncWith | Sync map with overlapping map |
| updateOccupancy | Update occupancy probability at locations |
| world2grid | Convert world coordinates to grid indices |
| world2local | Convert world coordinates to local coordinates |

## Examples

### Insert Laser Scans into Occupancy Map

Create an empty occupancy grid map.

```
map = occupancyMap(10,10,20);
```

Specify the pose of the vehicle, ranges, angles, and the maximum range of the laser scan.

```
pose = [5,5,0];
ranges = 3*ones(100,1);
angles = linspace(-pi/2,pi/2,100);
maxrange = 20;
```

Create a `lidarScan` object with the specified ranges and angles.

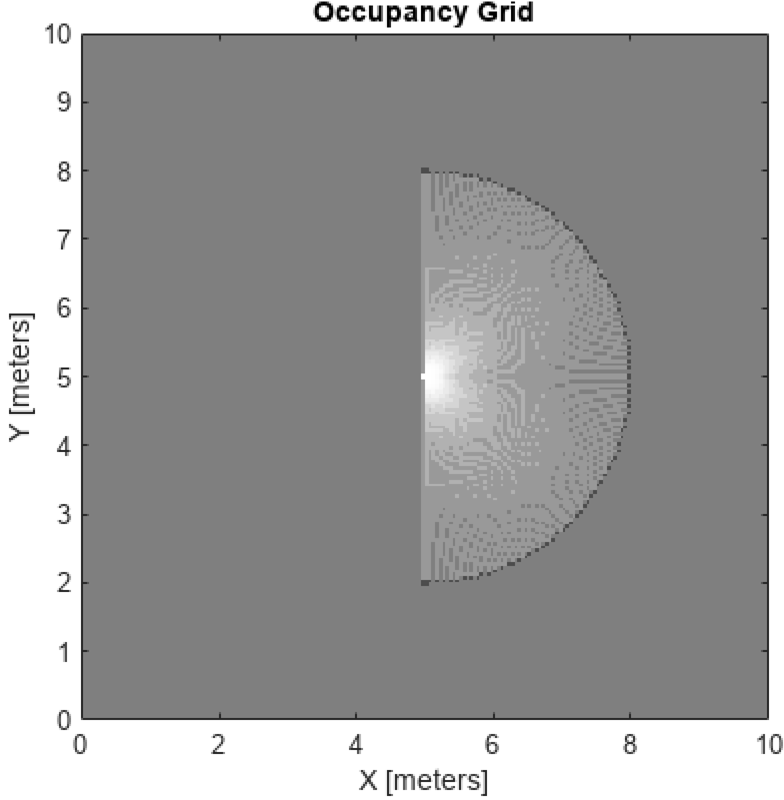
```
scan = lidarScan(ranges,angles);
```

Insert the laser scan data into the occupancy map.

```
insertRay(map,pose,scan,maxrange);
```

Show the map to see the results of inserting the laser scan.

```
show(map)
```



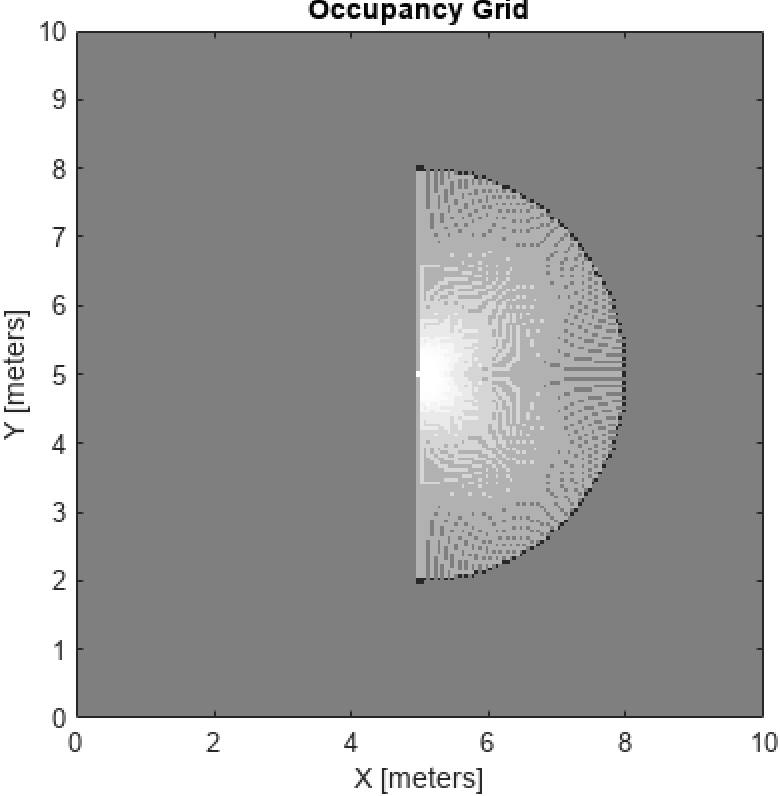

Check the occupancy of the spot directly in front of the vehicle.

```
getOccupancy(map,[8 5])
```

```
ans = 0.7000
```

Add a second reading and view the update to the occupancy values. The additional reading increases the confidence in the readings. The free and occupied values become more distinct.

```
insertRay(map,pose,scan,maxrange);
show(map)
```




```
getOccupancy(map,[8 5])
```

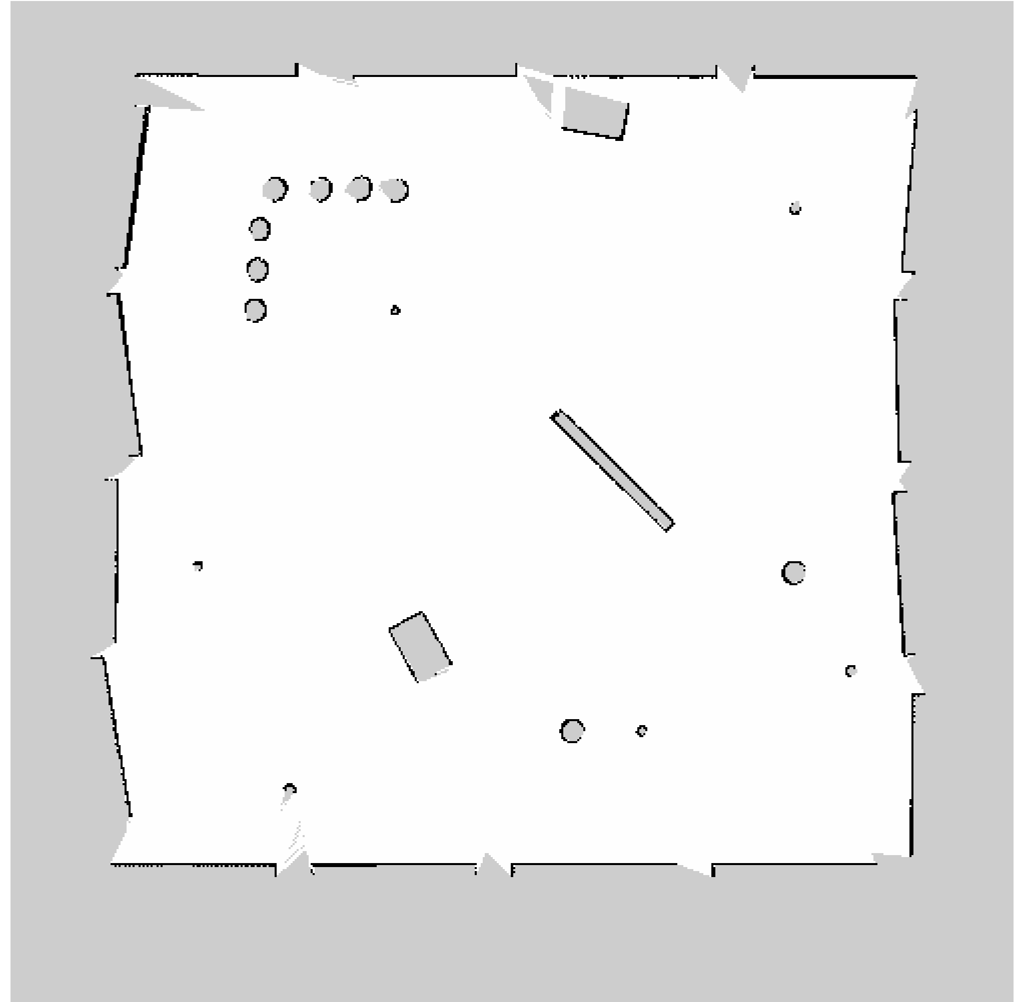
```
ans = 0.8448
```

#### Convert PGM Image to Map

Convert a portable graymap (PGM) file containing a ROS map into an `occupancyMap` for use in MATLAB.

Import the image using `imread`. Crop the image to the playpen area.

```
image = imread('playpen_map.pgm');
imageCropped = image(750:1250,750:1250);
imshow(imageCropped)
```

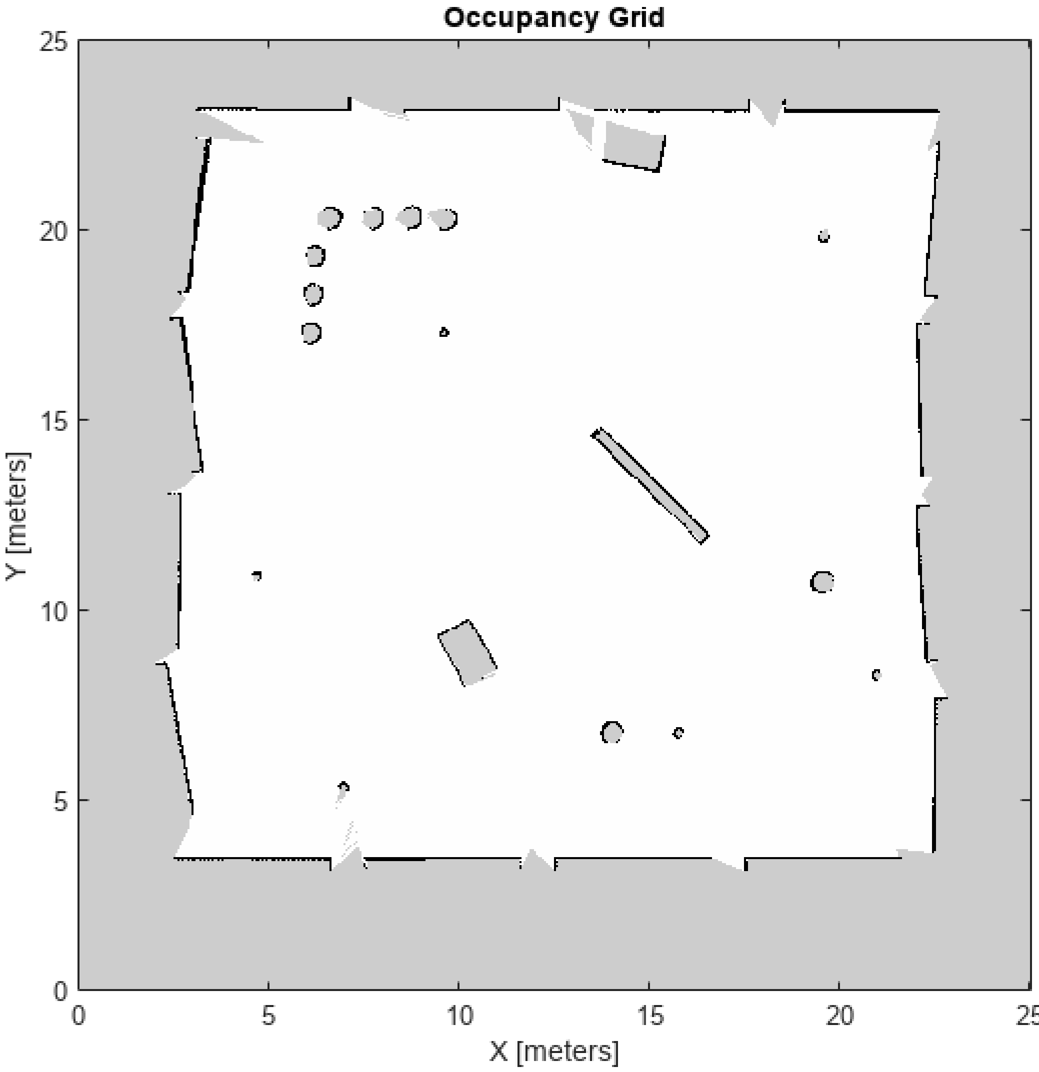


PGM values are expressed from 0 to 255 as `uint8`. Normalize these values by converting the cropped image to `double` and dividing each cell by 255. This image shows obstacles as values close to 0. Subtract the normalized image from 1 to get occupancy values with 1 representing occupied space.

```
imageNorm = double(imageCropped)/255;
imageOccupancy = 1 - imageNorm;
```

Create the `occupancyMap` object using an adjusted map image. The imported map resolution is 20 cells per meter.

```
map = occupancyMap(imageOccupancy,20);
show(map)
```




## Limitations

Occupancy values have a limited resolution of ±0.001. The values are stored as `int16` using a log-odds representation. This data type limits resolution, but saves memory when storing large maps in MATLAB. When calling `setOccupancy` and then `getOccupancy`, the value returned might not equal the value you set. For more information, see the log-odds representations section in “Occupancy Grids”.

If memory size is a limitation, consider using `binaryOccupancyMap` instead. The binary occupancy map uses less memory with binary values, but still works with Navigation Toolbox algorithms and other applications.

## Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

As of MATLAB R2022a, default map behavior during code generation has changed, which may result in backwards compatibility issues. Maps such as `occupancyMap` now support fixed-size code generation (`DynamicMemoryAllocation="off"`).

1. Maps that are either default-constructed or constructed with compile-time constant size information (or matrices that are of compile-time constant size) produce fixed-size maps.
2. To restore the previous behavior, use the `coder.ignoreConst` function when specifying size inputs, or `coder.varsize` matrix variable name specified as a string scalar or character vector, prior to constructing the map.

## See Also

`binaryOccupancyMap` | `mobileRobotPRM` | `controllerPurePursuit` | `rosReadOccupancyGrid` | `rosWriteOccupancyGrid`

### Topics

"Create Egocentric Occupancy Maps Using Range Sensors"
"Build Occupancy Map from Lidar Scans and Poses"
"Occupancy Grids"

# checkOccupancy

Check if locations are free or occupied

## Syntax

```
iOccval = checkOccupancy(map,xy)
iOccval = checkOccupancy(map,xy,'local')
iOccval = checkOccupancy(map,ij,'grid')
[iOccval,validPts] = checkOccupancy( ___ )
```

```
occMatrix = checkOccupancy(map)
occMatrix = checkOccupancy(map,bottomLeft,matSize)
occMatrix = checkOccupancy(map,bottomLeft,matSize,'local')
occMatrix = checkOccupancy(map,topLeft,matSize,'grid')
```

## Description

`iOccval = checkOccupancy(map,xy)` returns an array of occupancy values at the `xy` locations. Each row is a separate `xy` location in the grid. Occupancy values can be obstacle free (`0`), occupied (`1`), or unknown (–1) based on the `OccupiedThreshold` and `FreeThreshold` properties of the `map` object.

`iOccval = checkOccupancy(map,xy,'local')` returns an array of occupancy values at the `xy` locations in the local frame. The local frame is based on the `LocalOriginInWorld` property of the `map`.

`iOccval = checkOccupancy(map,ij,'grid')` specifies `ij` grid cell indices instead of `xy` locations.

`[iOccval,validPts] = checkOccupancy( ___ )` also outputs an `n`-element vector of logical values indicating whether input coordinates are within the map limits.

`occMatrix = checkOccupancy(map)` returns a matrix that contains the occupancy status of each location. Obstacle-free cells return `0`, occupied cells return `1`. Unknown locations, including outside the map, return `-1`.

`occMatrix = checkOccupancy(map,bottomLeft,matSize)` returns a matrix of occupancy values by specifying the bottom-left corner location in world coordinates and the matrix size in meters.

`occMatrix = checkOccupancy(map,bottomLeft,matSize,'local')` returns a matrix of occupancy values by specifying the bottom-left corner location in local coordinates and the matrix size in meters.

`occMatrix = checkOccupancy(map,topLeft,matSize,'grid')` returns a matrix of occupancy values by specifying the top-left corner location in grid coordinates and the grid size.

## Examples

### Get Occupancy Values and Check Occupancy Status

Access occupancy values and check their occupancy status based on the occupied and free thresholds of the `occupancyMap` object.

Create a matrix and populate it with values. Use this matrix to create an occupancy map.

```
p = 0.5*ones(20,20);
p(11:20,11:20) = 0.75*ones(10,10);
map = occupancyMap(p,10);
```

Get the occupancy of different locations and check their occupancy statuses. The occupancy status returns 0 for free space and 1 for occupied space. Unknown values return –1.

```
pocc = getOccupancy(map,[1.5 1])
```

```
pocc = 0.7500
```

```
occupied = checkOccupancy(map,[1.5 1])
```

```
occupied = 1
```

```
pocc2 = getOccupancy(map,[5 5],'grid')
```

```
pocc2 = 0.5000
```

```
occupied2 = checkOccupancy(map,[5 5],'grid')
```

```
occupied2 = -1
```

## Input Arguments

**`map` — Map representation**
`occupancyMap` object

Map representation, specified as a `occupancyMap` object. This object represents the environment of the vehicle. The object contains a matrix grid with values representing the probability of the occupancy of that cell. Values close to 1 represent a high certainty that the cell contains an obstacle. Values close to 0 represent certainty that the cell is not occupied and obstacle free.

**`xy` — World coordinates**
*n*-by-2 matrix

World coordinates, specified as an *n*-by-2 matrix of `[x y]` pairs, where *n* is the number of world coordinates.

Data Types: `double`

**`ij` — Grid positions**
*n*-by-2 matrix

Grid positions, specified as an *n*-by-2 matrix of `[i j]` pairs in `[rows cols]` format, where *n* is the number of grid positions.

Data Types: `double`

**bottomLeft — Location of output matrix in world or local**
two-element vector | [xCoord yCoord]

Location of bottom left corner of output matrix in world or local coordinates, specified as a two-element vector, [xCoord yCoord]. Location is in world or local coordinates based on syntax.

Data Types: double

**matSize — Output matrix size**
two-element vector | [xLength yLength] | [gridRow gridCol]

Output matrix size, specified as a two-element vector, [xLength yLength], or [gridRow gridCol]. Size is in world, local, or grid coordinates based on syntax.

Data Types: double

**topLeft — Location of grid**
two-element vector | [iCoord jCoord]

Location of top left corner of grid, specified as a two-element vector, [iCoord jCoord].

Data Types: double

## Output Arguments

**iOccval — Interpreted occupancy values**
*n*-by-1 column vector

Interpreted occupancy values, returned as an *n*-by-1 column vector equal in length to xy or ij.

Occupancy values can be obstacle free (0), occupied (1), or unknown (–1). These values are determined from the actual probability values and the OccupiedThreshold and FreeThreshold properties of the map object.

**validPts — Valid map locations**
*n*-by-1 column vector

Valid map locations, returned as an *n*-by-1 column vector equal in length to xy or ij. Locations inside the map return a value of 1. Locations outside the map limits return a value of 0.

**occMatrix — Matrix of occupancy values**
matrix

Matrix of occupancy values, returned as matrix with size equal to matSize or the size of your map. Occupancy values can be obstacle free (0), occupied (1), or unknown (-1).

# Version History

**Introduced in R2019b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

`occupancyMap` | `getOccupancy` | `binaryOccupancyMap`

# copy

Create copy of 2-D occupancy map

## Syntax

```
copyMap = copy(map)
```

## Description

`copyMap = copy(map)` creates a deep copy of the `occupancyMap` object with the same properties.

## Examples

### Copy Occupancy Grid Map

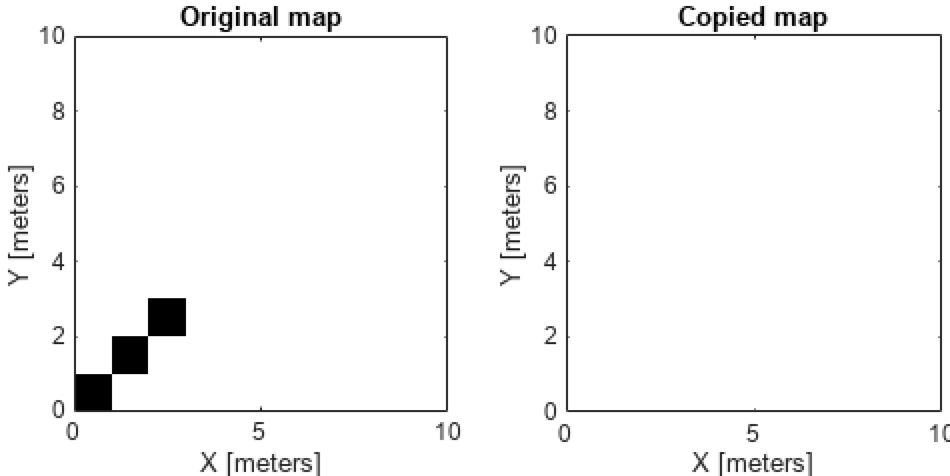
Copy an occupancy grid map object. Once copied, the original object can be modified without affecting the copied map.

Create an occupancy grid with zeros for an empty map.

```
p = zeros(10);
map = occupancyMap(p);
```

Copy the occupancy grid map. Modify the original map. The copied map is not modified. Plot the two maps side by side.

```
mapCopy = copy(map);
setOccupancy(map,[1:3;1:3]',ones(3,1));
subplot(1,2,1)
show(map)
title('Original map')
subplot(1,2,2)
show(mapCopy)
title('Copied map')
```




## Input Arguments

**map — Map representation**
occupancyMap object

Map representation, specified as a occupancyMap object. This object represents the environment of the vehicle. The object contains a matrix grid with values representing the probability of the occupancy of that cell. Values close to 1 represent a high probability that the cell contains an obstacle. Values close to 0 represent a high probability that the cell is not occupied and obstacle free.

## Output Arguments

**copyMap — Copied map representation**
occupancyMap object

Map representation, specified as a occupancyMap object. The properties are the same as the input object, map, but the copy has a different object handle.

# Version History

**Introduced in R2019b**

## See Also

`binaryOccupancyMap` | `occupancyMap` | `occupancyMatrix` | `getOccupancy`

### Topics

"Occupancy Grids"

# getOccupancy

Get occupancy probability of locations

## Syntax

```
occVal = getOccupancy(map,xy)
occVal = getOccupancy(map,xy,'local')
occVal = getOccupancy(map,ij,'grid')
[occVal,validPts] = getOccupancy( ___ )

occMatrix = getOccupancy(map)
occMatrix = getOccupancy(map,bottomLeft,matSize)
occMatrix = getOccupancy(map,bottomLeft,matSize,'local')
occMatrix = getOccupancy(map,topLeft,matSize,'grid')
```

## Description

`occVal = getOccupancy(map,xy)` returns an array of probability occupancy values at the `xy` locations in the world frame. Values close to 1 represent a high probability that the cell contains an obstacle. Values close to 0 represent a high probability that the cell is not occupied and obstacle free. Unknown locations, including outside the map, return `map.DefaultValue`.

`occVal = getOccupancy(map,xy,'local')` returns an array of occupancy values at the `xy` locations in the local frame.

`occVal = getOccupancy(map,ij,'grid')` specifies `ij` grid cell indices instead of `xy` locations.

`[occVal,validPts] = getOccupancy( ___ )` additionally outputs an `n`-element vector of logical values indicating whether input coordinates are within the map limits.

`occMatrix = getOccupancy(map)` returns all occupancy values in the map as a matrix.

`occMatrix = getOccupancy(map,bottomLeft,matSize)` returns a matrix of occupancy values by specifying the bottom-left corner location in world coordinates and the matrix size in meters.

`occMatrix = getOccupancy(map,bottomLeft,matSize,'local')` returns a matrix of occupancy values by specifying the bottom-left corner location in local coordinates and the matrix size in meters.

`occMatrix = getOccupancy(map,topLeft,matSize,'grid')` returns a matrix of occupancy values by specifying the top-left corner location in grid indices and the matrix size.

## Examples

### Insert Laser Scans into Occupancy Map

Create an empty occupancy grid map.

```
map = occupancyMap(10,10,20);
```

Specify the pose of the vehicle, ranges, angles, and the maximum range of the laser scan.

```
pose = [5,5,0];
ranges = 3*ones(100,1);
angles = linspace(-pi/2,pi/2,100);
maxrange = 20;
```

Create a `lidarScan` object with the specified ranges and angles.

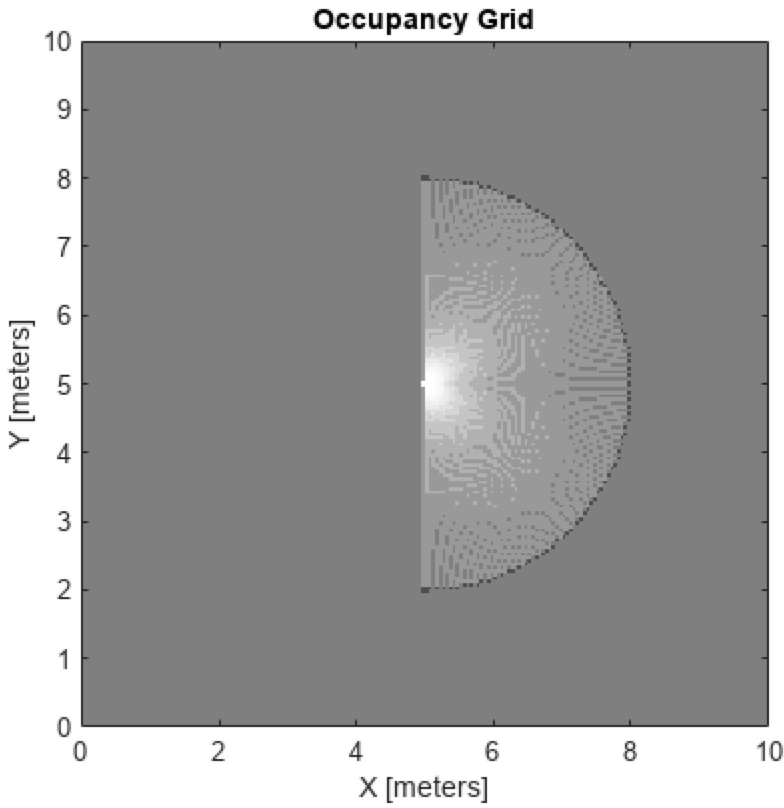
```
scan = lidarScan(ranges,angles);
```

Insert the laser scan data into the occupancy map.

```
insertRay(map,pose,scan,maxrange);
```

Show the map to see the results of inserting the laser scan.

```
show(map)
```

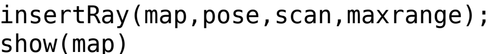



Check the occupancy of the spot directly in front of the vehicle.

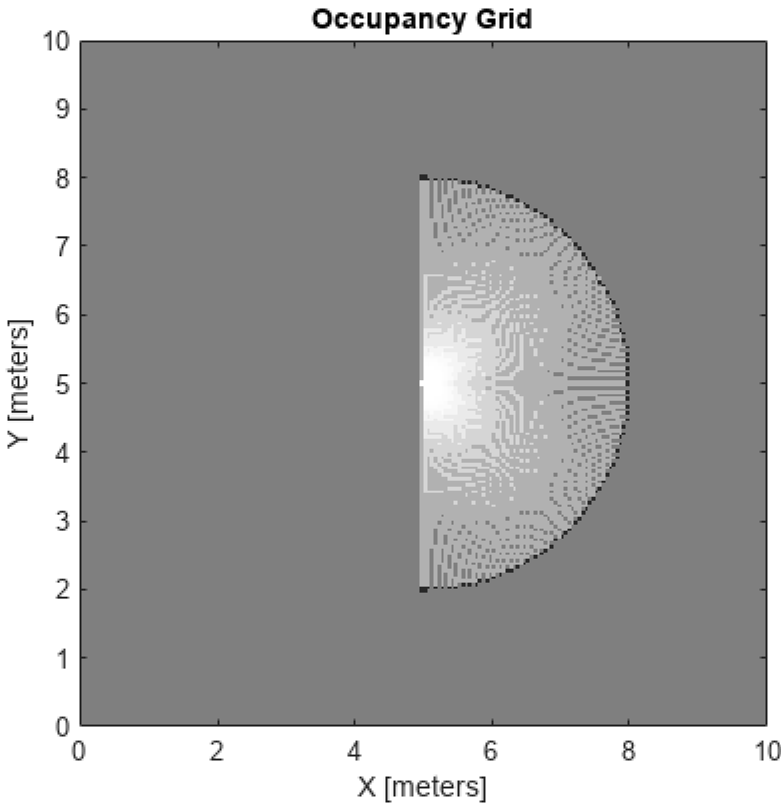
```
getOccupancy(map,[8 5])
```

```
ans = 0.7000
```

Add a second reading and view the update to the occupancy values. The additional reading increases the confidence in the readings. The free and occupied values become more distinct.



```
insertRay(map,pose,scan,maxrange);
show(map)
```




```
getOccupancy(map,[8 5])
```

```
ans = 0.8448
```

### Get Occupancy Values and Check Occupancy Status

Access occupancy values and check their occupancy status based on the occupied and free thresholds of the `occupancyMap` object.

Create a matrix and populate it with values. Use this matrix to create an occupancy map.

```
p = 0.5*ones(20,20);
p(11:20,11:20) = 0.75*ones(10,10);
map = occupancyMap(p,10);
```

Get the occupancy of different locations and check their occupancy statuses. The occupancy status returns 0 for free space and 1 for occupied space. Unknown values return –1.

```
pocc = getOccupancy(map,[1.5 1])
```

```
pocc = 0.7500
```

```
occupied = checkOccupancy(map,[1.5 1])
```

```
occupied = 1
```

```
pocc2 = getOccupancy(map,[5 5],'grid')
```

```
pocc2 = 0.5000
```

```
occupied2 = checkOccupancy(map,[5 5],'grid')
```

```
occupied2 = -1
```

## Input Arguments

**map — Map representation**
occupancyMap object

Map representation, specified as a `occupancyMap` object. This object represents the environment of the vehicle. The object contains a matrix grid with values representing the probability of the occupancy of that cell. Values close to 1 represent a high probability that the cell contains an obstacle. Values close to 0 represent a high probability that the cell is not occupied and obstacle free.

**xy — World coordinates**
*n*-by-2 matrix

World coordinates, specified as an *n*-by-2 matrix of `[x y]` pairs, where *n* is the number of world coordinates.

Data Types: `double`

**ij — Grid positions**
*n*-by-2 matrix

Grid positions, specified as an *n*-by-2 matrix of `[i j]` pairs in `[rows cols]` format, where *n* is the number of grid positions.

Data Types: `double`

**bottomLeft — Location of output matrix in world or local**
two-element vector | `[xCoord yCoord]`

Location of bottom left corner of output matrix in world or local coordinates, specified as a two-element vector, `[xCoord yCoord]`. Location is in world or local coordinates based on syntax.

Data Types: `double`

**matSize — Output matrix size**
two-element vector | `[xLength yLength]` | `[gridRow gridCol]`

Output matrix size, specified as a two-element vector, `[xLength yLength]` or `[gridRow gridCol]`. Size is in world, local, or grid coordinates based on syntax.

Data Types: `double`

**topLeft — Location of grid**
two-element vector | `[iCoord jCoord]`

Location of top left corner of grid, specified as a two-element vector, `[iCoord jCoord]`.

Data Types: `double`

## Output Arguments

**`occVal` — Probability occupancy values**
column vector

Probability occupancy values, returned as a column vector the same length as either `xy` or `ij`.

Values close to 0 represent a high probability that the cell is not occupied and obstacle free.

**`validPts` — Valid map locations**
*n*-by-1 column vector

Valid map locations, returned as an *n*-by-1 column vector equal in length to `xy` or `ij`. Locations inside the map return a value of 1. Locations outside the map limits return a value of 0.

**`occMatrix` — Matrix of occupancy values**
matrix

Matrix of occupancy values, returned as matrix with size equal to `matSize` or the size of `map`.

Values close to 0 represent a high probability that the cell is not occupied and obstacle free.

## Limitations

Occupancy values have a limited resolution of ±0.001. The values are stored as `int16` using a log-odds representation. This data type limits resolution, but saves memory when storing large maps in MATLAB. When calling `setOccupancy` and then `getOccupancy`, the value returned might not equal the value you set. For more information, see the log-odds representations section in “Occupancy Grids”.

# Version History

**Introduced in R2019b**

## See Also

`occupancyMap` | `checkOccupancy`

**Topics**

“Occupancy Grids” (Robotics System Toolbox)

# grid2local

Convert grid indices to local coordinates

## Syntax

`xy = grid2local(map,ij)`

## Description

`xy = grid2local(map,ij)` converts a `[row col]` array of grid indices, `ij`, to an array of local coordinates, `xy`.

## Examples

### Convert Grid Indices in Occupancy Map to Local Coordinates

Create an empty occupancy map with a width and height of 10 meters.

```
map = occupancyMap(10,10);
```

Get local coordinates from grid indices.

```
[i,j] = meshgrid(1:5);
xyLocal = grid2local(map,[i(:) j(:)]);
```

## Input Arguments

**`map` — Map representation**
`occupancyMap` object | `mapLayer` object | `multiLayerMap` object | `signedDistanceMap` object

Map representation, specified as a `occupancyMap`, `mapLayer`, `multiLayerMap`, or `signedDistanceMap` object.

**`ij` — Grid positions**
*n*-by-2 vertical array

Grid positions, specified as an *n*-by-2 vertical array of `[i j]` pairs in `[rows cols]` format, where *n* is the number of grid positions.

## Output Arguments

**`xy` — Local coordinates**
*n*-by-2 vertical array

Local coordinates, specified as an *n*-by-2 vertical array of `[x y]` pairs, where *n* is the number of local coordinates.

## Version History

**Introduced in R2019b**

### R2023a: Signed Distance Map Support

The `grid2local` function now supports the `signedDistanceMap` object as a new map representation for the `map` argument.

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Objects

`multiLayerMap` | `mapLayer` | `occupancyMap` | `binaryOccupancyMap` | `signedDistanceMap`

### Functions

`local2grid` | `grid2world`

# grid2world

Convert grid indices to world coordinates

## Syntax

`xy = grid2world(map,ij)`

## Description

`xy = grid2world(map,ij)` converts a `[`*row col*`]` array of grid indices, `ij`, to an array of world coordinates, `xy`.

## Examples

### Convert Grid Indices in Occupancy Map to World Coordinates

Create an empty occupancy map with a width and height of 10 meters.

```
map = occupancyMap(10,10);
```

Get world coordinates from grid indices.

```
[i,j] = meshgrid(1:5);
xyWorld = grid2world(map,[i(:) j(:)]);
```

## Input Arguments

**`map` — Map representation**
`occupancyMap` object | `mapLayer` object | `multiLayerMap` object | `signedDistanceMap` object

Map representation, specified as a `occupancyMap`, `mapLayer`, `multiLayerMap`, or `signedDistanceMap` object.

**`ij` — Grid positions**
*n*-by-2 matrix

Grid positions, specified as an *n*-by-2 matrix of `[`*i j*`]` pairs in `[`*rows cols*`]` format, where *n* is the number of grid positions. The grid cell locations are counted from the top left corner of the grid.

Data Types: `double`

## Output Arguments

**`xy` — World coordinates**
*n*-by-2 matrix

World coordinates, returned as an *n*-by-2 matrix of `[`*x y*`]` pairs, where *n* is the number of world coordinates.

Data Types: `double`

# Version History

**Introduced in R2019b**

### R2023a: Signed Distance Map Support

The `grid2world` function now supports the `signedDistanceMap` object as a new map representation for the `map` argument.

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`world2grid` | `grid2local`

### Objects

`multiLayerMap` | `mapLayer` | `occupancyMap` | `binaryOccupancyMap` | `signedDistanceMap`

### Functions

### Topics

"Occupancy Grids"

# inflate

Inflate each occupied location

## Syntax

```
inflate(map,radius)
inflate(map,gridradius,'grid')
```

## Description

`inflate(map,radius)` inflates each occupied position of the specified `map` by the `radius`, specified in meters. Occupied location values are based on the `map.OccupiedThreshold` property. `radius` is rounded up to the nearest equivalent cell based on the resolution of the map. Values are modified using *grayscale inflation* to inflate higher probability values across the grid. This inflation increases the size of the occupied locations in the map.

`inflate(map,gridradius,'grid')` inflates each occupied position by the `gridradius`, specified in number of cells.

## Examples

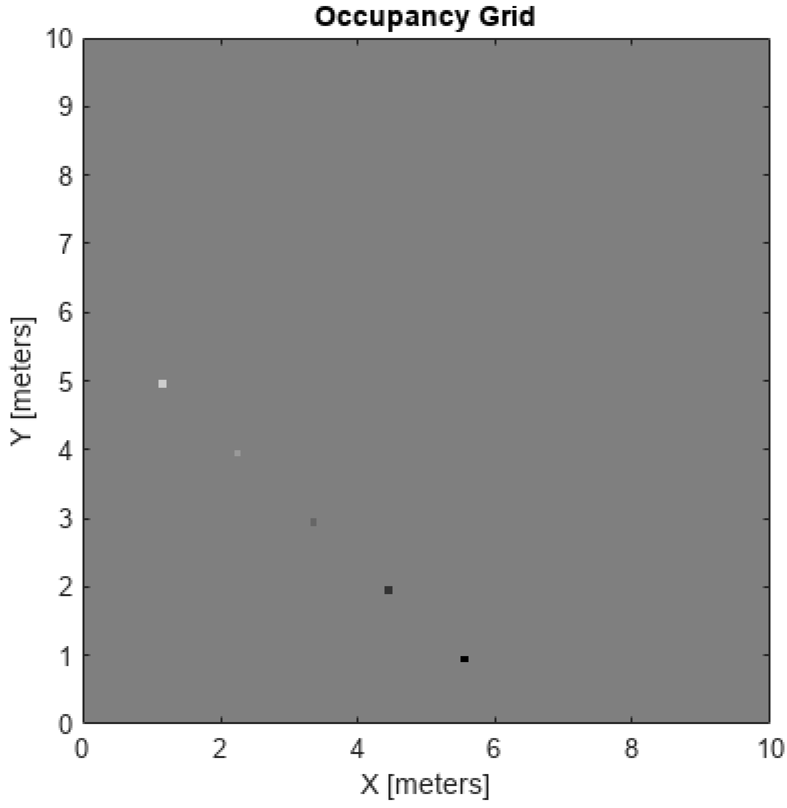
### Create and Modify Occupancy Map

Create an empty map of 10-by-10 meters in size.

```
map = occupancyMap(10,10,10);
```

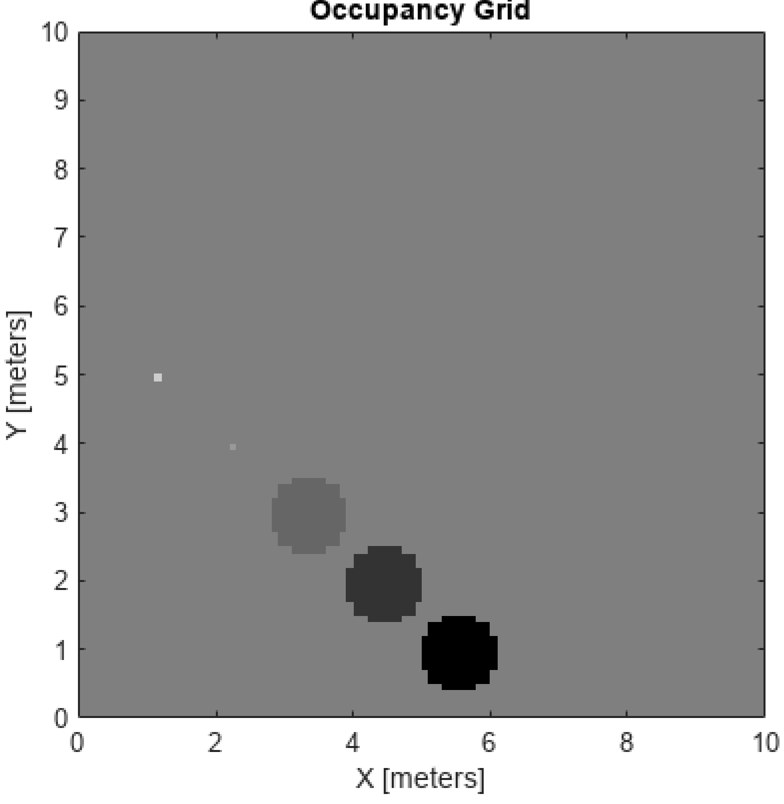
Update the occupancy of specific world locations with new probability values and display the map.

```
x = [1.2; 2.3; 3.4; 4.5; 5.6];
y = [5.0; 4.0; 3.0; 2.0; 1.0];

pvalues = [0.2; 0.4; 0.6; 0.8; 1];

updateOccupancy(map,[x y],pvalues)
figure
show(map)
```




Inflate the occupied areas by a radius of 0.5 m. The larger occupancy values overwrite the smaller values.

```
inflate(map,0.5)
figure
show(map)
```

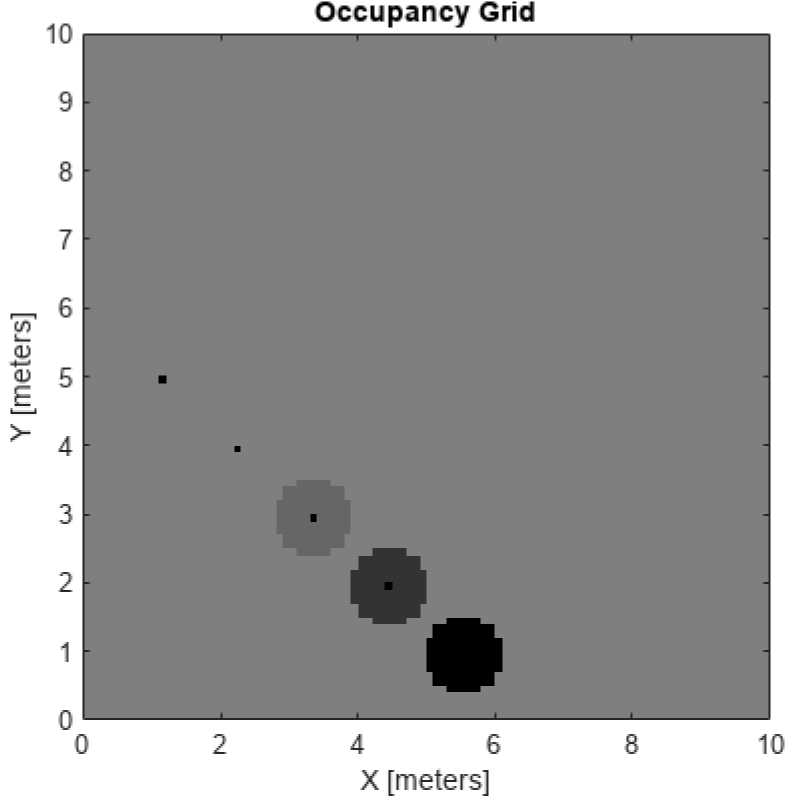



Get the grid locations from the world locations.

```
ij = world2grid(map,[x y]);
```

Set occupancy values for the grid locations.

```
setOccupancy(map,ij,ones(5,1),'grid')
figure
show(map)
```




## Input Arguments

**map — Map representation**
occupancyMap object

Map representation, specified as a occupancyMap object. This object represents the environment of the vehicle. The object contains a matrix grid with values representing the probability of the occupancy of that cell. Values close to 1 represent a high probability that the cell contains an obstacle. Values close to 0 represent a high probability that the cell is not occupied and obstacle free.

**radius — Dimension that defines by how much to inflate occupied locations**
scalar

Dimension that defines by how much to inflate occupied locations, specified as a scalar in meters. radius is rounded up to the nearest equivalent cell value.

Data Types: double

**gridradius — Number of cells by which to inflate the occupied locations**
positive integer scalar

Number of cells by which to inflate the occupied locations, specified as a positive integer scalar.

Data Types: double

## More About

### Grayscale Inflation

In *grayscale inflation*, the `strel` function creates a circular structuring element using the inflation radius. The grayscale inflation of $A(x, y)$ by $B(x, y)$ is defined as:

$(A \oplus B)(x, y) = \max \{A(x - x', y' - y') + B(x', y') \mid (x', y') \in D_B\}$.

$D_B$ is the domain of the probability values in the structuring element $B$. $A(x,y)$ is assumed to be $+\infty$ outside the domain of the grid.

Grayscale inflation acts as a local maximum operator and finds the highest probability values for nearby cells. The `inflate` method uses this definition to inflate the higher probability values throughout the grid. This inflation increases the size of any occupied locations and creates a buffer zone for vehicles to use as they navigate.

# Version History

**Introduced in R2019b**

## See Also

`binaryOccupancyMap` | `occupancyMap` | `getOccupancy`

**Topics**

"Occupancy Grids"

# insertRay

Insert ray from laser scan observation

## Syntax

```
insertRay(map,pose,scan,maxrange)
insertRay(map,pose,ranges,angles,maxrange)
insertRay(map,startpt,endpoints)
insertRay( ___ ,invModel)
```

## Description

`insertRay(map,pose,scan,maxrange)` inserts one or more lidar scan sensor observations in the occupancy grid, `map`, using the input `lidarScan` object, `scan`, to get ray endpoints. The ray endpoints are considered free space if the input scan ranges are below `maxrange`. Cells observed as occupied are updated with an observation of 0.7. All other points along the ray are treated as obstacle free and updated with an observation of 0.4. Endpoints above `maxrange` are not updated. `NaN` values are ignored. This behavior correlates to the inverse sensor model.

`insertRay(map,pose,ranges,angles,maxrange)` specifies the range readings as vectors defined by the input `ranges` and `angles`.

`insertRay(map,startpt,endpoints)` inserts observations between the line segments from the start point to the end points. The endpoints are updated with a probability observation of 0.7. Cells along the line segments are updated with an observation of 0.4.

`insertRay( ___ ,invModel)` inserts rays with updated probabilities given in the two-element vector, `invModel`, that corresponds to obstacle-free and occupied observations. Use any of the previous syntaxes to input the rays.

## Examples

### Insert Laser Scans into Occupancy Map

Create an empty occupancy grid map.

```
map = occupancyMap(10,10,20);
```

Specify the pose of the vehicle, ranges, angles, and the maximum range of the laser scan.

```
pose = [5,5,0];
ranges = 3*ones(100,1);
angles = linspace(-pi/2,pi/2,100);
maxrange = 20;
```

Create a `lidarScan` object with the specified ranges and angles.

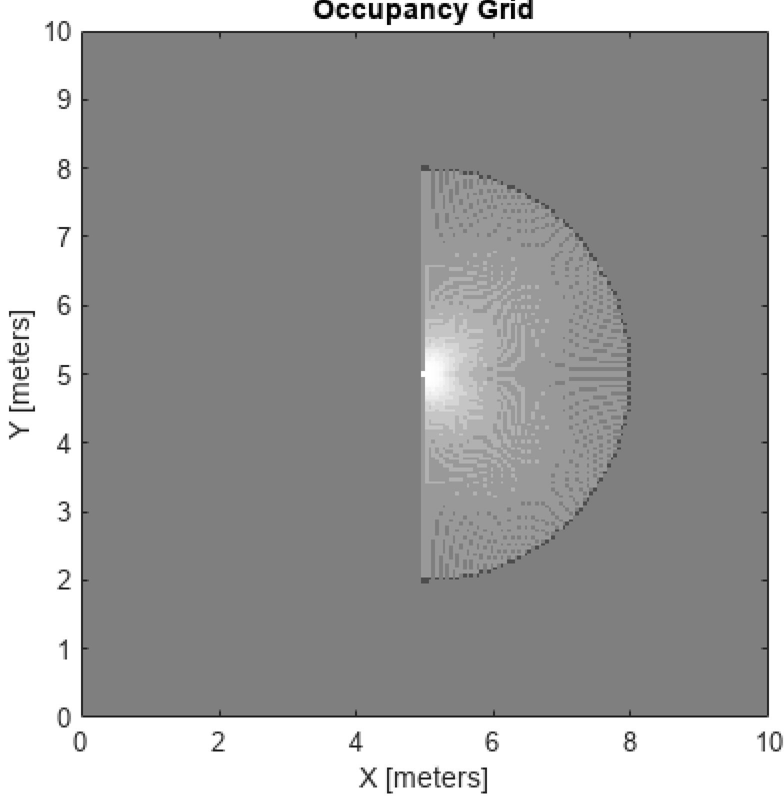
```
scan = lidarScan(ranges,angles);
```

Insert the laser scan data into the occupancy map.

```
insertRay(map,pose,scan,maxrange);
```

Show the map to see the results of inserting the laser scan.

```
show(map)
```



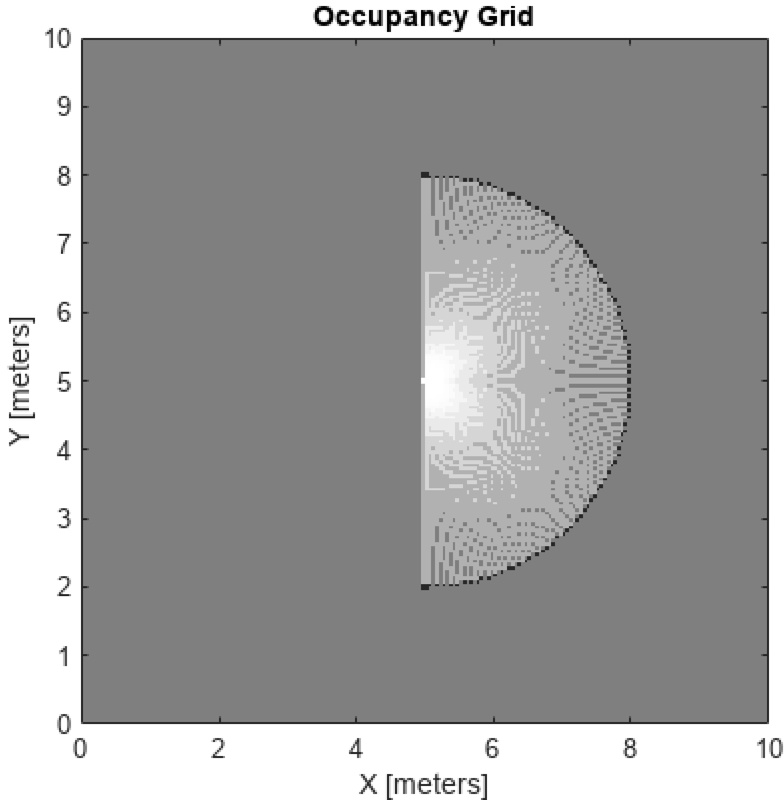

Check the occupancy of the spot directly in front of the vehicle.

```
getOccupancy(map,[8 5])
```

```
ans = 0.7000
```

Add a second reading and view the update to the occupancy values. The additional reading increases the confidence in the readings. The free and occupied values become more distinct.

```
insertRay(map,pose,scan,maxrange);
show(map)
```




```
getOccupancy(map,[8 5])
```

```
ans = 0.8448
```

## Input Arguments

**map — Map representation**
occupancyMap object

Map representation, specified as a `occupancyMap` object. This object represents the environment of the vehicle. The object contains a matrix grid with values representing the probability of the occupancy of that cell. Values close to 1 represent a high probability that the cell contains an obstacle. Values close to 0 represent a high probability that the cell is not occupied and obstacle free.

**pose — Position and orientation of vehicle**
three-element vector

Position and orientation of vehicle, specified as an `[x y theta]` vector. The vehicle pose is an *x* and *y* position with angular orientation *theta* (in radians) measured from the *x*-axis.

**scan — Lidar scan readings**
lidarScan object

Lidar scan readings, specified as a `lidarScan` object.

**`ranges` — Range values from scan data**
vector

Range values from scan data, specified as a vector of elements measured in meters. These range values are distances from a sensor at given `angles`. The vector must be the same length as the corresponding `angles` vector.

**`angles` — Angle values from scan data**
vector

Angle values from scan data, specified as a vector of elements measured in radians. These angle values correspond to the given `ranges`. The vector must be the same length as the corresponding `ranges` vector.

**`maxrange` — Maximum range of sensor**
scalar

Maximum range of laser range sensor, specified as a scalar in meters. Range values greater than or equal to `maxrange` are considered free along the whole length of the ray, up to `maxrange`.

**`startpt` — Start point for rays**
two-element vector

Start point for rays, specified as a two-element vector, `[x y]`, in the world coordinate frame. All rays are line segments that originate at this point.

**`endpoints` — Endpoints for rays**
*n*-by-2 matrix

Endpoints for rays, specified as an *n*-by-2 matrix of `[x y]` pairs in the world coordinate frame, where *n* is the length of `ranges` or `angles`. All rays are line segments that originate at `startpt`.

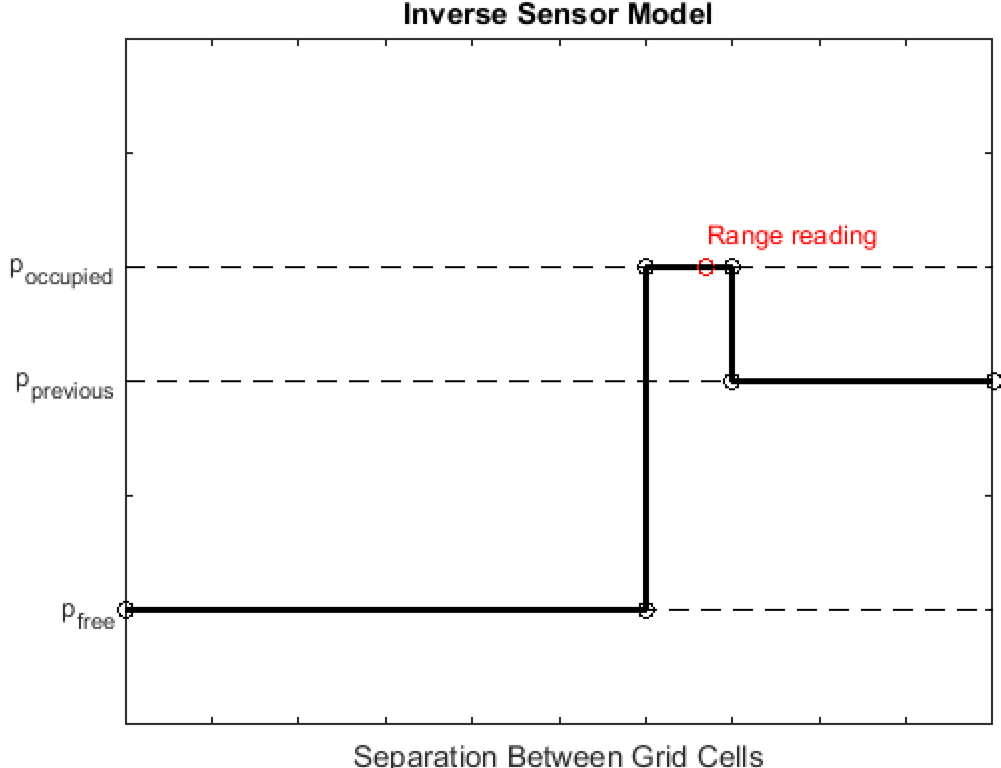
**`invModel` — Inverse sensor model values**
two-element vector

Inverse sensor model values, specified as a two-element vector corresponding to obstacle-free and occupied probabilities. Points along the ray are updated according to the inverse sensor model and the specified range readings. `NaN` range values are ignored. Range values greater than `maxrange` are not updated. See “Inverse Sensor Model” on page 2-969.

## More About

### Inverse Sensor Model

The inverse sensor model determines how values are set along a ray from a range sensor reading to the obstacles in the map. You can customize this model by specifying different probabilities for free and occupied locations in the `invModel` argument. `NaN` range values are ignored. Range values greater than `maxrange` are not updated.




Grid locations that contain range readings are updated with the occupied probability. Locations before the reading are updated with the free probability. All locations after the reading are not updated.

# Version History

**Introduced in R2019b**

## See Also

`occupancyMap` | `raycast` | `binaryOccupancyMap` | `lidarScan`

**Topics**

"Occupancy Grids"

# local2grid

Convert local coordinates to grid indices

## Syntax

```
ij = local2grid(map,xy)
```

## Description

`ij = local2grid(map,xy)` converts an array of local coordinates, `xy`, to an array of grid indices, `ij` in `[row col]` format.

## Examples

### Convert Local Coordinates in Occupancy Map to Grid Indices

Create an empty occupancy map with a width and height of 10 meters.

```
map = occupancyMap(10,10);
```

Get grid indices from local coordinates.

```
[xLocal,yLocal] = meshgrid(0:0.5:2);
ij = local2grid(map,[xLocal(:) yLocal(:)]);
```

## Input Arguments

**map — Map representation**
`occupancyMap` object | `mapLayer` object | `multiLayerMap` object | `signedDistanceMap` object

Map representation, specified as a `occupancyMap`, `mapLayer`, `multiLayerMap`, or `signedDistanceMap` object.

**xy — Local coordinates**
*n*-by-2 matrix

Local coordinates, specified as an *n*-by-2 matrix of `[x y]` pairs, where *n* is the number of local coordinates.

## Output Arguments

**ij — Grid positions**
*n*-by-2 matrix

Grid positions, returned as an *n*-by-2 matrix of `[i j]` pairs in `[row col]` format, where *n* is the number of grid positions. The grid cell locations start at (1,1) and are counted from the top left corner of the grid.

## Version History

**Introduced in R2019b**

#### R2023a: Signed Distance Map Support

The `local2grid` function now supports the `signedDistanceMap` object as a new map representation for the `map` argument.

## Extended Capabilities

#### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

#### Objects

`multiLayerMap` | `mapLayer` | `occupancyMap` | `binaryOccupancyMap` | `signedDistanceMap`

#### Functions

`grid2local` | `local2world`

#### Topics

"Occupancy Grids"

# local2world

Convert local coordinates to world coordinates

## Syntax

`xyWorld = local2world(map,xy)`

## Description

`xyWorld = local2world(map,xy)` converts an array of local coordinates to world coordinates

## Examples

### Convert Local Coordinates in Occupancy Map to World Coordinates

Create an empty occupancy map with a width and height of 10 meters.

```
map = occupancyMap(10,10);
```

Get world coordinates from local coordinates.

```
[xLocal,yLocal] = meshgrid(0:0.5:2);
xyWorld = local2world(map,[xLocal(:) yLocal(:)]);
```

## Input Arguments

**map — Map representation**
`occupancyMap` object | `mapLayer` object | `multiLayerMap` object | `signedDistanceMap` object

Map representation, specified as a `occupancyMap`, `mapLayer`, `multiLayerMap`, or `signedDistanceMap` object.

**xy — Local coordinates**
*n*-by-2 matrix

Local coordinates, specified as an *n*-by-2 matrix of `[x y]` pairs, where *n* is the number of world coordinates.

Data Types: `double`

## Output Arguments

**xyWorld — World coordinates**
*n*-by-2 matrix

World coordinates, specified as an *n*-by-2 matrix of `[x y]` pairs, where *n* is the number of world coordinates.

Data Types: `double`

# Version History

**Introduced in R2019b**

### R2023a: Signed Distance Map Support

The `local2world` function now supports the `signedDistanceMap` object as a new map representation for the `map` argument.

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
`multiLayerMap` | `mapLayer` | `occupancyMap` | `binaryOccupancyMap` | `signedDistanceMap`

**Functions**
`world2local` | `local2grid`

**Topics**
"Occupancy Grids"

# move

Move map in world frame

## Syntax

```
move(map,moveValue)
move(map,moveValue,Name=Value)
```

## Description

`move(map,moveValue)` moves the local origin of the map to an absolute location, `moveValue`, in the world frame, and updates the map limits. Move values are truncated based on the resolution of the map. By default, newly revealed regions are set to `map.DefaultValue`.

`move(map,moveValue,Name=Value)` specifies additional options specified by one or more name-value arguments.

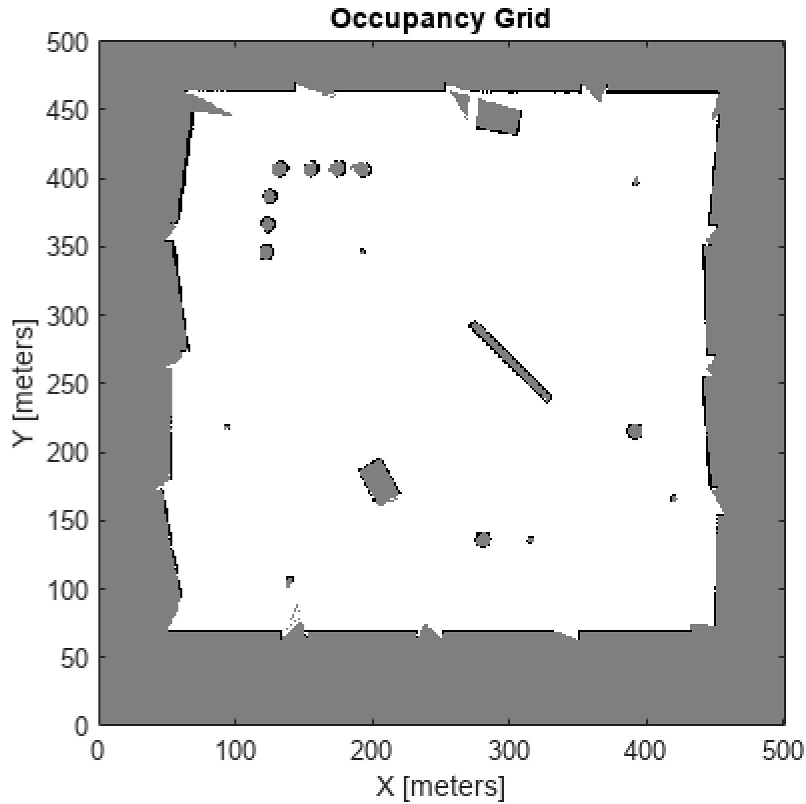
## Examples

### Move Local Map and Sync with World Map

This example shows how to move a local egocentric map and sync it with a larger world map. This process emulates a vehicle driving in an environment and getting updates on obstacles in the new areas.

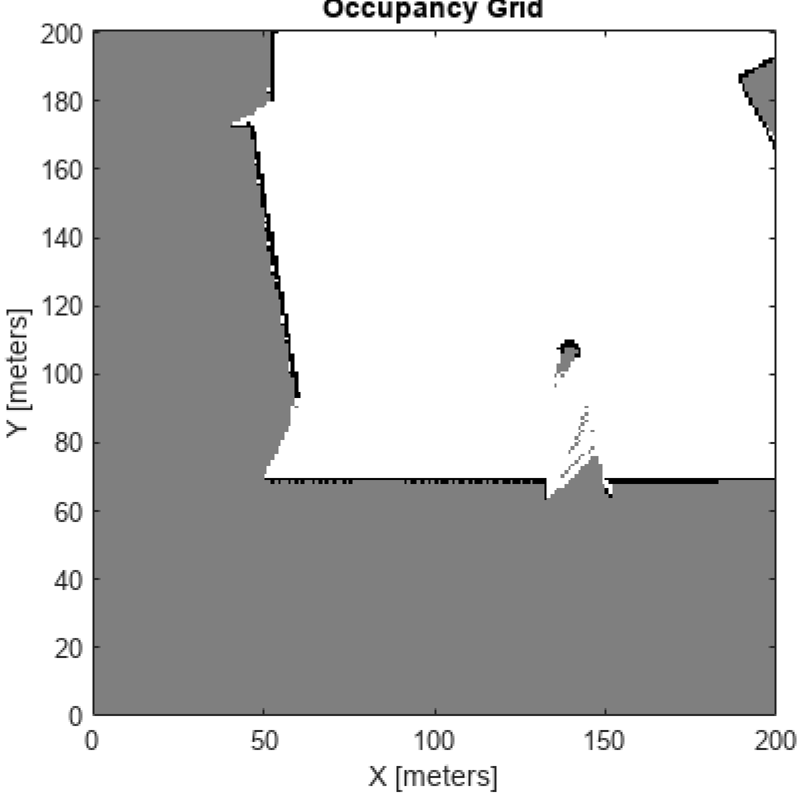
Load example maps. Create an occupancy map from the `ternaryMap`.

```
load exampleMaps.mat
map = occupancyMap(ternaryMap);
show(map)
```




Create a smaller local map.

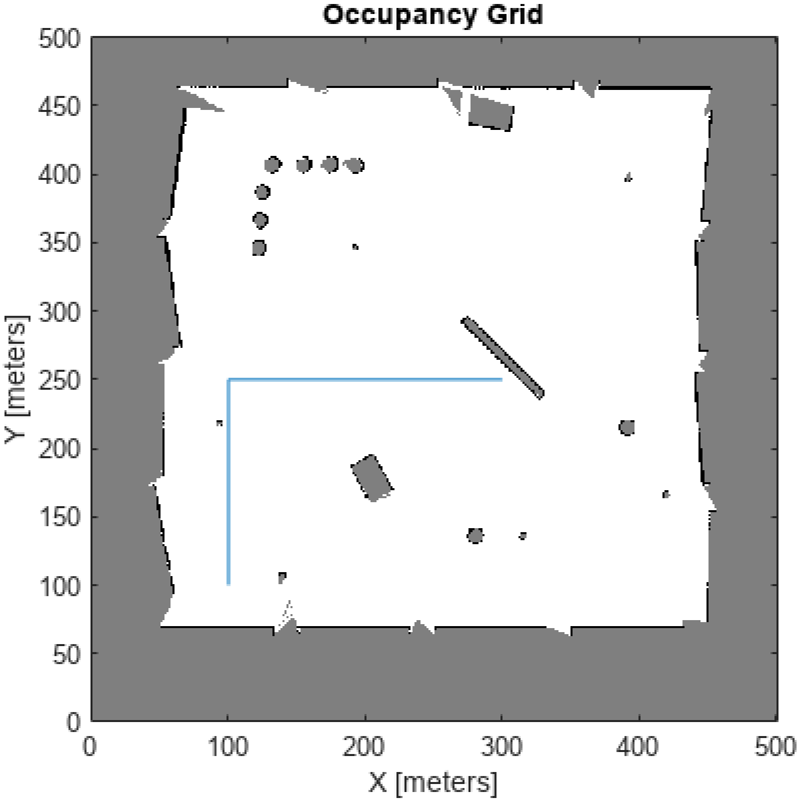
```
mapLocal = occupancyMap(ternaryMap(end-200:end,1:200));
show(mapLocal)
```




Follow a path planned in the world map and update the local map as you move your local frame.

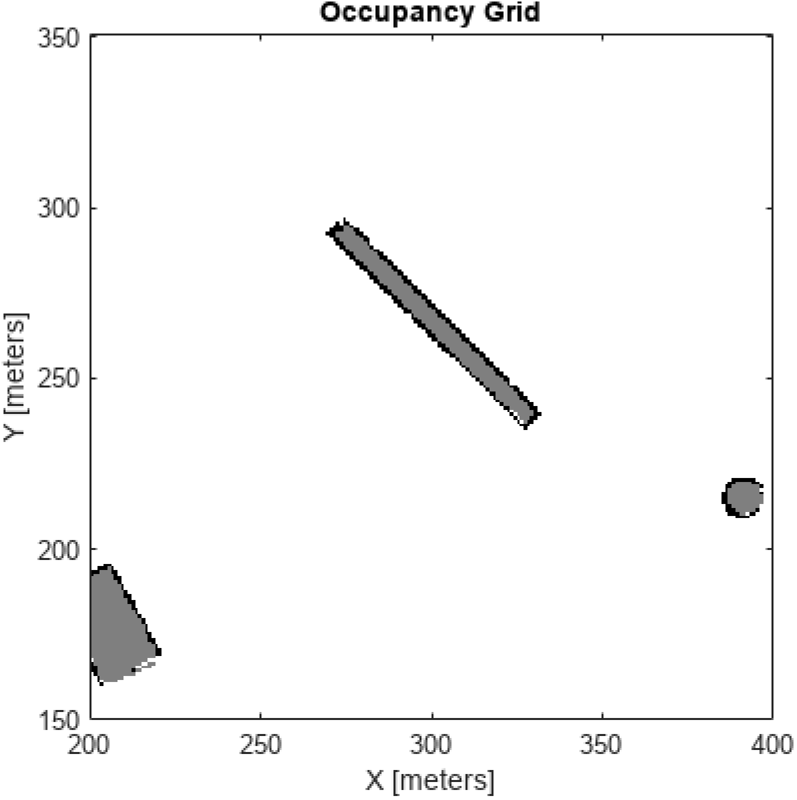
Specify path locations and plot on the map.

```
path = [100 100
        100 250
        200 250
        300 250];
show(map)
hold on
plot(path(:,1),path(:,2))
hold off
```




Create a loop for moving between points by the map resolution. Divide the difference between points by the map resolution to see how many incremental moves you can make.

```
for i = 1:length(path)-1
    moveAmount = (path(i+1,:)-path(i,:))/map.Resolution;
    for j = 1:abs(moveAmount(1)+moveAmount(2))
        moveValue = sign(moveAmount).*map.Resolution;
        move(mapLocal,moveValue,"MoveType","relative")
        syncWith(mapLocal,map)
        show(mapLocal)
        drawnow limitrate
    end
end
```




## Input Arguments

**map — Map representation**
occupancyMap object | mapLayer object | multiLayerMap object | signedDistanceMap object

Map representation, specified as a occupancyMap, mapLayer, multiLayerMap, or signedDistanceMap object.

**moveValue — Local map origin move value**
[x y] vector

Local map origin move value, specified as an [x y] vector. By default, the value is an absolute location to move the local origin to in the world frame. Use the MoveType name-value pair to specify a relative move.

### Name-Value Pair Arguments

Specify optional pairs of arguments as Name1=Value1,...,NameN=ValueN, where Name is the argument name and Value is the corresponding value. Name-value arguments must appear after other arguments, but the order of the pairs does not matter.

*Before R2021a, use commas to separate each name and value, and enclose* Name *in quotes.*

Example: MoveType="relative"

**MoveType — Type of move**
"absolute" (default) | "relative"

Type of move, specified as "absolute" or "relative". For relative moves, specify a relative [x y] vector for moveValue based on your current local frame.

Data Types: char | string

**FillValue — Fill value for revealed locations**
0 (default) | 1

Fill value for revealed locations because of the shifted map limits, specified as 0 or 1.

**SyncWith — Secondary map to sync with**
occupancyMap object

Secondary map to sync with, specified as a occupancyMap object. Any revealed locations based on the move are updated with values in this map using the world coordinates.

# Version History

**Introduced in R2019b**

### R2023a: Signed Distance Map Support

The move function now supports the signedDistanceMap object as a new map representation for the map argument.

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Objects

multiLayerMap | mapLayer | occupancyMap | binaryOccupancyMap | signedDistanceMap

### Functions

occupancyMatrix

# occupancyMatrix

Convert occupancy map to matrix

## Syntax

```
mat = occupancyMatrix(map)
mat = occupancyMatrix(map,'ternary')
```

## Description

`mat = occupancyMatrix(map)` returns probability values stored in the occupancy grid object as a matrix.

`mat = occupancyMatrix(map,'ternary')` returns the occupancy status of each grid cell as a matrix. The `OccupiedThreshold` and `FreeThreshold` properties on the occupancy grid determine the obstacle free cells (0) and occupied cells (1). Unknown values are returned as –1.

## Examples

### Convert Occupancy Map to Matrix

Create an empty occupancy map with a width and height of 10 meters.

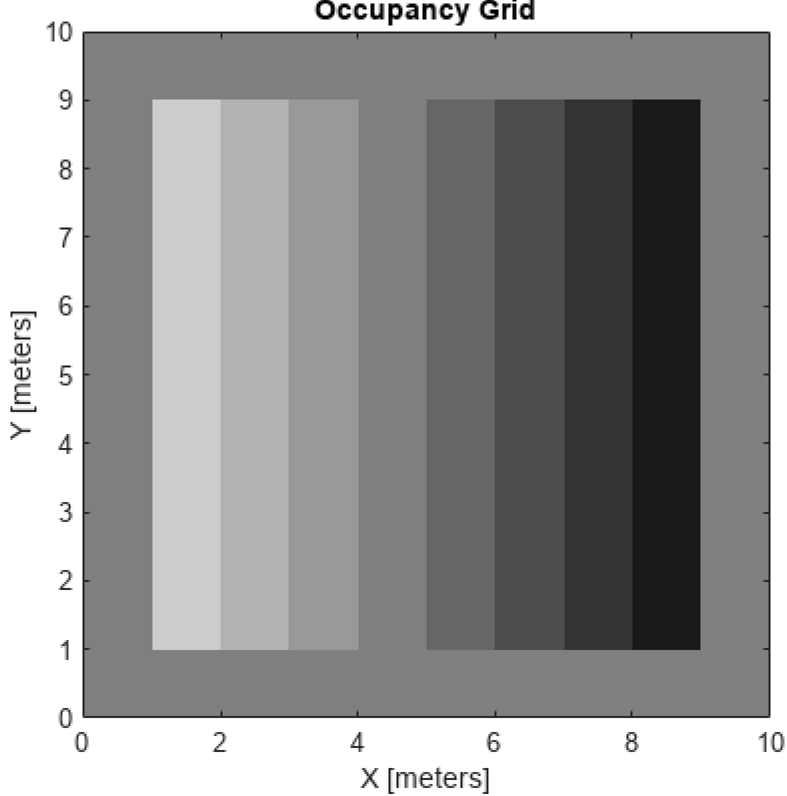
```
map = occupancyMap(10,10);
```

Specify probability occupancy values as an 8-by-8 matrix.

```
inputMatrix = repmat(0.2:0.1:0.9,8,1);
```

Assign the probability occupancy values matrix to the map.

```
setOccupancy(map,[1 1],inputMatrix)
show(map)
```




Convert occupancy map to probability occupancy values matrix.

```
occupancyMatrix(map)
```

```
ans = 10×10

    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5
    0.5000    0.2000    0.3000    0.4000    0.5000    0.6000    0.7000    0.8000    0.9000    0.5
    0.5000    0.2000    0.3000    0.4000    0.5000    0.6000    0.7000    0.8000    0.9000    0.5
    0.5000    0.2000    0.3000    0.4000    0.5000    0.6000    0.7000    0.8000    0.9000    0.5
    0.5000    0.2000    0.3000    0.4000    0.5000    0.6000    0.7000    0.8000    0.9000    0.5
    0.5000    0.2000    0.3000    0.4000    0.5000    0.6000    0.7000    0.8000    0.9000    0.5
    0.5000    0.2000    0.3000    0.4000    0.5000    0.6000    0.7000    0.8000    0.9000    0.5
    0.5000    0.2000    0.3000    0.4000    0.5000    0.6000    0.7000    0.8000    0.9000    0.5
    0.5000    0.2000    0.3000    0.4000    0.5000    0.6000    0.7000    0.8000    0.9000    0.5
    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5000    0.5
```

Convert occupancy map to occupancy values matrix.

```
occupancyMatrix(map,"ternary")
```

```
ans = 10×10

    -1    -1    -1    -1    -1    -1    -1    -1    -1    -1
    -1    -1    -1    -1    -1    -1     1     1     1    -1
    -1    -1    -1    -1    -1    -1     1     1     1    -1
    -1    -1    -1    -1    -1    -1     1     1     1    -1
```

```
    -1    -1    -1    -1    -1    -1     1     1     1    -1
    -1    -1    -1    -1    -1    -1     1     1     1    -1
    -1    -1    -1    -1    -1    -1     1     1     1    -1
    -1    -1    -1    -1    -1    -1     1     1     1    -1
    -1    -1    -1    -1    -1    -1     1     1     1    -1
    -1    -1    -1    -1    -1    -1    -1    -1    -1    -1
```

## Input Arguments

**`map` — Map representation**
`occupancyMap` object

Map representation, specified as a `occupancyMap` object. This object represents the environment of the vehicle. The object contains a matrix grid with values representing the probability of the occupancy of that cell. Values close to 1 represent a high probability that the cell contains an obstacle. Values close to 0 represent a high probability that the cell is not occupied and obstacle free.

## Output Arguments

**`mat` — Occupancy grid values**
matrix

Occupancy grid values, returned as an *h*-by-*w* matrix, where *h* and *w* are defined by the two elements of the `GridSize` property of the occupancy grid object.

Data Types: `double`

# Version History

**Introduced in R2019b**

## See Also

`occupancyMap` | `getOccupancy` | `show` | `binaryOccupancyMap`

**Topics**
"Occupancy Grids"

# raycast

Compute cell indices along a ray

## Syntax

```
[endpoints,midpoints] = raycast(map,pose,range,angle)
[endpoints,midpoints] = raycast(map,p1,p2)
```

## Description

`[endpoints,midpoints] = raycast(map,pose,range,angle)` returns cell indices of the specified `map` for all cells traversed by a ray originating from the specified `pose` at the specified `angle` and `range` values. `endpoints` contains all indices touched by the end of the ray, with all other points included in `midpoints`.

`[endpoints,midpoints] = raycast(map,p1,p2)` returns the cell indices of the line segment between the two specified points.

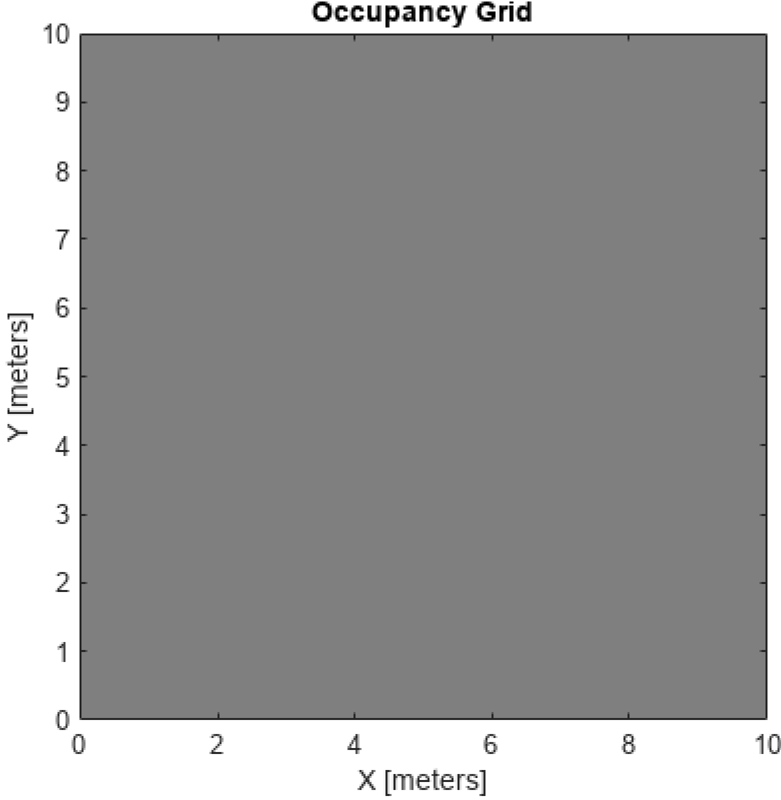
## Examples

### Get Grid Cells Along A Ray

Use the `raycast` method to generate cell indices for all cells traversed by a ray.

Create an empty map. A low-resolution map is used to illustrate the affected grid locations.

```
map = occupancyMap(10,10,1);
show(map)
```

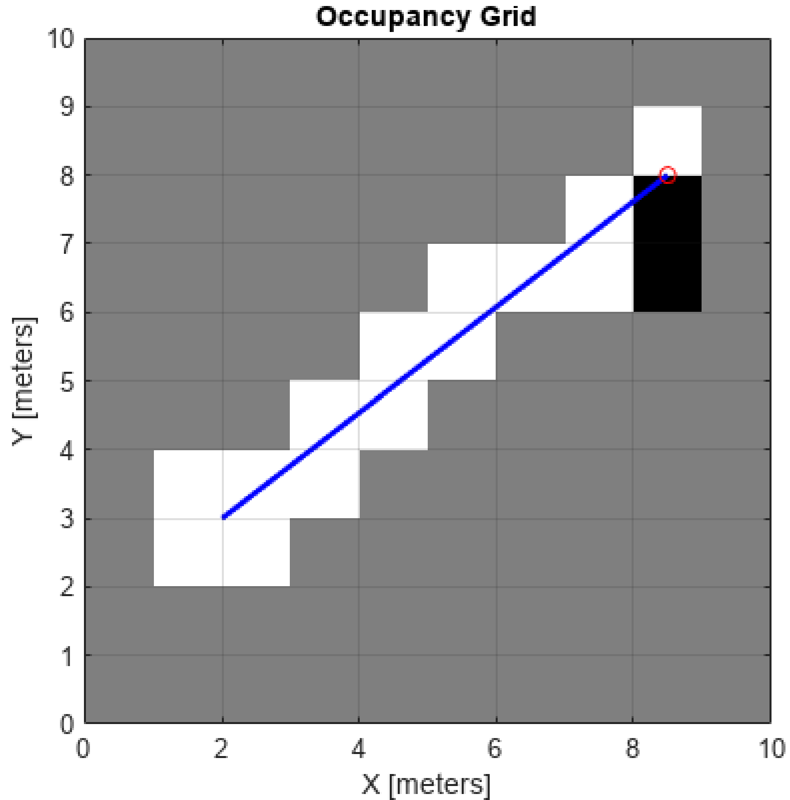



Get the grid indices of the midpoints and end points of a ray from `[2 3]` to `[8.5 8]`. Set occupancy values for these grid indices. Midpoints are treated as open space. Update endpoints with an occupied observation.

```
p1 = [2 3];
p2 = [8.5 8];
[endPts,midPts] = raycast(map,p1,p2);
setOccupancy(map,midPts,zeros(length(midPts),1),'grid');
setOccupancy(map,endPts,ones(length(endPts),1),'grid');
```

Plot the original ray over the map. Each grid cell touched by the line is updated. The starting point overlaps multiple cells, and the line touches the edge of certain cells, but all the cells are still updated.

```
show(map)
hold on
plot([p1(1) p2(1)],[p1(2) p2(2)],'-b','LineWidth',2)
plot(p2(1),p2(2),'or')
grid on
```




## Input Arguments

**map — Map representation**
occupancyMap object

Map representation, specified as a `occupancyMap` object. This object represents the environment of the sensor. The object contains a matrix grid with values representing the probability of the occupancy of that cell. Values close to 1 represent a high probability that the cell contains an obstacle. Values close to 0 represent a high probability that the cell is not occupied and obstacle free.

**pose — Position and orientation of sensor**
three-element vector

Position and orientation of sensor, specified as an `[x y theta]` vector. The sensor pose is an *x* and *y* position with angular orientation *theta* (in radians) measured from the *x*-axis.

**range — Range of ray**
scalar

Range of ray, specified as a scalar in meters.

**angle — Angle of ray**
scalar

Angle of ray, specified as a scalar in radians. The angle value is for the corresponding `range`.

**p1 — Starting point of ray**
two-element vector

Starting point of ray, specified as an `[x y]` two-element vector. The point is defined in the world frame.

**p2 — Endpoint of ray**
two-element vector

Endpoint of ray, specified as an `[x y]` two-element vector. The point is defined in the world frame.

## Output Arguments

**`endpoints` — Endpoint grid indices**
*n*-by-2 matrix

Endpoint indices, returned as an *n*-by-2 matrix of `[i j]` pairs, where *n* is the number of grid indices. The endpoints are where the `range` value hits at the specified `angle`. Multiple indices are returned when the endpoint lies on the boundary of multiple cells.

**`midpoints` — Midpoint grid indices**
*n*-by-2 matrix

Midpoint indices, returned as an *n*-by-2 matrix of `[i j]` pairs, where *n* is the number of grid indices. This argument includes all grid indices the ray intersects, excluding the endpoint.

# Version History

**Introduced in R2019b**

## See Also

`occupancyMap`

**Topics**

"Occupancy Grids"

# rayIntersection

Find intersection points of rays and occupied map cells

## Syntax

```
intersectionPts = rayIntersection(map,pose,angles,maxrange)
intersectionPts = rayIntersection(map,pose,angles,maxrange,threshold)
```

## Description

`intersectionPts = rayIntersection(map,pose,angles,maxrange)` returns intersection points of rays and occupied cells in the specified `map`. Rays emanate from the specified `pose` and `angles`. Intersection points are returned in the world coordinate frame. If there is no intersection up to the specified `maxrange`, `[NaN NaN]` is returned. By default, the `OccupiedThreshold` property is used to determine occupied cells.

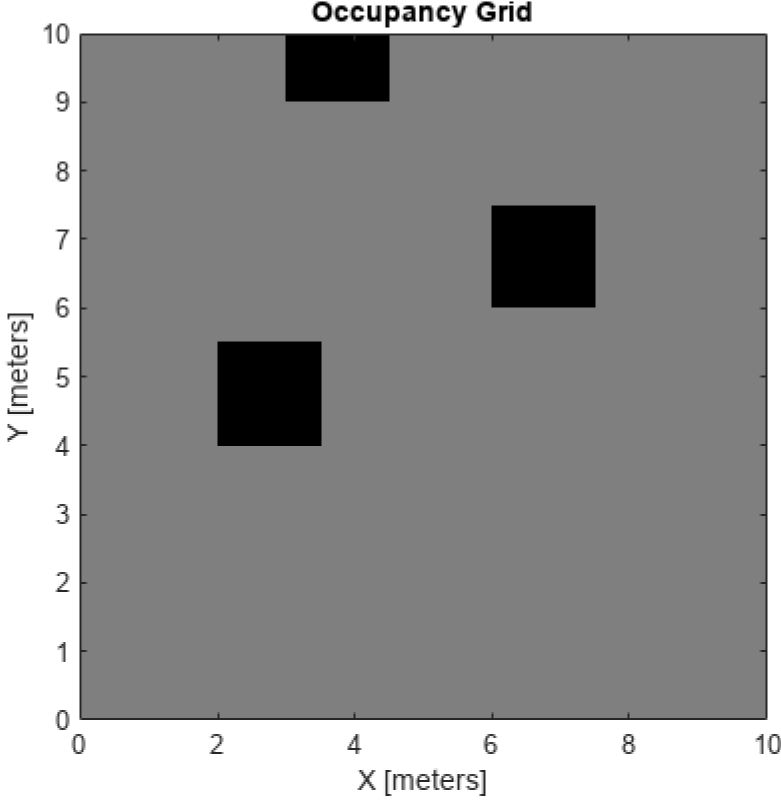
`intersectionPts = rayIntersection(map,pose,angles,maxrange,threshold)` returns intersection points based on the specified `threshold` for the occupancy values. Values greater than or equal to the threshold are considered occupied.

## Examples

### Get Ray Intersection Points on Occupancy Map

Create an occupancy grid map. Add obstacles and inflate them. A lower resolution map is used to illustrate the importance of using grid cells. Show the map.

```
map = occupancyMap(10,10,2);
obstacles = [4 10; 3 5; 7 7];
setOccupancy(map,obstacles,ones(length(obstacles),1))
inflate(map,0.25)
show(map)
```




Find the intersection points of occupied cells and rays that emit from the given vehicle pose. Specify the max range and angles for these rays. The last ray does not intersect with an obstacle within the max range, so it has no collision point.

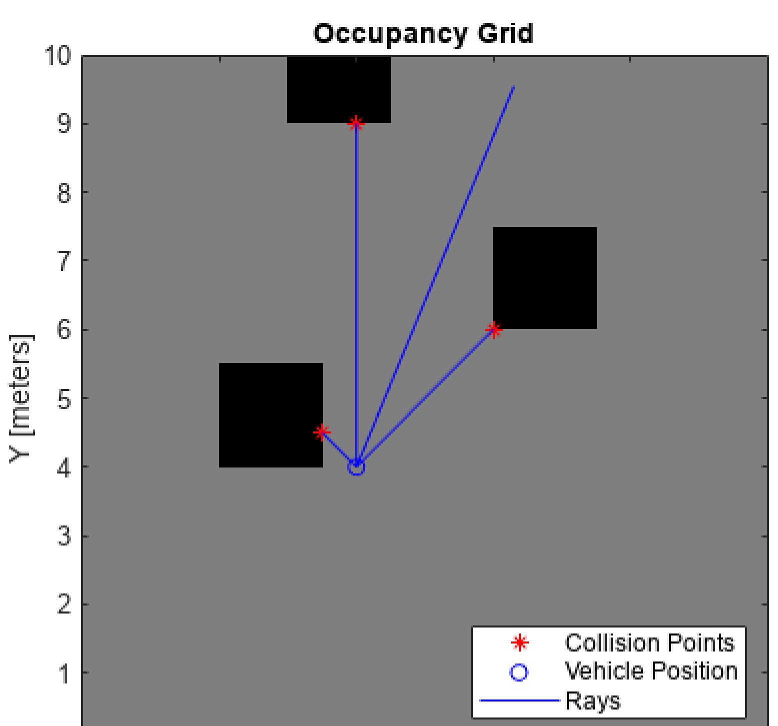
```
maxrange = 6;
angles = [pi/4,-pi/4,0,-pi/8];
vehiclePose = [4,4,pi/2];
intsectionPts = rayIntersection(map,vehiclePose,angles,maxrange,0.7)
```

```
intsectionPts = 4×2

    3.5000    4.5000
    6.0000    6.0000
    4.0000    9.0000
       NaN       NaN
```

Plot the intersection points and plot rays from the pose to the intersection points.

```
hold on
plot(intsectionPts(:,1),intsectionPts(:,2),'*r') % Intersection points
plot(vehiclePose(1),vehiclePose(2),'ob') % Vehicle pose
for i = 1:3
    plot([vehiclePose(1),intsectionPts(i,1)],...
        [vehiclePose(2),intsectionPts(i,2)],'-b') % Plot intersecting rays
end
plot([vehiclePose(1),vehiclePose(1)-6*sin(angles(4))],...
    [vehiclePose(2),vehiclePose(2)+6*cos(angles(4))],'-b') % No intersection ray
```

```
legend('Collision Points','Vehicle Position','Rays','Location','SouthEast')
```




## Input Arguments

**map — Map representation**
occupancyMap object

Map representation, specified as a `occupancyMap` object. This object represents the environment of the sensor. The object contains a matrix grid with values representing the probability of the occupancy of that cell. Values close to 1 represent a high probability that the cell contains an obstacle. Values close to 0 represent a high probability that the cell is not occupied and obstacle free.

**pose — Position and orientation of sensor**
three-element vector

Position and orientation of sensor, specified as an `[x y theta]` vector. The sensor pose is an *x* and *y* position with angular orientation *theta* (in radians) measured from the *x*-axis.

**angles — Ray angles emanating from sensor**
vector

Ray angles emanating from the sensor, specified as a vector with elements in radians. These angles are relative to the specified sensor `pose`.

**`maxrange` — Maximum range of sensor**
scalar

Maximum range of laser range sensor, specified as a scalar in meters. Range values greater than or equal to `maxrange` are considered free along the whole length of the ray, up to `maxrange`.

**`threshold` — Threshold for occupied cells**
scalar from 0 to 1

Threshold for occupied cells, specified as a scalar from 0 to 1. Occupancy values greater than or equal to the threshold are treated as occupied cells to trigger intersections.

## Output Arguments

**`intersectionPts` — Intersection points**
*n*-by-2 matrix

Intersection points, returned as *n*-by-2 matrix of `[x y]` pairs in the world frame, where *n* is the length of `angles`.

# Version History

**Introduced in R2019b**

## See Also

`occupancyMap` | `raycast` | `updateOccupancy` | `binaryOccupancyMap`

**Topics**

"Occupancy Grids"

# setOccupancy

Set occupancy probability of locations

## Syntax

```
setOccupancy(map,xy,occval)
```

```
setOccupancy(map,xy,occval,'local')
setOccupancy(map,ij,occval,'grid')
validPts = setOccupancy( ___ )
```

```
setOccupancy(map,bottomLeft,inputMatrix)
setOccupancy(map,bottomLeft,inputMatrix,'local')
setOccupancy(map,topLeft,inputMatrix,'grid')
```

## Description

`setOccupancy(map,xy,occval)` assigns the occupancy values to each coordinate specified in `xy`. `occval` can be a column vector the same size of `xy` or a scalar, which is applied to all coordinates.

`setOccupancy(map,xy,occval,'local')` assigns occupancy values, `occval`, to the input array of local coordinates, `xy`, as local coordinates.

`setOccupancy(map,ij,occval,'grid')` assigns occupancy values, `occval`, to the input array of grid indices, `ij`, as `[rows cols]`.

`validPts = setOccupancy( ___ )` outputs an `n`-element vector of logical values indicating whether input coordinates are within the map limits.

`setOccupancy(map,bottomLeft,inputMatrix)` assigns a matrix of occupancy values by specifying the bottom-left corner location in world coordinates.

`setOccupancy(map,bottomLeft,inputMatrix,'local')` assigns a matrix of occupancy values by specifying the bottom-left corner location in local coordinates.

`setOccupancy(map,topLeft,inputMatrix,'grid')` assigns a matrix of occupancy values by specifying the top-left cell index in grid indices and the matrix size.

## Examples

### Create and Modify Occupancy Map

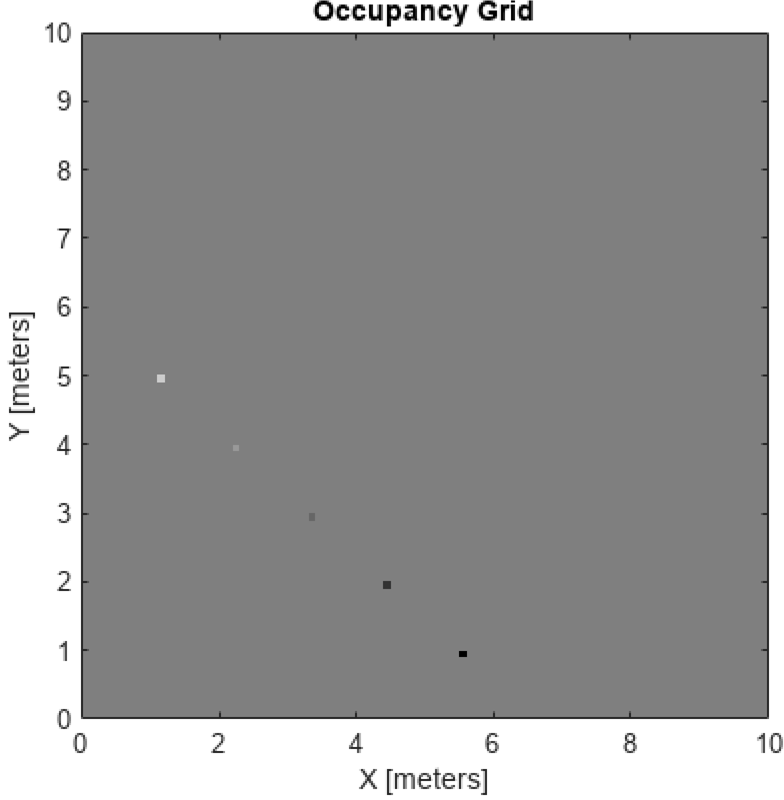
Create an empty map of 10-by-10 meters in size.

```
map = occupancyMap(10,10,10);
```

Update the occupancy of specific world locations with new probability values and display the map.

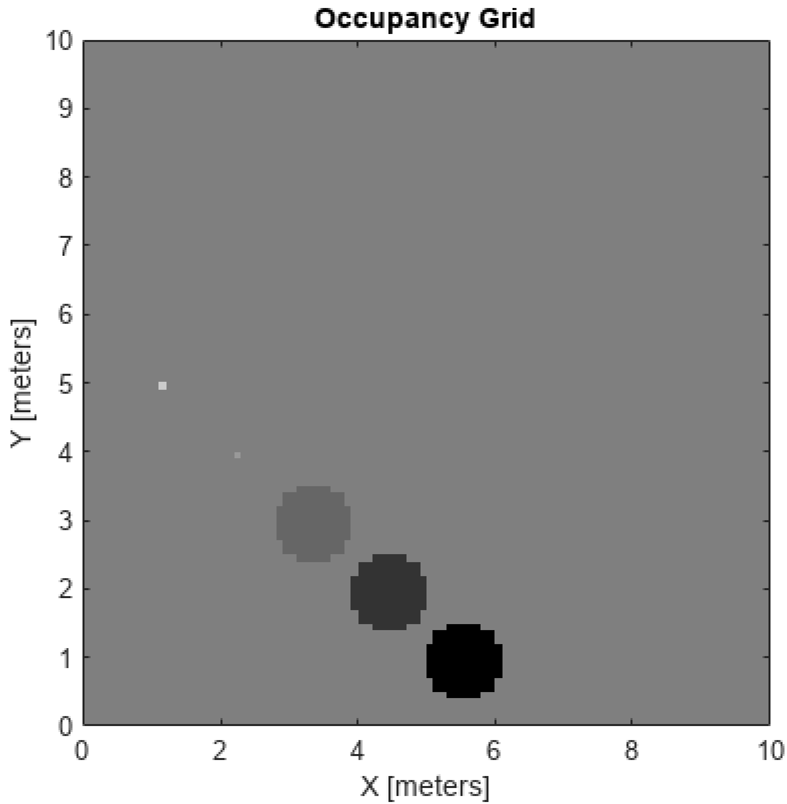
```
x = [1.2; 2.3; 3.4; 4.5; 5.6];
y = [5.0; 4.0; 3.0; 2.0; 1.0];
```

```
pvalues = [0.2; 0.4; 0.6; 0.8; 1];

updateOccupancy(map,[x y],pvalues)
figure
show(map)
```




Inflate the occupied areas by a radius of 0.5 m. The larger occupancy values overwrite the smaller values.

```
inflate(map,0.5)
figure
show(map)
```

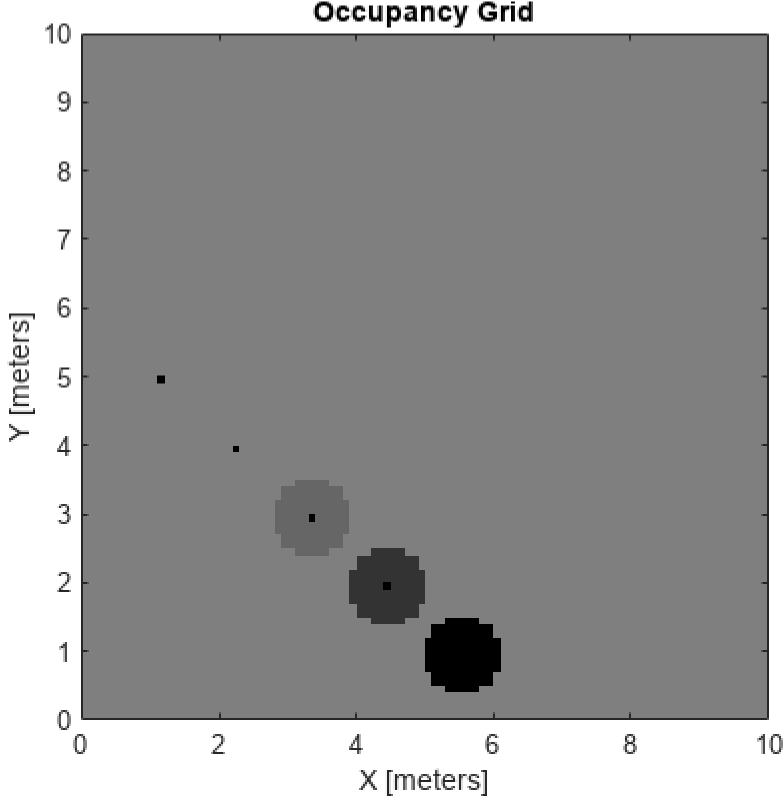



Get the grid locations from the world locations.

```
ij = world2grid(map,[x y]);
```

Set occupancy values for the grid locations.

```
setOccupancy(map,ij,ones(5,1),'grid')
figure
show(map)
```




## Input Arguments

**`map` — Map representation**
`occupancyMap` object

Map representation, specified as a `occupancyMap` object. This object represents the environment of the vehicle. The object contains a matrix grid with values representing the probability of the occupancy of that cell. Values close to 1 represent a high probability that the cell contains an obstacle. Values close to 0 represent a high probability that the cell is not occupied and obstacle free.

**`xy` — World coordinates**
*n*-by-2 matrix

World coordinates, specified as an *n*-by-2 matrix of `[x y]` pairs, where *n* is the number of world coordinates.

Data Types: `double`

**`ij` — Grid positions**
*n*-by-2 matrix

Grid positions, specified as an *n*-by-2 matrix of `[i j]` pairs in `[rows cols]` format, where *n* is the number of grid positions.

Data Types: `double`

**`occval` — Probability occupancy values**
scalar | column vector

Probability occupancy values, specified as a scalar or a column vector the same size as either `xy` or `ij`. A scalar input is applied to all coordinates in either `xy` or `ij`.

Values close to 0 represent a high probability that the cell is not occupied and obstacle free.

**`inputMatrix` — Occupancy values**
matrix

Occupancy values, specified as a matrix. Values are given between 0 and 1 inclusively.

**`bottomLeft` — Location of output matrix in world or local**
two-element vector | `[xCoord yCoord]`

Location of bottom left corner of output matrix in world or local coordinates, specified as a two-element vector, `[xCoord yCoord]`. Location is in world or local coordinates based on syntax.

Data Types: `double`

**`topLeft` — Location of grid**
two-element vector | `[iCoord jCoord]`

Location of top left corner of grid, specified as a two-element vector, `[iCoord jCoord]`.

Data Types: `double`

## Output Arguments

**`validPts` — Valid map locations**
*n*-by-1 column vector

Valid map locations, returned as an *n*-by-1 column vector equal in length to `xy` or `ij`. Locations inside the map return a value of 1. Locations outside the map limits return a value of 0.

## Limitations

Occupancy values have a limited resolution of ±0.001. The values are stored as `int16` using a log-odds representation. This data type limits resolution, but saves memory when storing large maps in MATLAB. When calling `setOccupancy` and then `getOccupancy`, the value returned might not equal the value you set. For more information, see the log-odds representations section in “Occupancy Grids”.

# Version History

**Introduced in R2019b**

## See Also

`occupancyMap` | `getOccupancy` | `binaryOccupancyMap`

### Topics
"Occupancy Grids"

# show

Display 2-D occupancy map

## Syntax

```
show(map)
show(map,'local')
show(map,'grid')
show( ___ ,Name,Value)
mapImage = show( ___ )
```

## Description

`show(map)` displays the occupancy grid `map` in the current axes, with the axes labels representing the world coordinates.

`show(map,'local')` displays the occupancy grid `map` in the current axes, with the axes labels representing the local coordinates instead of world coordinates.

`show(map,'grid')` displays the occupancy grid `map` in the current axes, with the axes labels representing the grid coordinates.

`show( ___ ,Name,Value)` specifies additional options specified by one or more name-value pair arguments.

`mapImage = show( ___ )` returns the handle to the image object created by `show`.

## Examples

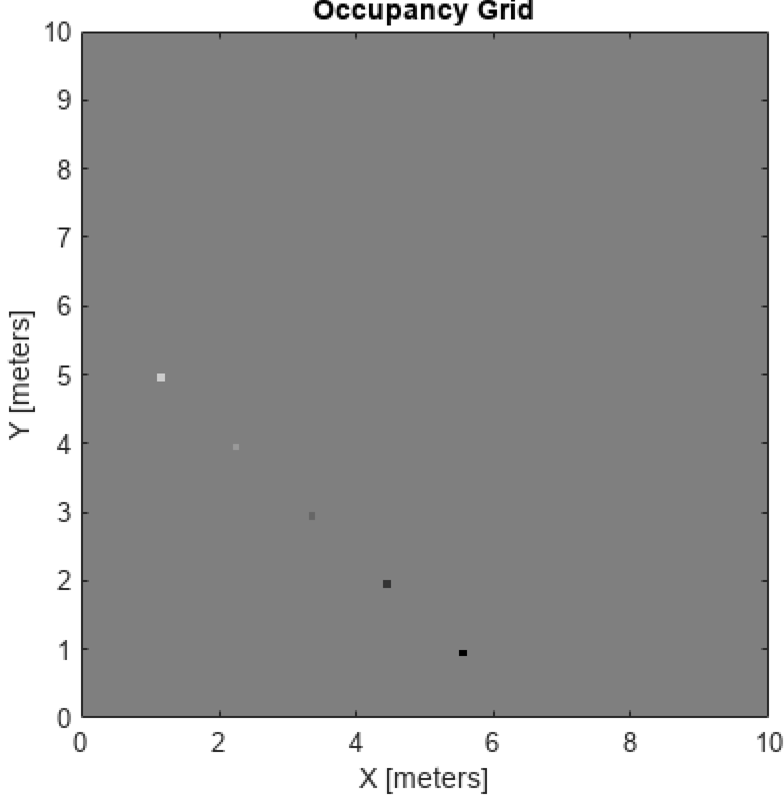
### Create and Modify Occupancy Map

Create an empty map of 10-by-10 meters in size.

```
map = occupancyMap(10,10,10);
```

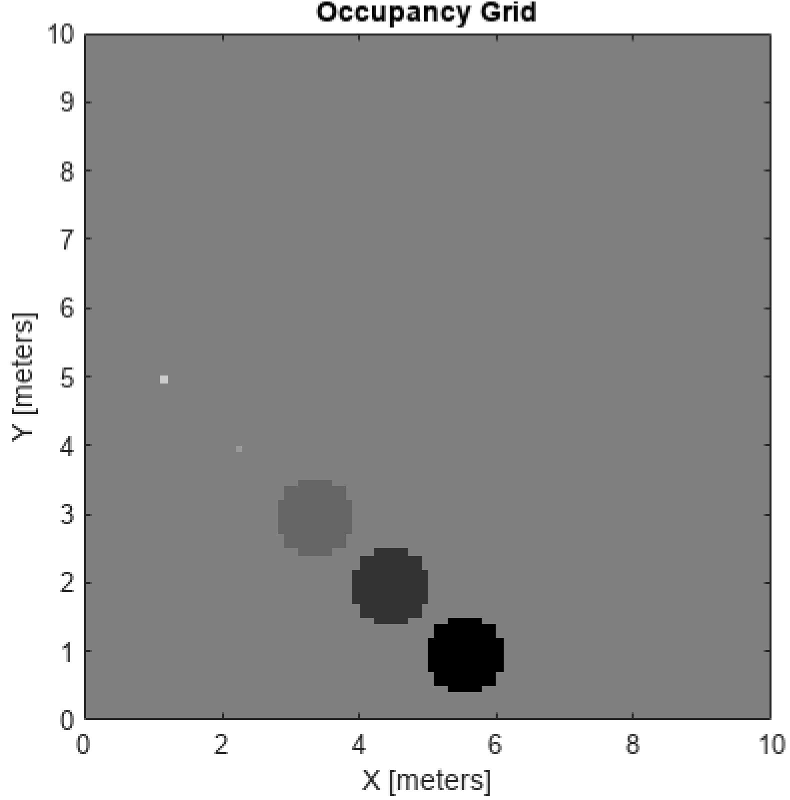
Update the occupancy of specific world locations with new probability values and display the map.

```
x = [1.2; 2.3; 3.4; 4.5; 5.6];
y = [5.0; 4.0; 3.0; 2.0; 1.0];

pvalues = [0.2; 0.4; 0.6; 0.8; 1];

updateOccupancy(map,[x y],pvalues)
figure
show(map)
```




Inflate the occupied areas by a radius of 0.5 m. The larger occupancy values overwrite the smaller values.

```
inflate(map,0.5)
figure
show(map)
```

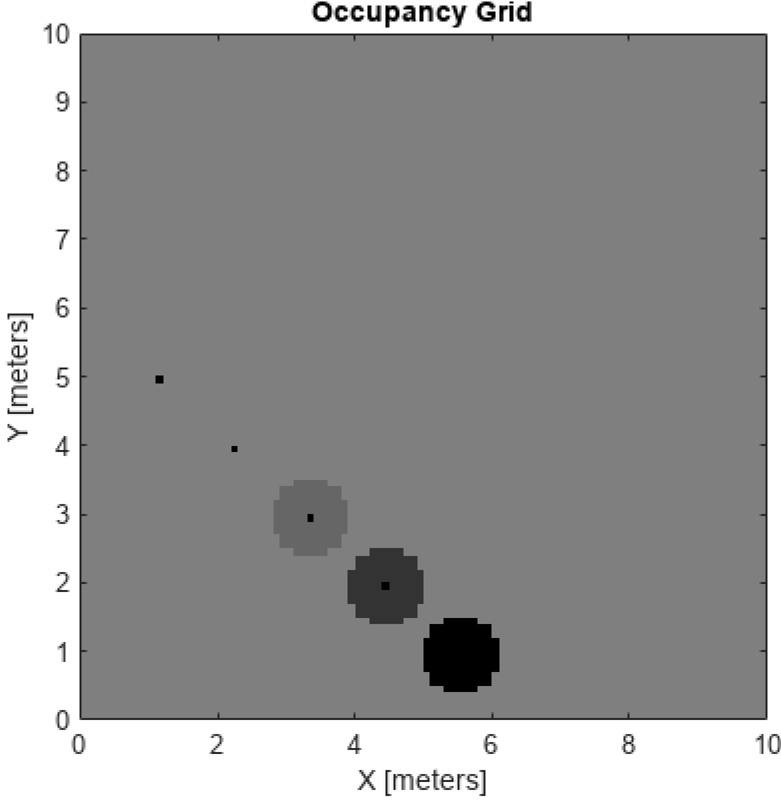



Get the grid locations from the world locations.

```
ij = world2grid(map,[x y]);
```

Set occupancy values for the grid locations.

```
setOccupancy(map,ij,ones(5,1),'grid')
figure
show(map)
```

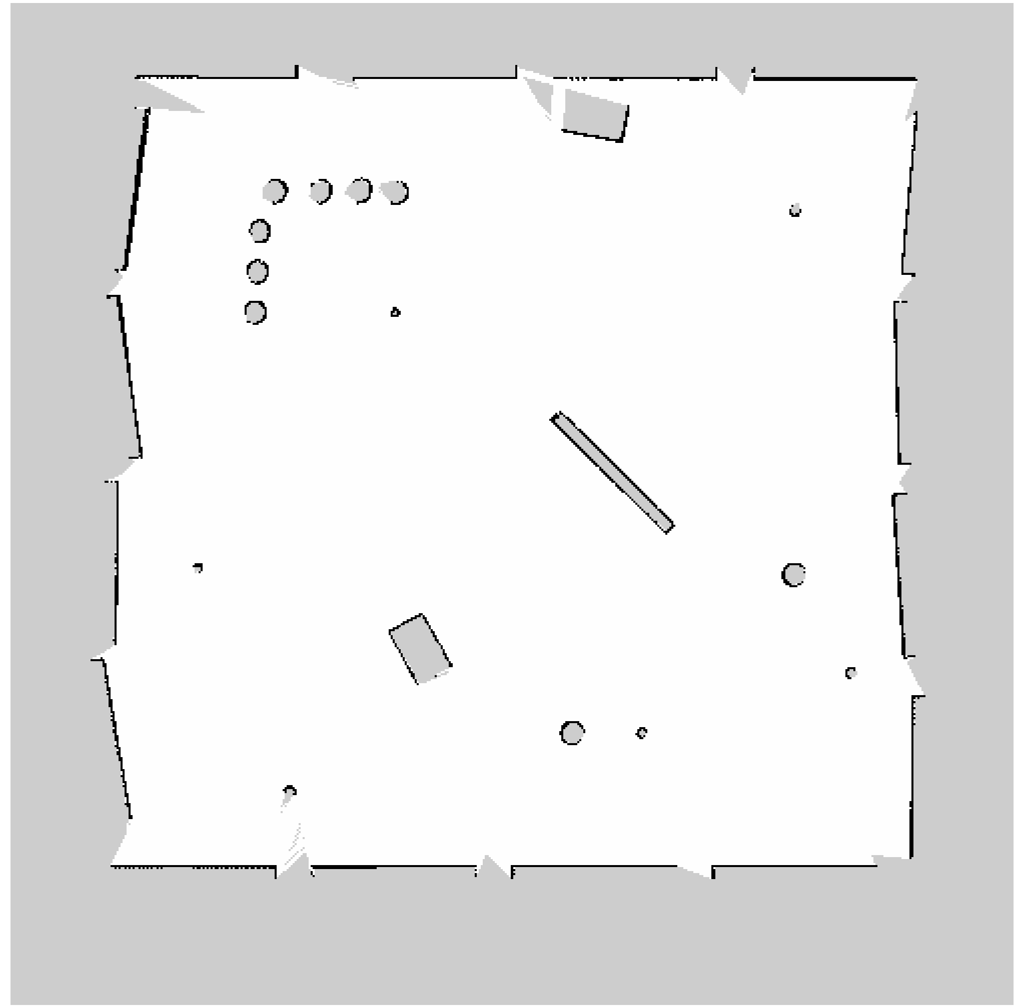



### Convert PGM Image to Map

Convert a portable graymap (PGM) file containing a ROS map into an `occupancyMap` for use in MATLAB.

Import the image using `imread`. Crop the image to the playpen area.

```
image = imread('playpen_map.pgm');
imageCropped = image(750:1250,750:1250);
imshow(imageCropped)
```

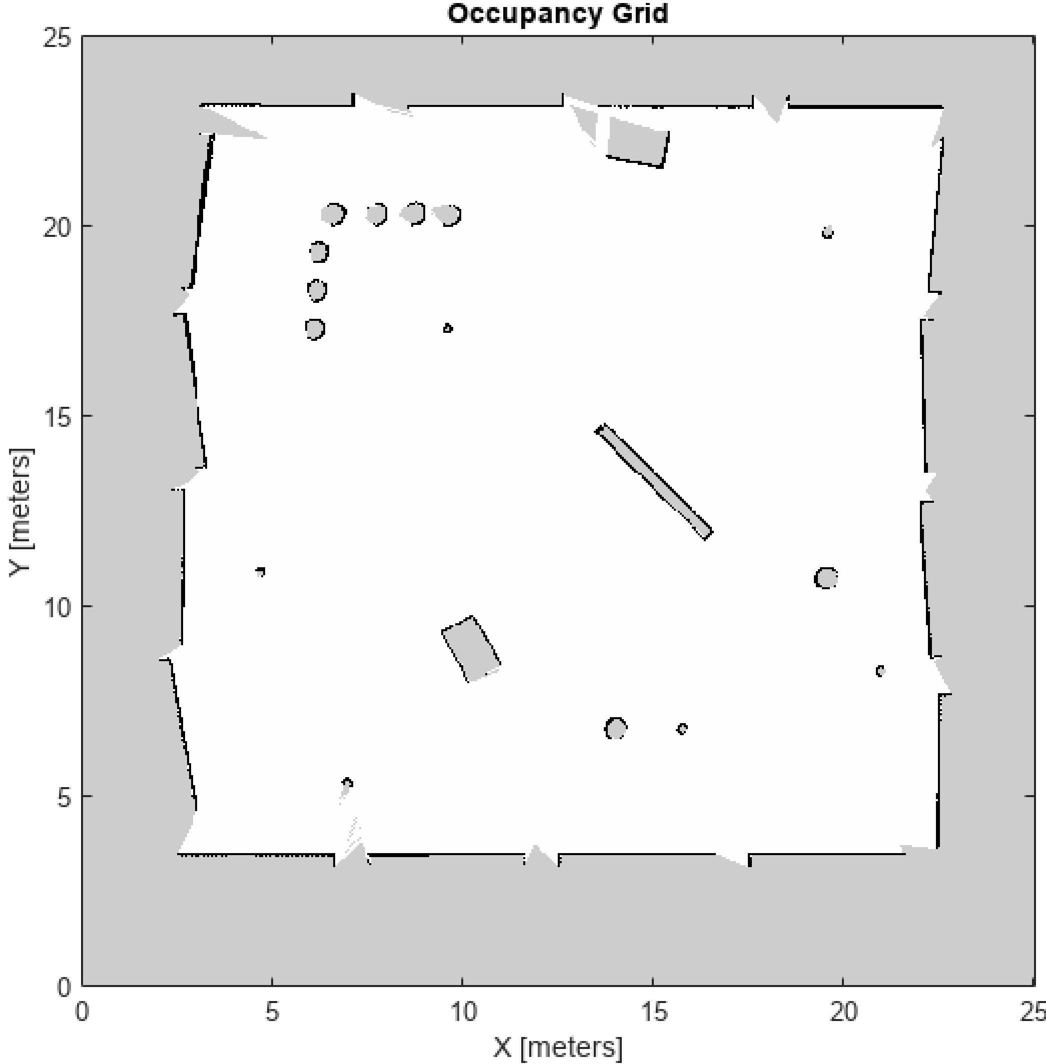


PGM values are expressed from 0 to 255 as `uint8`. Normalize these values by converting the cropped image to `double` and dividing each cell by 255. This image shows obstacles as values close to 0. Subtract the normalized image from 1 to get occupancy values with 1 representing occupied space.

```
imageNorm = double(imageCropped)/255;
imageOccupancy = 1 - imageNorm;
```

Create the `occupancyMap` object using an adjusted map image. The imported map resolution is 20 cells per meter.

```
map = occupancyMap(imageOccupancy,20);
show(map)
```




## Input Arguments

**map — Map representation**
`occupancyMap` object

Map representation, specified as a `occupancyMap` object. This object represents the environment of the vehicle. The object contains a matrix grid with values representing the probability of the occupancy of that cell. Values close to 1 represent a high probability that the cell contains an obstacle. Values close to 0 represent a high probability that the cell is not occupied and obstacle free.

#### Name-Value Pair Arguments

Specify optional pairs of arguments as `Name1=Value1,...,NameN=ValueN`, where `Name` is the argument name and `Value` is the corresponding value. Name-value arguments must appear after other arguments, but the order of the pairs does not matter.

*Before R2021a, use commas to separate each name and value, and enclose* `Name` *in quotes.*

Example: `'Parent',axHandle`

**`Parent` — Axes to plot the map**
`Axes` object | `UIAxes` object

Axes to plot the map specified as either an `Axes` or `UIAxes` object. See `axes` or `uiaxes`.

**`FastUpdate` — Update existing map plot**
`0` (default) | `1`

Update existing map plot, specified as `0` or `1`. If you previously plotted your map on your figure, set to `1` for a faster update to the figure. This is useful for updating the figure in a loop for fast animations.

### Outputs

**`mapImage` — Map image**
object handle

Map image, specified as an object handle.

## Version History

**Introduced in R2019b**

### See Also

`axes` | `occupancyMap` | `occupancyMatrix` | `binaryOccupancyMap`

# syncWith

Sync map with overlapping map

## Syntax

```
mat = syncWith(map,sourcemap)
```

## Description

`mat = syncWith(map,sourcemap)` updates `map` with data from another `occupancyMap` object, `sourcemap`. Locations in `map` that are also found in `sourcemap` are updated. All other cells in `map` retain their current values.

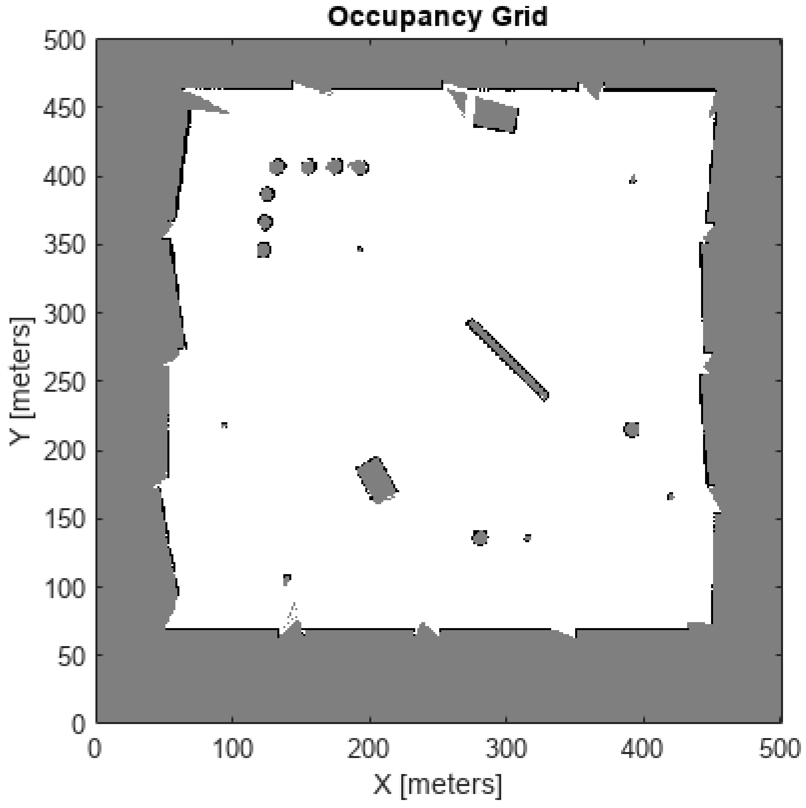
## Examples

### Move Local Map and Sync with World Map

This example shows how to move a local egocentric map and sync it with a larger world map. This process emulates a vehicle driving in an environment and getting updates on obstacles in the new areas.

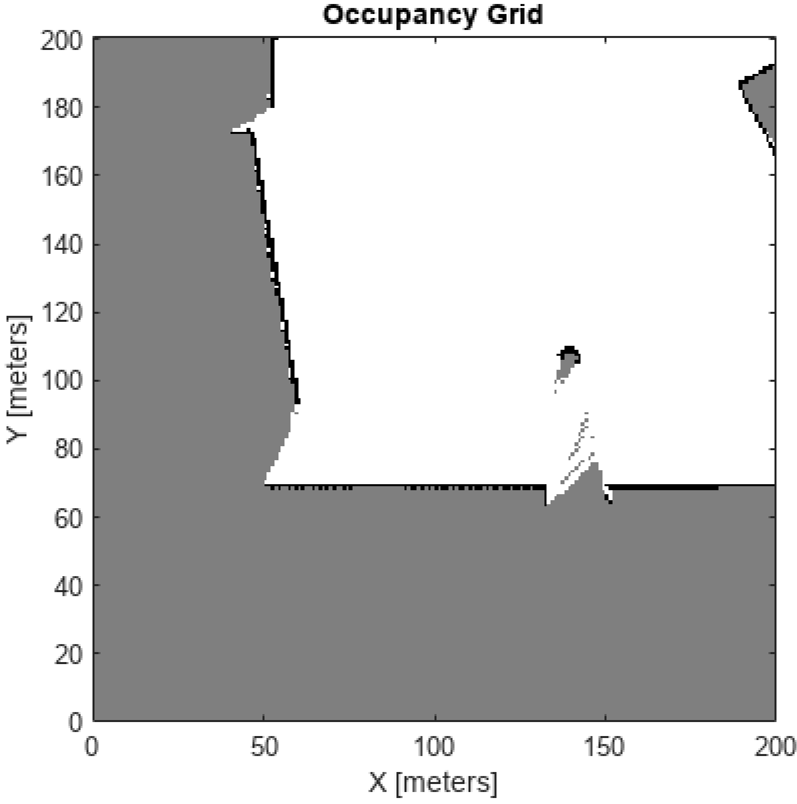
Load example maps. Create an occupancy map from the `ternaryMap`.

```
load exampleMaps.mat
map = occupancyMap(ternaryMap);
show(map)
```




Create a smaller local map.

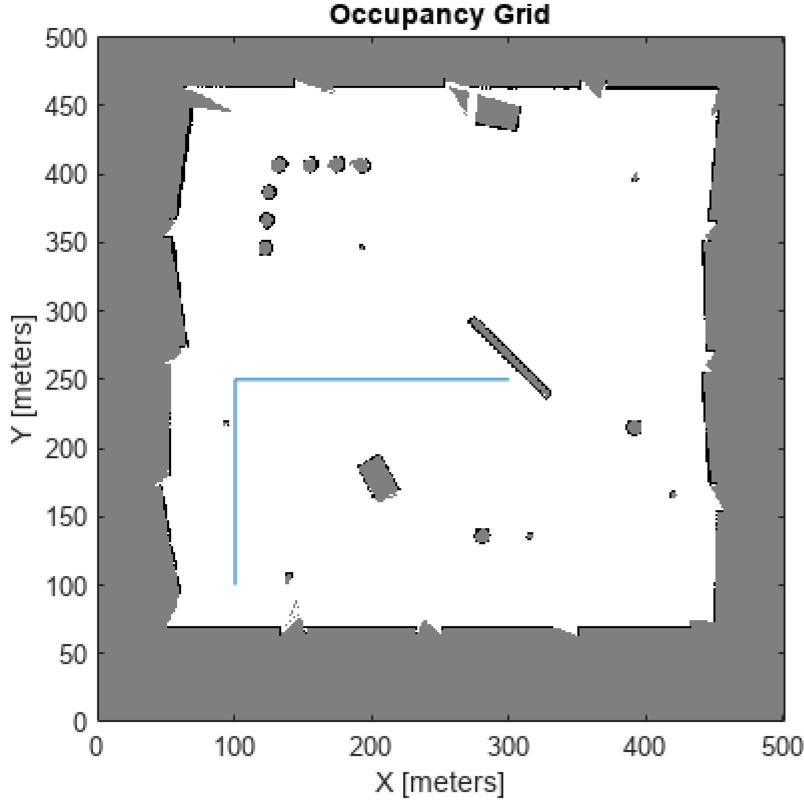
```
mapLocal = occupancyMap(ternaryMap(end-200:end,1:200));
show(mapLocal)
```




Follow a path planned in the world map and update the local map as you move your local frame.

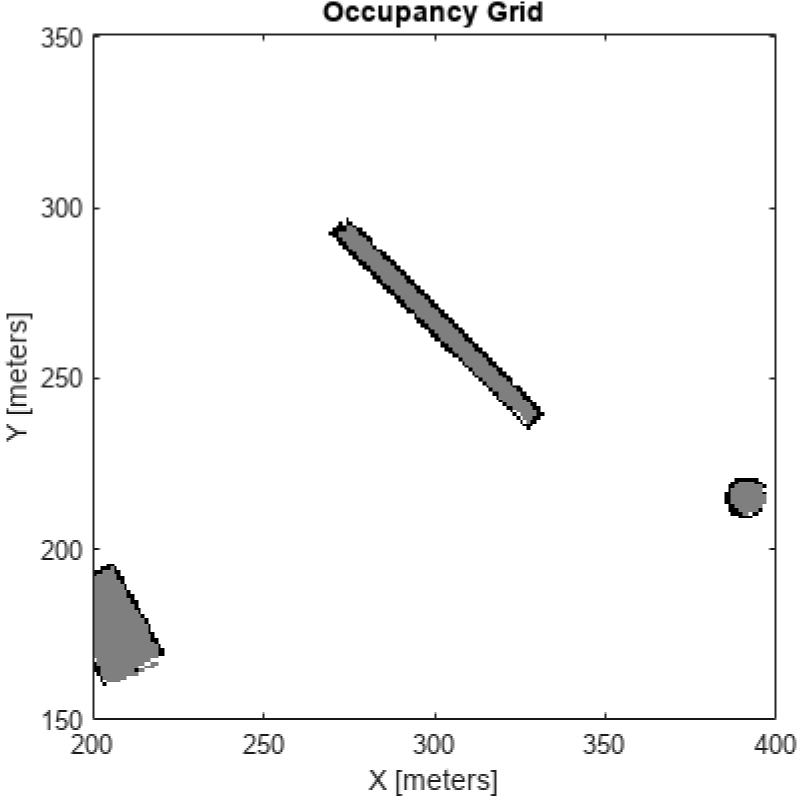
Specify path locations and plot on the map.

```
path = [100 100
        100 250
        200 250
        300 250];
show(map)
hold on
plot(path(:,1),path(:,2))
hold off
```




Create a loop for moving between points by the map resolution. Divide the difference between points by the map resolution to see how many incremental moves you can make.

```
for i = 1:length(path)-1
    moveAmount = (path(i+1,:)-path(i,:))/map.Resolution;
    for j = 1:abs(moveAmount(1)+moveAmount(2))
        moveValue = sign(moveAmount).*map.Resolution;
        move(mapLocal,moveValue,"MoveType","relative")
        syncWith(mapLocal,map)
        show(mapLocal)
        drawnow limitrate
    end
end
```




## Input Arguments

**map — Map representation**
occupancyMap object | mapLayer object | multiLayerMap object | signedDistanceMap object

Map representation, specified as a `occupancyMap`, `mapLayer`, `multiLayerMap`, or `signedDistanceMap` object.

**sourcemap — Source map data**
occupancyMap object | mapLayer object | multiLayerMap object | signedDistanceMap object

Source map data, specified as a `occupancyMap`, `mapLayer`, `multiLayerMap`, or `signedDistanceMap` object.

# Version History

**Introduced in R2019b**

**R2023a: syncWith supports signed distance maps**

`syncWith` supports the `signedDistanceMap` object as a new map representation for the `map` and `sourcemap` arguments.

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`multiLayerMap` | `mapLayer` | `occupancyMap` | `binaryOccupancyMap` | `signedDistanceMap`

### Topics

"Occupancy Grids"

# updateOccupancy

Update occupancy probability at locations

## Syntax

```
updateOccupancy(map,occMatrix)
```

```
updateOccupancy(map,locations,obs)
updateOccupancy(map,xy,obs,'world')
updateOccupancy(map,xy,obs,'local')
updateOccupancy(map,ij,obs,'grid')
```

```
updateOccupancy(map,bottomLeft,obsMatrix)
updateOccupancy(map,bottomLeft,obsMatrix,'world')
updateOccupancy(map,bottomLeft,obsMatrix,'local')
updateOccupancy(map,topLeft,obsMatrix,'grid')
```

## Description

`updateOccupancy(map,occMatrix)` probabilistically integrates a matrix of occupancy values, `occMatrix`, with the current occupancy matrix of the `occupancyMap` object `map`. The size of the matrix must be equal to the `GridSize` property of map.

`updateOccupancy(map,locations,obs)` probabilistically integrates observation values, `obs`, into the occupancy map cells corresponding to the *n*-by-2 matrix of world coordinates `locations`. Observation values are determined based on the “Inverse Sensor Model” on page 2-1016.

`updateOccupancy(map,xy,obs,'world')` probabilistically integrates observation values, `obs`, into the cells corresponding to the *n*-by-2 matrix of world coordinates `xy`.

`updateOccupancy(map,xy,obs,'local')` probabilistically integrates observation values, `obs`, into the cells corresponding to the *n*-by-2 matrix of local coordinates `xy`.

`updateOccupancy(map,ij,obs,'grid')` probabilistically integrates observation values, `obs`, into the cells corresponding to the *n*-by-2 matrix of grid indices `ij`.

`updateOccupancy(map,bottomLeft,obsMatrix)` probabilistically integrates an *m*-by-*n* matrix of observation values, `obsMatrix`, into a subregion in the map. Specify the bottom-left corner of the subregion as a world position, `bottomLeft`. The subregion extends *m* rows up and *n* columns to the right from the specified position.

`updateOccupancy(map,bottomLeft,obsMatrix,'world')` probabilistically integrates an *m*-by-*n* matrix of observation values, `obsMatrix`, into a subregion in the map. Specify the bottom-left corner of the subregion as a world position, `bottomLeft`. The subregion extends *m* rows up and *n* columns to the right from the specified position.

`updateOccupancy(map,bottomLeft,obsMatrix,'local')` probabilistically integrates an *m*-by-*n* matrix of observation values, `obsMatrix`, into a subregion in the map. Specify the bottom-left corner of the subregion as a local position, `bottomLeft`. The subregion extends *m* rows up and *n* columns to the right from the specified position.

`updateOccupancy(map,topLeft,obsMatrix,'grid')` probabilistically integrates an *m*-by-*n* matrix of observation values, `obsMatrix`, into a subregion in the map. Specify the top-left corner of the subregion as a grid index, `topLeft`. The subregion extends *m* rows down and *n* columns to the right from the specified index.

## Examples

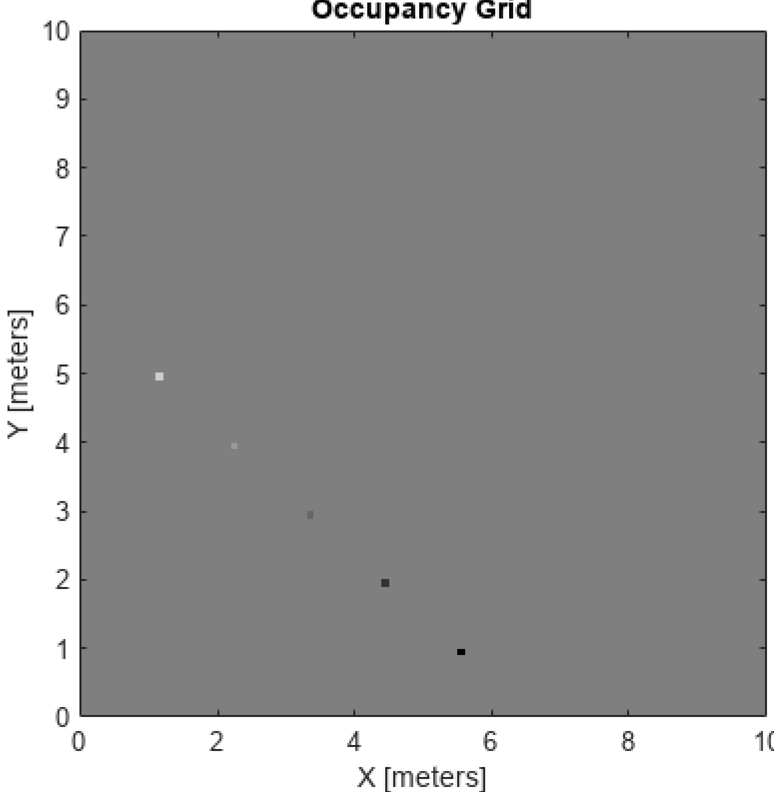
### Create and Modify Occupancy Map

Create an empty map of 10-by-10 meters in size.

```
map = occupancyMap(10,10,10);
```

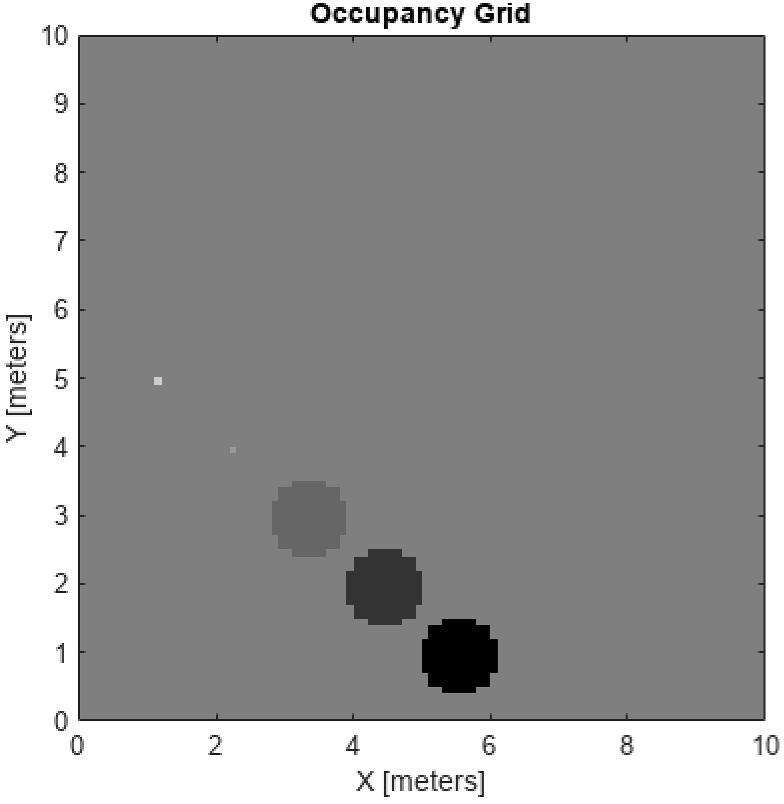
Update the occupancy of specific world locations with new probability values and display the map.

```
x = [1.2; 2.3; 3.4; 4.5; 5.6];
y = [5.0; 4.0; 3.0; 2.0; 1.0];

pvalues = [0.2; 0.4; 0.6; 0.8; 1];

updateOccupancy(map,[x y],pvalues)
figure
show(map)
```




Inflate the occupied areas by a radius of 0.5 m. The larger occupancy values overwrite the smaller values.

```
inflate(map,0.5)
figure
show(map)
```

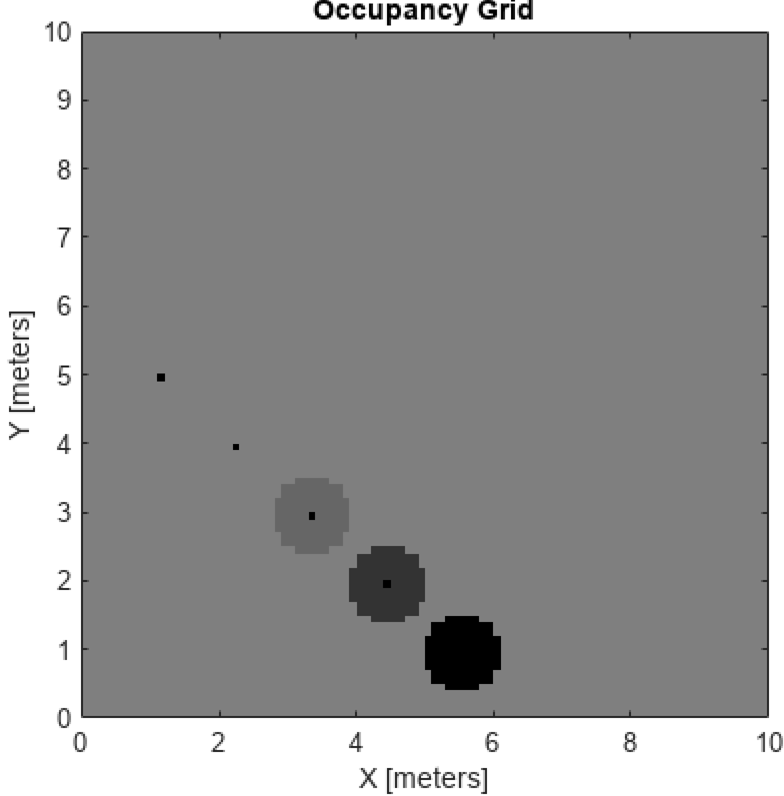



Get the grid locations from the world locations.

```
ij = world2grid(map,[x y]);
```

Set occupancy values for the grid locations.

```
setOccupancy(map,ij,ones(5,1),'grid')
figure
show(map)
```




## Input Arguments

**map — Map representation**
occupancyMap object

Map representation, specified as an occupancyMap object. This object represents the environment of the vehicle. The object contains a matrix grid with each value representing the probability of the occupancy of that cell. Values close to 1 represent a high probability that the cell contains an obstacle. Values close to 0 represent a high probability that the cell is not occupied and contains no obstacles.

**occMatrix — Matrix of occupancy values**
numeric matrix | logical matrix

Matrix of occupancy values, specified as a matrix. The size of the matrix must be equal to the GridSize property of map.

The occupancy values can be of any numeric type, with values between 0 and 1. If the matrix is logical, the default occupancy values of 0.7 (true) and 0.4 (false) are used.

Example: `updateOccupancy(map,ones(map.GridSize)*0.6)`

Data Types: single | double | logical

**locations — Cell locations in world coordinates**
*n*-by-2 matrix

Cell locations in world coordinates, specified as an *n*-by-2 matrix with rows of the form [*x y*], where *n* is the number of world coordinates. The function ignores locations outside of the map boundaries.

Example: `updateOccupancy(map,[1 1; 3 3; 5 5],false)`

Data Types: `single` | `double`

**`bottomLeft` — Location of bottom-left corner of observation matrix**
two-element vector

Location of the bottom-left corner of the observation matrix, specified as a two-element vector of the form `[xCoord yCoord]`. The location is in world or local coordinates, based on the syntax.

Example: `updateOccupancy(map,[2 2],[0.2 0.4; 0.6 0.8],'world')`

Data Types: `single` | `double`

**`topLeft` — Location of top-left corner of grid**
two-element vector

Location of the top-left corner of the grid, specified as a two-element vector of form `[iCoord jCoord]`.

Example: `updateOccupancy(map,[2 2],[0.2 0.4; 0.6 0.8],'grid')`

Data Types: `single` | `double`

**`xy` — World or local coordinates**
*n*-by-2 matrix

World or local coordinates, specified as an *n*-by-2 matrix with rows of the form `[x y]`, where *n* is the number of coordinates.

Example: `updateOccupancy(map,[2 2; 4 4; 6 6],[0.2; 0.4; 0.6],'world')`

Data Types: `single` | `double`

**`ij` — Grid positions**
*n*-by-2 matrix

Grid positions, specified as an *n*-by-2 matrix with rows of the form `[i j]` in `[rows cols]` format, where *n* is the number of grid positions.

Example: `updateOccupancy(map,[2 2; 4 4; 6 6],[0.2; 0.4; 0.6],'grid')`

Data Types: `single` | `double`

**`obs` — Probability observation values**
*n*-element numeric column vector | *n*-element logical column vector | numeric scalar | logical scalar

Probability observation values, specified as a numeric or logical scalar or a numeric or logical *n*-element column vector the same size as either `locations`, `xy`, or `ij`.

`obs` values can be any value from 0 to 1, but if `obs` is a logical vector, the default observation values of 0.7 (`true`) and 0.4 (`false`) are used. If `obs` is a numeric or a logical scalar, the value is applied to all coordinates in `locations`, `xy`, or `ij`. These values correlate to the “Inverse Sensor Model” on page 2-1016 for ray casting.

Example: `updateOccupancy(map,[2 2; 4 4; 6 6],[0.2; 0.4; 0.6],'local')`

Data Types: `single` | `double` | `logical`

**`obsMatrix` — Matrix of probability observation values**
*m*-by-*n* numeric matrix | *m*-by-*n* logical matrix

Matrix of probability observation values, specified as an *m*-by-*n* numeric or logical matrix.

The observation values can be of any numeric type with value between 0 and 1. If the matrix is logical, the default observation values of 0.7 (`true`) and 0.4 (`false`) are used.

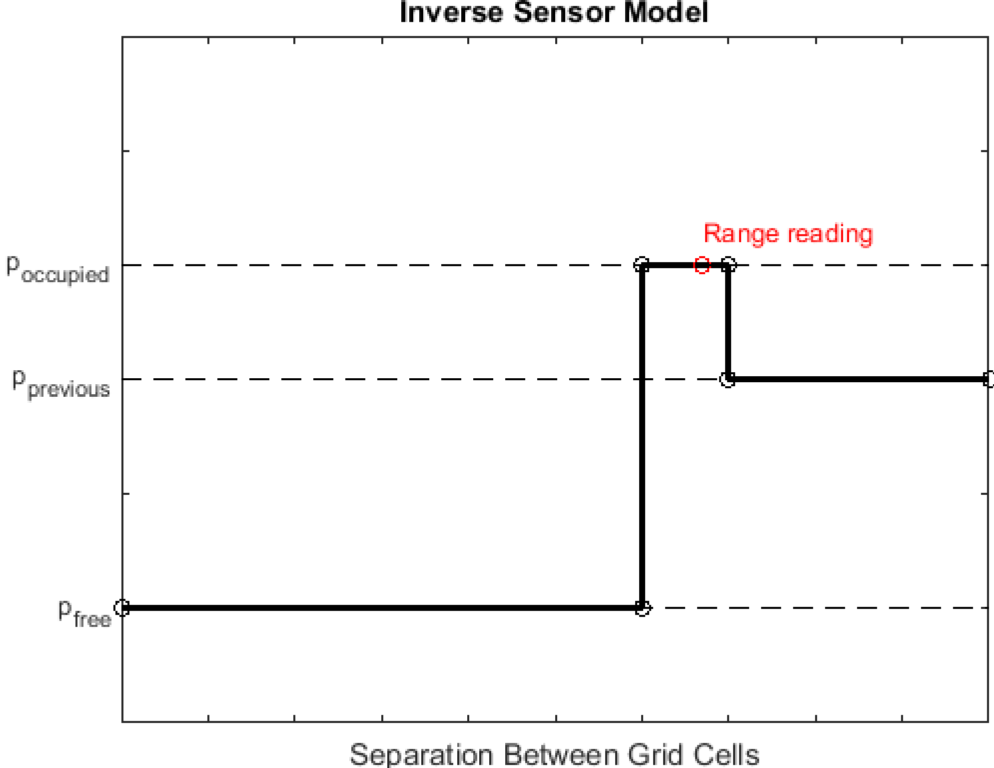
Example: `updateOccupancy(map,[2 2],[0.2 0.4; 0.6 0.8])`

Data Types: `single` | `double` | `logical`

## More About

### Inverse Sensor Model

The inverse sensor model determines how values are set along a ray from a range sensor reading to the obstacles in the map. `NaN` range values are ignored. Range values greater than `maxrange` are not updated.




Grid locations that contain range readings are updated with the occupied probability. Locations before the reading are updated with the free probability. All locations after the reading are not updated.

## Version History

**Introduced in R2019b**

## See Also

`occupancyMap` | `setOccupancy` | `binaryOccupancyMap`

### Topics

"Occupancy Grids"

# world2grid

Convert world coordinates to grid indices

## Syntax

`ij = world2grid(map,xy)`

## Description

`ij = world2grid(map,xy)` converts an array of world coordinates, `xy`, to an array of grid indices, `ij` in `[`*`row col`*`]` format.

## Examples

### Convert World Coordinates in Occupancy Map to Grid Indices

Create an empty occupancy map with a width and height of 10 meters.

```
map = occupancyMap(10,10);
```

Get grid indices from world coordinates.

```
[xWorld,yWorld] = meshgrid(0:0.5:2);
ij = world2grid(map,[xWorld(:) yWorld(:)]);
```

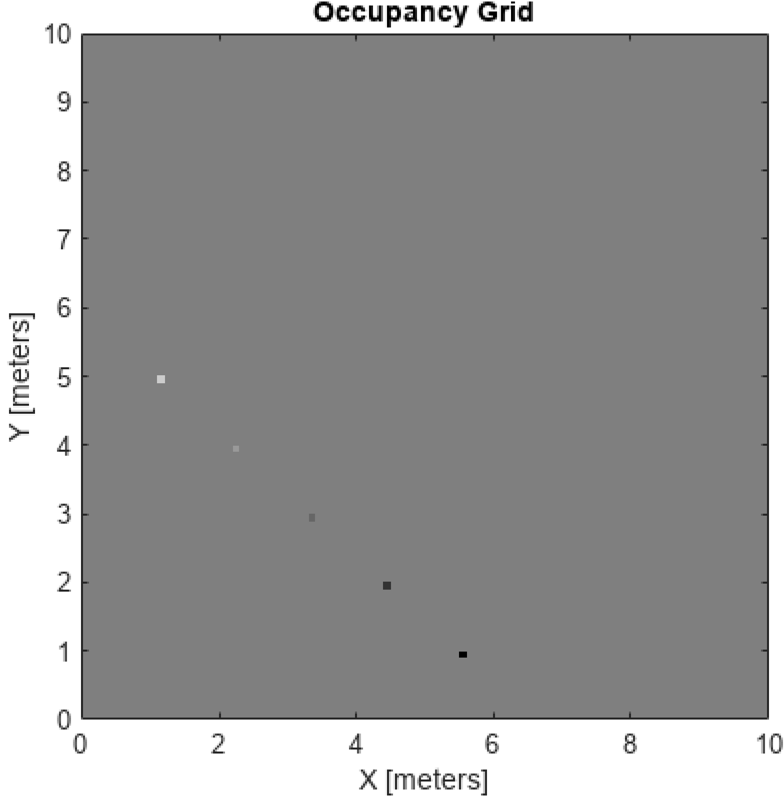
### Create and Modify Occupancy Map

Create an empty map of 10-by-10 meters in size.

```
map = occupancyMap(10,10,10);
```

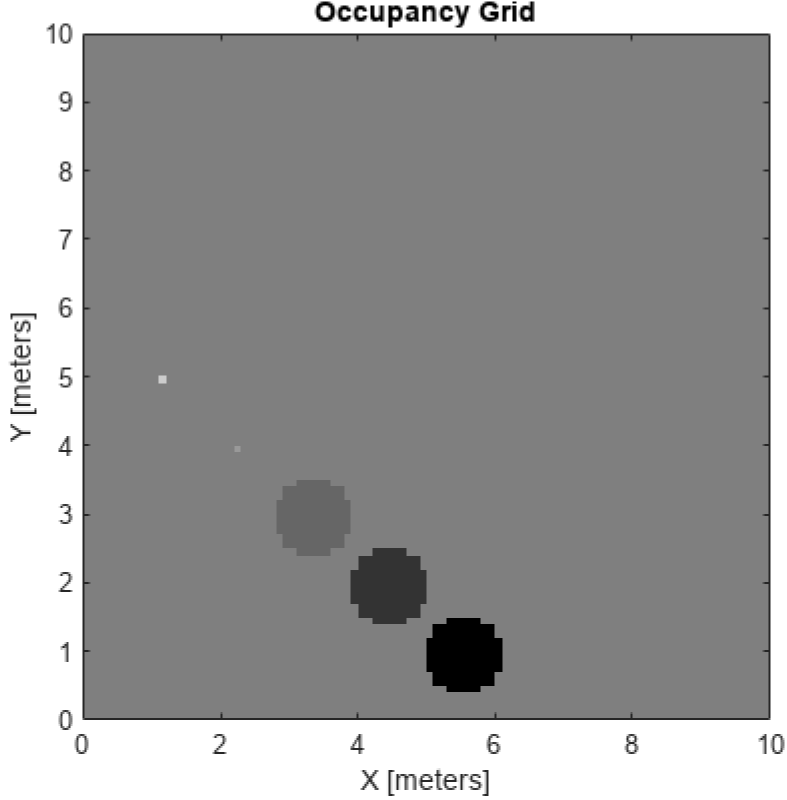
Update the occupancy of specific world locations with new probability values and display the map.

```
x = [1.2; 2.3; 3.4; 4.5; 5.6];
y = [5.0; 4.0; 3.0; 2.0; 1.0];

pvalues = [0.2; 0.4; 0.6; 0.8; 1];

updateOccupancy(map,[x y],pvalues)
figure
show(map)
```




Inflate the occupied areas by a radius of 0.5 m. The larger occupancy values overwrite the smaller values.

```
inflate(map,0.5)
figure
show(map)
```

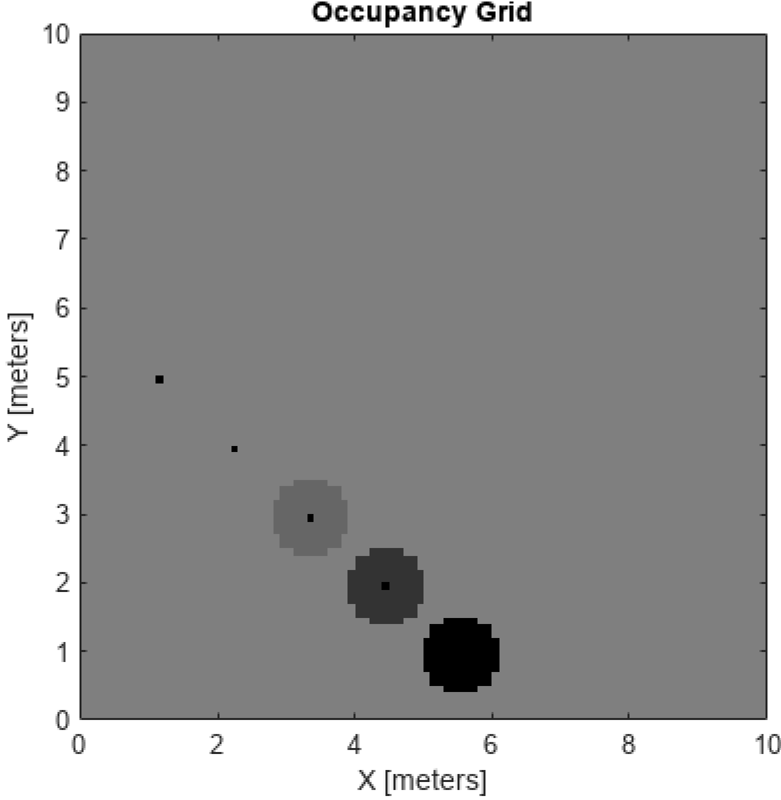



Get the grid locations from the world locations.

```
ij = world2grid(map,[x y]);
```

Set occupancy values for the grid locations.

```
setOccupancy(map,ij,ones(5,1),'grid')
figure
show(map)
```




## Input Arguments

**map — Map representation**
occupancyMap object | mapLayer object | multiLayerMap object | signedDistanceMap object

Map representation, specified as a occupancyMap, mapLayer, multiLayerMap, or signedDistanceMap object.

**xy — World coordinates**
*n*-by-2 matrix

World coordinates, specified as an *n*-by-2 matrix of [*x y*] pairs, where *n* is the number of world coordinates.

Data Types: double

## Output Arguments

**ij — Grid indices**
*n*-by-2 matrix

Grid indices, returned as an *n*-by-2 matrix of [*i j*] pairs in [*row col*] format, where *n* is the number of grid positions. The grid cell locations are counted from the top left corner of the grid.

Data Types: double

## Version History

**Introduced in R2019b**

### R2023a: Signed Distance Map Support

The `world2grid` function now supports the `signedDistanceMap` object as a new map representation for the `map` argument.

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**

`multiLayerMap` | `mapLayer` | `occupancyMap` | `binaryOccupancyMap` | `signedDistanceMap`

**Functions**

`grid2world` | `world2local`

**Topics**

"Occupancy Grids"

# rangeSensor

Simulate range-bearing sensor readings

## Description

The `rangeSensor` System object is a range-bearing sensor that is capable of outputting range and angle measurements based on the given sensor pose and occupancy map. The range-bearing readings are based on the obstacles in the occupancy map.

To simulate a range-bearing sensor using this object:

1. Create the `rangeSensor` object and set its properties.
2. Call the object with arguments, as if it were a function.

To learn more about how System objects work, see What Are System Objects?

# Creation

## Syntax

```
rbsensor = rangeSensor
rbsensor = rangeSensor(Name,Value)
```

### Description

`rbsensor = rangeSensor` returns a `rangeSensor` System object, `rbsensor`. The sensor is capable of outputting range and angle measurements based on the sensor pose and an occupancy map.

`rbsensor = rangeSensor(Name,Value)` sets properties for the sensor using one or more name-value pairs. Unspecified properties have default values. Enclose each property name in quotes.

## Properties

Unless otherwise indicated, properties are *nontunable*, which means you cannot change their values after calling the object. Objects lock when you call them, and the `release` function unlocks them.

If a property is *tunable*, you can change its value at any time.

For more information on changing property values, see System Design in MATLAB Using System Objects.

**Range — Minimum and maximum detectable range**
`[0 20]` (default) | 1-by-2 positive real-valued vector

The minimum and maximum detectable range, specified as a 1-by-2 positive real-valued vector. Units are in meters.

Example: `[1 15]`

**Tunable:** Yes

Data Types: `single` | `double`

**`HorizontalAngle` — Minimum and maximum horizontal detection angle**
`[-pi pi]` (default) | 1-by-2 real-valued vector

Minimum and maximum horizontal detection angle, specified as a 1-by-2 real-valued vector. Units are in radians.

Example: `[-pi/3 pi/3]`

Data Types: `single` | `double`

**`HorizontalAngleResolution` — Resolution of horizontal angle readings**
`0.0244` (default) | positive scalar

Resolution of horizontal angle readings, specified as a positive scalar. The resolution defines the angular interval between two consecutive sensor readings. Units are in radians.

Example: `0.01`

Data Types: `single` | `double`

**`RangeNoise` — Standard deviation of range noise**
`0` (default) | positive scalar

The standard deviation of range noise, specified as a positive scalar. The range noise is modeled as a zero-mean white noise process with the specified standard deviation. Units are in meters.

Example: `0.01`

**Tunable:** Yes

Data Types: `single` | `double`

**`HorizontalAngleNoise` — Standard deviation of horizontal angle noise**
`0` (default) | positive scalar

The standard deviation of horizontal angle noise, specified as a positive scalar. The range noise is modeled as a zero-mean white noise process with the specified standard deviation. Units are in radians.

Example: `0.01`

**Tunable:** Yes

Data Types: `single` | `double`

**`NumReadings` — Number of output readings**
`258` (default) | positive integer

This property is read-only.

Number of output readings for each pose of the sensor, specified as a positive integer. This property depends on the `HorizonalAngle` and `HorizontalAngleResolution` properties.

Data Types: `single` | `double`

## Usage

### Syntax

```
[ranges,angles] = rbsensor(pose,map)
```

#### Description

`[ranges,angles] = rbsensor(pose,map)` returns the range and angle readings from the 2-D pose information and the ground-truth map.

#### Input Arguments

**pose — Pose of sensor in map**
*N*-by-3 real-valued matrix

Poses of the sensor in the 2-D map, specified as an *N*-by-3 real-valued matrix, where *N* is the number of poses to simulate the sensor. Each row of the matrix corresponds to a pose of the sensor in the order of [$x$, $y$, $\theta$]. $x$ and $y$ represent the position of the sensor in the map frame. The units of $x$ and $y$ are in meters. $\theta$ is the heading angle of the sensor with respect to the positive $x$-direction of the map frame. The units of $\theta$ are in radians.

**map — Ground-truth map**
`occupancyMap` object | `binaryOccupancyMap` object

Ground-truth map, specified as an `occupancyMap` or a `binaryOccupancyMap` object. For the `occupancyMap` input, the range-bearing sensor considers a cell as occupied and returns a range reading if the occupancy probability of the cell is greater than the value specified by the `OccupiedThreshold` property of the occupancy map.

#### Output Arguments

**ranges — Range readings**
*R*-by-*N* real-valued matrix

Range readings, specified as an *R*-by-*N* real-valued matrix. *N* is the number of poses for which the sensor is simulated, and *R* is the number of sensor readings per pose of the sensor. *R* is same as the value of the `NumReadings` property.

**angles — Angle readings**
*R*-by-1 real-valued vector

Angle readings, specified as an *R*-by-1 real-valued vector. *R* is the number of sensor readings per pose of the sensor. *R* is same as the value of the `NumReadings` property.

## Object Functions

To use an object function, specify the System object as the first input argument. For example, to release system resources of a System object named `obj`, use this syntax:

```
release(obj)
```

## Common to All System Objects

step Run System object algorithm
clone Create duplicate System object

## Examples

### Obtain Range and Bearing Readings

Create a range-bearing sensor.

```
rbsensor = rangeSensor;
```

Specify the pose of the sensor and the ground-truth map.

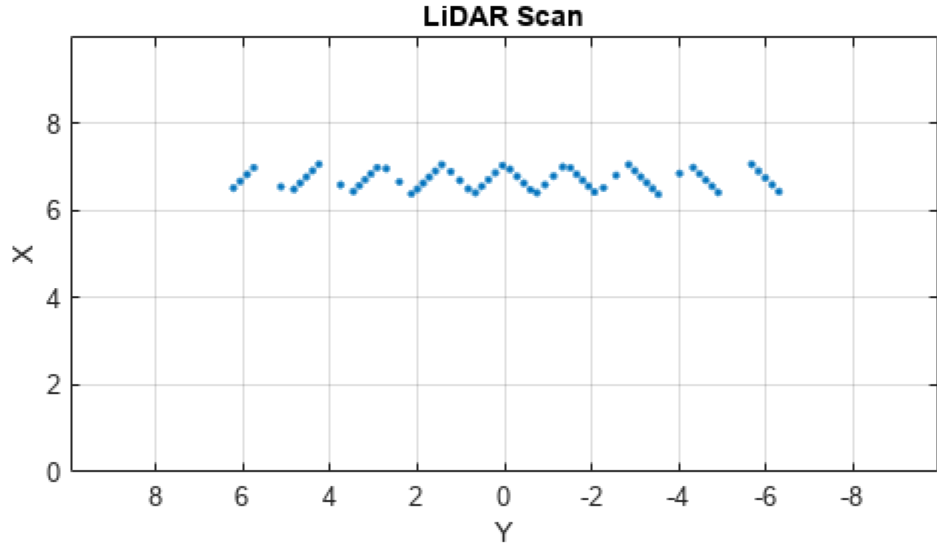
```
truePose = [0 0 pi/4];
trueMap = binaryOccupancyMap(eye(10));
```

Generate the sensor readings.

```
[ranges, angles] = rbsensor(truePose, trueMap);
```

Visualize the results using `lidarScan`.

```
scan = lidarScan(ranges, angles);
figure
plot(scan)
```



# Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

Usage notes and limitations:

- See “System Objects in MATLAB Code Generation” (MATLAB Coder).

## See Also

`occupancyMap` | `binaryOccupancyMap` | `lidarScan`

# world2local

Convert world coordinates to local coordinates

## Syntax

```
xyLocal = world2local(map,xy)
```

## Description

`xyLocal = world2local(map,xy)` converts an array of world coordinates to local coordinates.

## Examples

### Convert World Coordinates in Occupancy Map to Local Coordinates

Create an empty occupancy map with a width and height of 10 meters.

```
map = occupancyMap(10,10);
```

Get local coordinates from world coordinates.

```
[xWorld,yWorld] = meshgrid(0:0.5:2);
xyLocal = world2local(map,[xWorld(:) yWorld(:)]);
```

## Input Arguments

**map — Map representation**
`occupancyMap` object | `mapLayer` object | `multiLayerMap` object | `signedDistanceMap` object

Map representation, specified as a `occupancyMap`, `mapLayer`, `multiLayerMap`, or `signedDistanceMap` object.

**xy — World coordinates**
*n*-by-2 vertical array

World coordinates, specified as an *n*-by-2 vertical array of `[x y]` pairs, where *n* is the number of world coordinates.

## Output Arguments

**xyLocal — Local coordinates**
*n*-by-2 vertical array

Local coordinates, specified as an *n*-by-2 vertical array of `[x y]` pairs, where *n* is the number of local coordinates.

## Version History

**Introduced in R2019b**

#### R2023a: Signed Distance Map Support

The `world2local` function now supports the `signedDistanceMap` object as a new map representation for the `map` argument.

## Extended Capabilities

#### C/C++ Code Generation
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
`multiLayerMap` | `mapLayer` | `occupancyMap` | `binaryOccupancyMap` | `signedDistanceMap`

**Functions**
`grid2world` | `local2world`

# occupancyMap3D

Create 3-D occupancy map

## Description

The `occupancyMap3D` object stores a 3-D map and map information. The map is stored as probabilistic values in an octree data structure on page 2-1034. The class handles arbitrary environments and expands its size dynamically based on observation inputs. You can add observations as point clouds or as specific *xyz*-locations. These observations update the probability values. Probabilistic values represent the occupancy of locations. The octree data structure trims data appropriately to remain efficient both in memory and on disk.

## Creation

### Syntax

```
omap = occupancyMap3D
omap = occupancyMap3D(res)
omap = occupancyMap3D(res,Name,Value)
```

#### Description

`omap = occupancyMap3D` creates an empty 3-D occupancy map with no observations and default property values.

`omap = occupancyMap3D(res)` specifies a map resolution in cells/meter and sets the `Resolution` property.

`omap = occupancyMap3D(res,Name,Value)` specifies properties using one or more name-value arguments. For example, `"FreeThreshold",0.25` sets the threshold to consider cells obstacle-free as a probability value of 0.25.

### Properties

**`Resolution` — Grid resolution**
`1` (default) | positive scalar

Grid resolution in cells per meter, specified as a scalar. Specify resolution on construction. Inserting observations with precisions higher than this value are rounded down and applied at this resolution.

**`FreeThreshold` — Threshold to consider cells as obstacle-free**
`0.2` (default) | positive scalar

Threshold to consider cells as obstacle-free, specified as a positive scalar. Probability values below this threshold are considered obstacle-free.

**`OccupiedThreshold` — Threshold to consider cells as occupied**
`0.65` (default) | positive scalar

Threshold to consider cells as occupied, specified as a positive scalar. Probability values above this threshold are considered occupied.

#### `ProbabilitySaturation` — Saturation limits on probability values

`[0.001 0.999]` (default) | `[min max]` vector

Saturation limits on probability values, specified as a `[min max]` vector. Values above or below these saturation values are set to the `min` or `max` values. This property reduces oversaturating of cells when incorporating multiple observations.

## Object Functions

| | |
|---|---|
| checkOccupancy | Check if locations are free or occupied |
| getOccupancy | Get occupancy probability of locations |
| inflate | Inflate each occupied location |
| insertPointCloud | Insert 3-D points or point cloud observation into map |
| rayIntersection | Find intersection points of rays and occupied map cells |
| setOccupancy | Set occupancy probability of locations |
| show | Display 3-D occupancy map |
| updateOccupancy | Update occupancy probability at locations |

## Examples

### Create 3-D Occupancy Map and Inflate Points

The `occupancyMap3D` object stores obstacles in 3-D space, using sensor observations to map an environment. Create a map and add points from a point cloud to identify obstacles. Then inflate the obstacles in the map to ensure safe operating space around obstacles.

Create an `occupancyMap3D` object with a map resolution of 10 cells/meter.

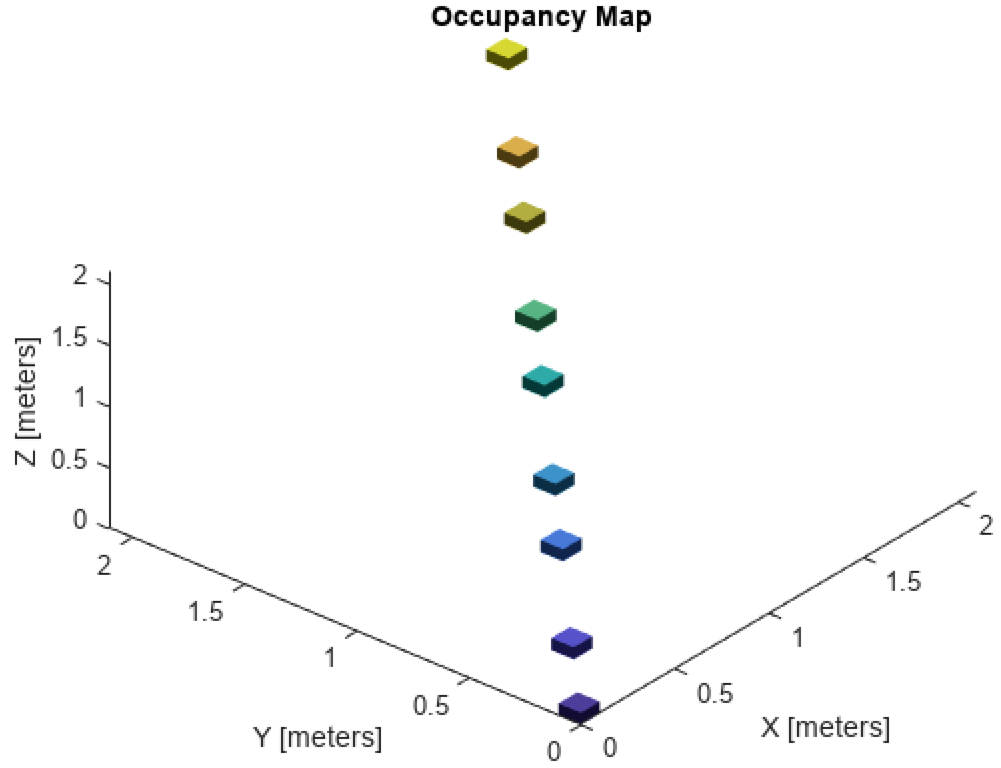
```
map3D = occupancyMap3D(10);
```

Define a set of 3-D points as an observation from a pose `[x y z qw qx qy qz]`. This pose is for the sensor that observes these points and is centered on the origin. Define two sets of points to insert multiple observations.

```
pose = [ 0 0 0 1 0 0 0];

points = repmat((0:0.25:2)', 1, 3);
points2 = [(0:0.25:2)' (2:-0.25:0)' (0:0.25:2)'];
maxRange = 5;
```

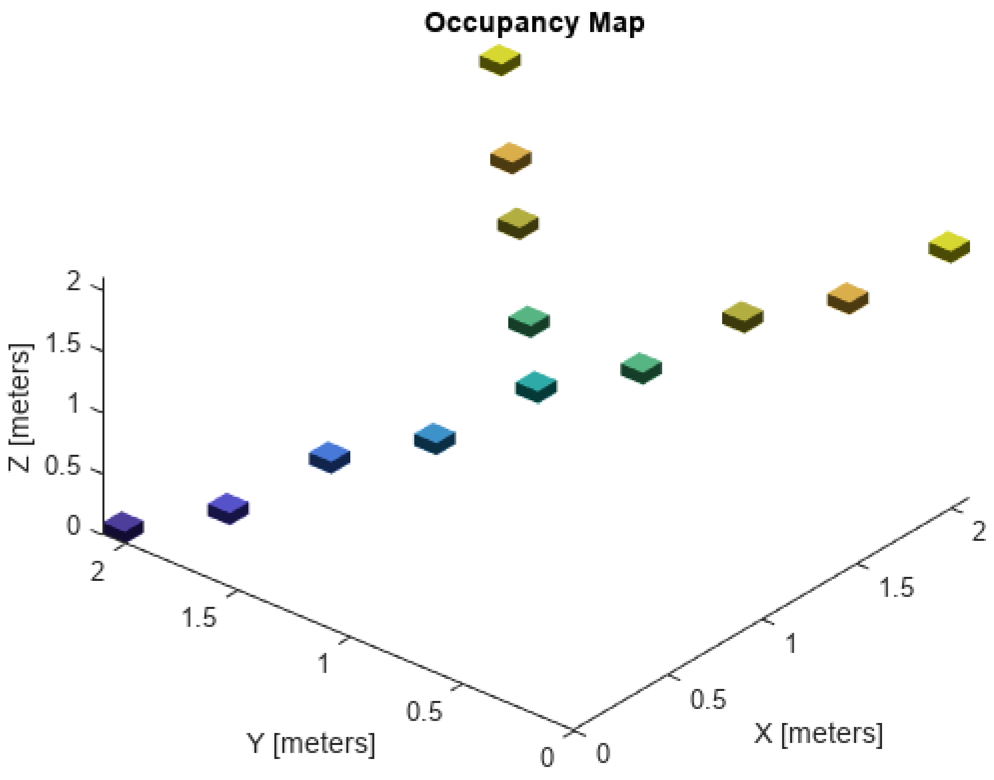
Insert the first set of points using `insertPointCloud`. The function uses the sensor pose and the given points to insert observations into the map. The colors displayed correlate to the height of the point only for illustrative purposes.

```
insertPointCloud(map3D,pose,points,maxRange)
show(map3D)
```



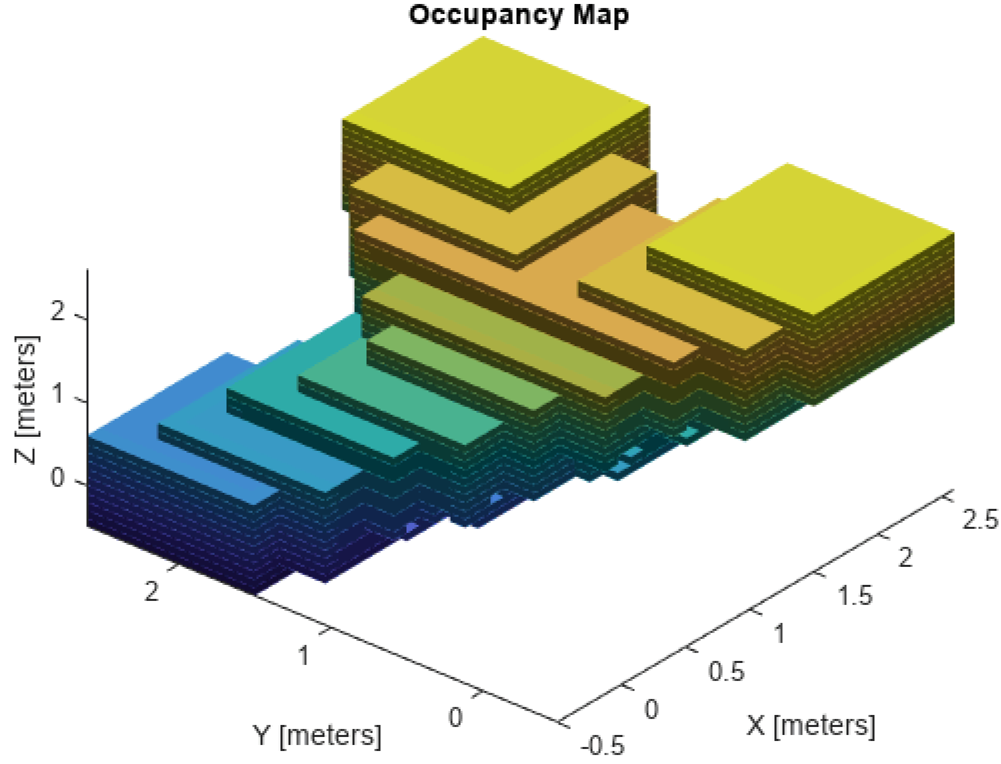

Insert the second set of points. The ray between the sensor pose (origin) and these points overlap points from the previous insertion. Therefore, the free space between the sensor and the new points are updated and marked as free space.

```
insertPointCloud(map3D,pose,points2,maxRange)
show(map3D)
```




Inflate the map to add a buffer zone for safe operation around obstacles. Define the vehicle radius and safety distance and use the sum of these values to define the inflation radius for the map.

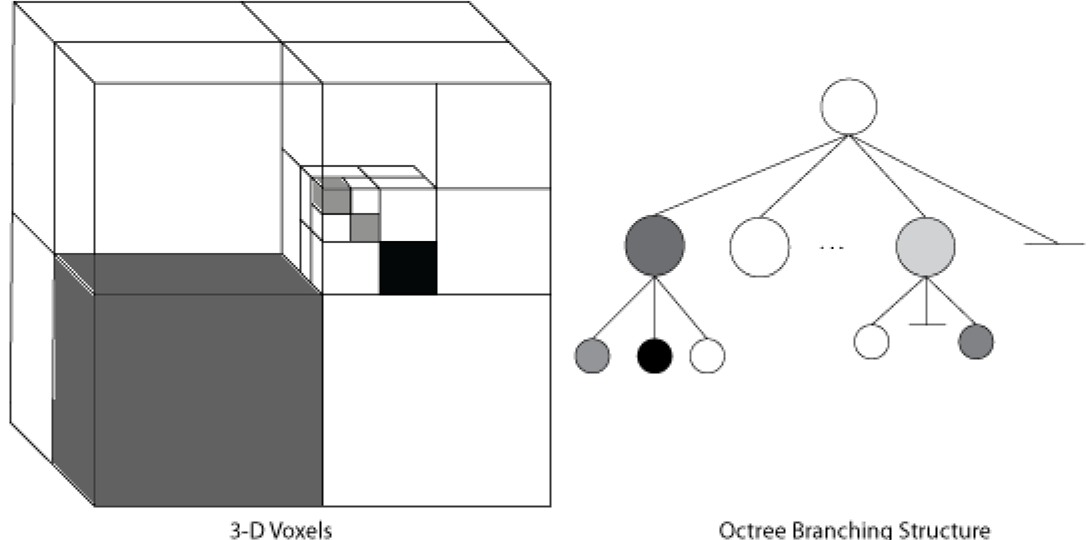
```
vehicleRadius = 0.2;
safetyRadius = 0.3;
inflationRadius = vehicleRadius + safetyRadius;
inflate(map3D, inflationRadius);

show(map3D)
```



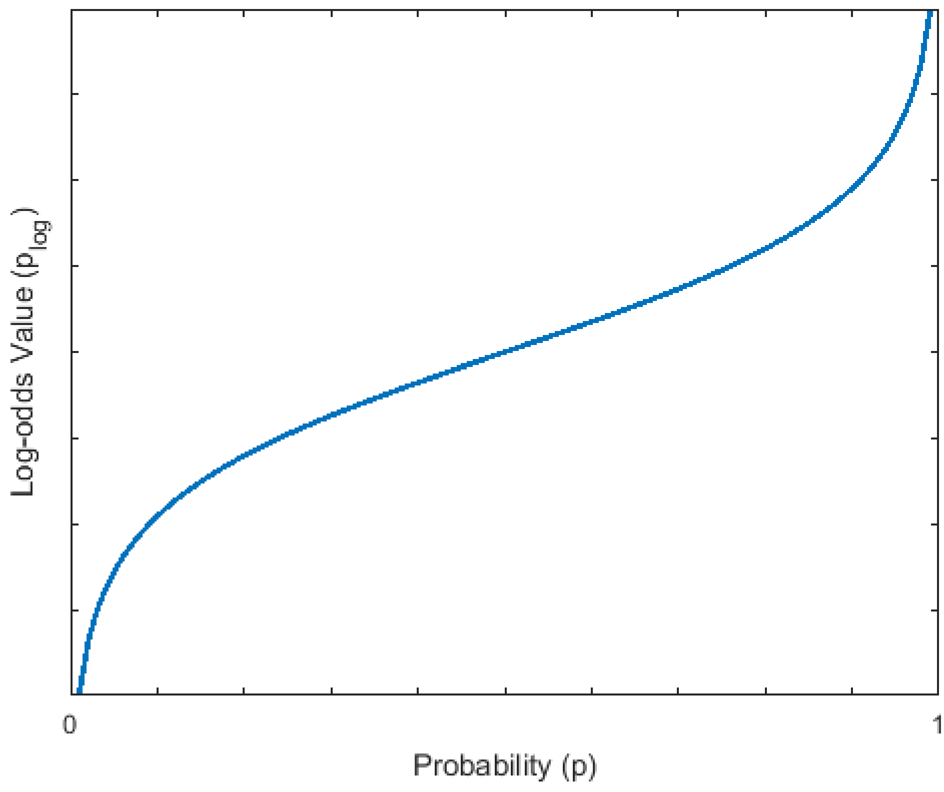

## Algorithms

### Octree Data Structure

The octree data structure is a hierarchical structure used for subdivision of an environment into cubic volumes called voxels. For a given map volume, the space is recursively subdivided into eight voxels until it achieves a desired map resolution (voxel size). This subdivision can be represented as a tree, which stores probability values for locations in the map.




The probability values in the tree have a log-odds representation. This representation enables locations to easily recover from dynamic observations, and reduces numerical errors due to small probabilities. To remain efficient in memory, lower branches of the tree are pruned in the structure if they share the same occupancy values using this log-odds representation.




The object handles the organization of this data structure, including the pruning of branches, internally. When using functions such as `setOccupancy`, `getOccupancy`, or `insertPointCloud`, specify all observations as spatial coordinates. The object determines insertions into the tree, and navigation through the tree, based on the spatial coordinates and the resolution of the map.

# Version History

**Introduced in R2019b**

## References

[1] Hornung, Armin, Kai M. Wurm, Maren Bennewitz, Cyrill Stachniss, and Wolfram Burgard. "OctoMap: an efficient probabilistic 3D mapping framework based on octrees." *Autonomous Robots* 34, no. 3 (April 2013): 189–206. https://doi.org/10.1007/s10514-012-9321-0.

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
occupancyMap | occupancyMap3DCollisionOptions | binaryOccupancyMap

**Functions**
checkMapCollision | insertPointCloud | inflate | setOccupancy | show | rosReadOccupancyMap3D

# occupancyMap3DCollisionOptions

Collision-checking options between 3-D occupancy map and collision geometries

## Description

The `occupancyMap3DCollisionOptions` object contains options for checking for collisions using the `checkMapCollision` function, between occupied cells of an `occupancyMap3D` object and collision geometry objects.

## Creation

### Syntax

```
OPTS = occupancyMap3DCollisionOptions
OPTS = occupancyMap3DCollisionOptions(Name=Value)
```

#### Description

`OPTS = occupancyMap3DCollisionOptions` returns a collision-checking options object,`OPTS`.

`OPTS = occupancyMap3DCollisionOptions(Name=Value)` specifies properties using one or more name-value arguments. For example, `occupancyMap3DCollisionOptions(SearchDepth=8)` sets the `SearchDepth` property of the `occupancyMap3DCollisionOptions` object to a depth of `8`.

### Properties

**`CheckBroadPhase` — Check collisions between AABBs of voxels and geometries**
`true` or `1` (default) | `false` or `0`

Check collisions between AABBs of voxels and geometries, specified as a logical 1 (`true`) or `0` (`false`).

If the `CheckNarrowPhase` property is `true`, the narrow phase checks only the voxels that failed the broad phase check.

Example: `occupancyMap3DCollisionOptions(CheckBroadPhase=false)`

Data Types: `logical`

**`CheckNarrowPhase` — Check collisions between voxels and raw input geometries**
`true` or `1` (default) | `false` or `1`

Check collisions between voxels and raw input geometries, specified as a logical 1 (`true`) or `0` (`false`).

If the `CheckBroadPhase` property is `true`, the narrow phase checks only the voxels that were in collision during the broad phase check.

Example: `occupancyMap3DCollisionOptions(CheckNarrowPhase=false)`

Data Types: `logical`

**`Exhaustive` — Exhaustive search mode**
`false` or `0` (default) | `true` or `1`

Exhaustive search mode, specified as a logical `0` (`false`) or `1` (`true`). When Exhaustive is specified as false, the collision-checking function stops collision checking on the first valid collision in either the broad phase or narrow phase . When specified as `true`, the collision-checking function continues collision checking until all voxels are checked.

Example: `occupancyMap3DCollisionOptions(Exhaustive=true)`

Data Types: `logical`

**`ReturnDistance` — Return closest point and distance**
`false` or `0` (default) | `true` or `1`

Return the closest point and distance, specified as a logical `0` (`false`) or `1` (`true`). When specified as `true`, the collision-checking function returns the minimum distance between collision geometries and the nearest voxels in the occupancy grid.

Example: `occupancyMap3DCollisionOptions(ReturnDistance=true)`

Data Types: `logical`

**`ReturnVoxels` — Return location and size of voxels in collision**
`false` or `0` (default) | `true` or `1`

Return the location and size of the voxels in collision, specified as a logical `0` (`false`) or `1` (`true`).

Example: `occupancyMap3DCollisionOptions(ReturnVoxels=true)`

Data Types: `logical`

**`SearchDepth` — Maximum search depth to check**
`16` (default) | integer in range [`0`, `16`]

Maximum search depth to check in the octree, specified as an integer in the range [`0`, `16`].

If a voxel at one search depth encompasses any voxel that is occupied at a greater search depth, then the entire volume of the encompassing voxel is considered occupied. For more information, see “Visualize 3-D Occupancy Maps with Varying Search Depths” on page 2-1068.

Example: `occupancyMap3DCollisionOptions(SearchDepth=8)`

Data Types: `uint8`

## Examples

### Check Collision Between 3-D Map and Collision Geometries

Create a 3-D occupancy map.

```
map = occupancyMap3D;
```

Specify 25 random coordinates in the occupancy map as occupied.

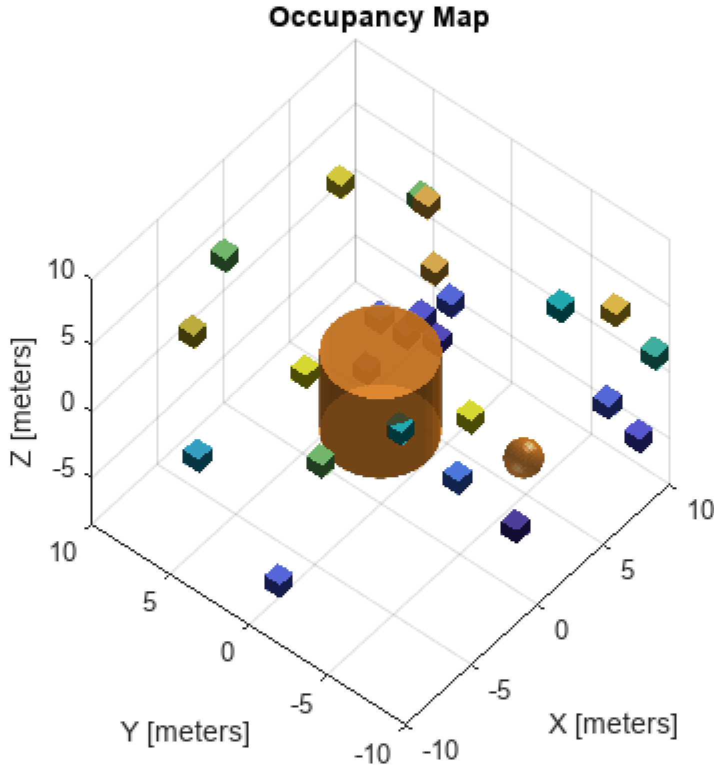
```
rng(0)
pt = (rand(25,3)-.5)*20;
setOccupancy(map,pt,1);
```

Create a collision sphere and a collision cylinder object.

```
sphere = collisionSphere(1);
cylinder = collisionCylinder(3,6);
sphere.Pose = trvec2tform([6.1 -4 -7.5]);
```

Visualize the occupancy map and collision geometry in the same figure.

```
exampleHelperPlotCylinderAndSphere(map,cylinder,sphere)
```




Perform only the broad-phase collision check for both the sphere and cylinder by setting the `CheckNarrowPhase` property of an `occupancyMap3DCollisionOptions` object to `false`. Return voxel information and the distance to the nearest occupied voxels.

```
bpOpts = occupancyMap3DCollisionOptions(CheckNarrowPhase=false,ReturnDistance=true,ReturnVoxels=t
[bpIsCollidingCylinder,bpResultsCylinder] = checkMapCollision(map,cylinder,bpOpts);
```

Check the voxel distances for the collision geometries. Note that, because the cylinder is in collision with voxels, the distance values are `NaN`. Because the sphere is not in collision with any voxels, its distance results are non-`NaN` values.

```
bpDistCylinder = bpResultsCylinder.DistanceInfo.Distance
```

```
bpDistCylinder = NaN
```

```
bpWitnessptsCylinder = bpResultsCylinder.DistanceInfo.WitnessPoints
```

```
bpWitnessptsCylinder = 3×2

   NaN   NaN
   NaN   NaN
   NaN   NaN
```

Because the cylinder is in collision with the voxels, the distance results contain `NaN` values. Since the sphere is not in collision with the voxels, the distance results consist of non-`NaN` values.

```
[bpIsCollidingSphere,bpResultsSphere] = checkMapCollision(map,sphere,bpOpts);
bpDistSphere = bpResultsSphere.DistanceInfo.Distance
```

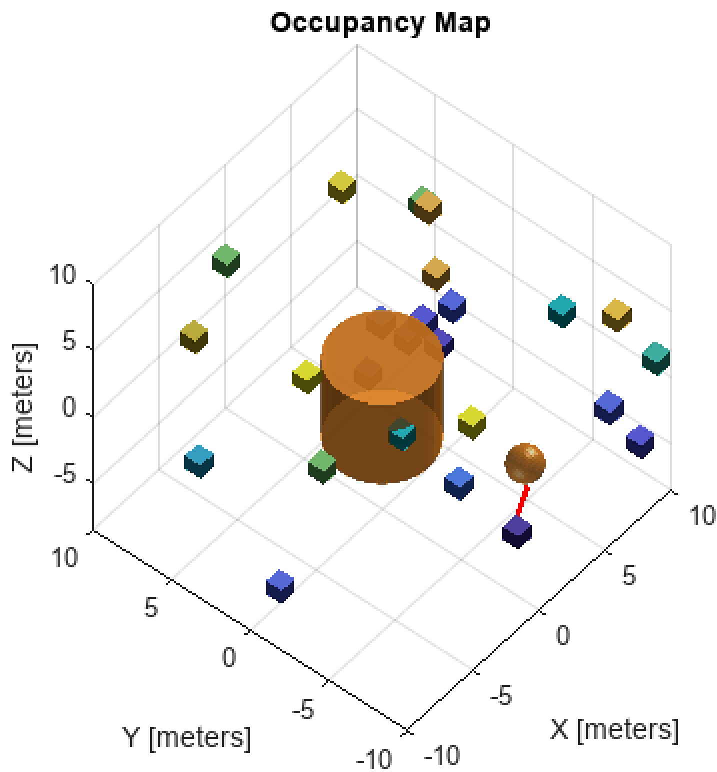
```
bpDistSphere = 2.3259
```

```
bpWitnessptsSphere = bpResultsSphere.DistanceInfo.WitnessPoints
```

```
bpWitnessptsSphere = 3×2

    3.0000    5.1000
   -6.0000   -5.0000
   -7.5000   -7.5000
```

Plot a line between the sphere and the closest voxel to it using its witness points.

```
figure
exampleHelperPlotCylinderAndSphere(map,cylinder,sphere)
hold on
plot3(bpWitnessptsSphere(1,:),bpWitnessptsSphere(2,:),bpWitnessptsSphere(3,:),LineWidth=2,Color=
hold off
```




Now perform a narrow-phase check, by using an `occupancyMap3DCollisionOptions` object with the `CheckNarrowPhase` property set to `true`.

```
npOpts = occupancyMap3DCollisionOptions(CheckNarrowPhase=true,ReturnDistance=true,ReturnVoxels=t
[npIsCollidingSphere,bpResultsSphere] = checkMapCollision(map,sphere,npOpts);
```

Return the voxel distance and witness point coordinates for the sphere. The distance and witness points are slightly more accurate this time, because the narrow phase uses the distance between the primitive and the voxel, whereas the broad phase before uses the distance between the axis-aligned bounding box (AABB) of the collision object and the voxel.

```
npDist = bpResultsSphere.DistanceInfo.Distance
```

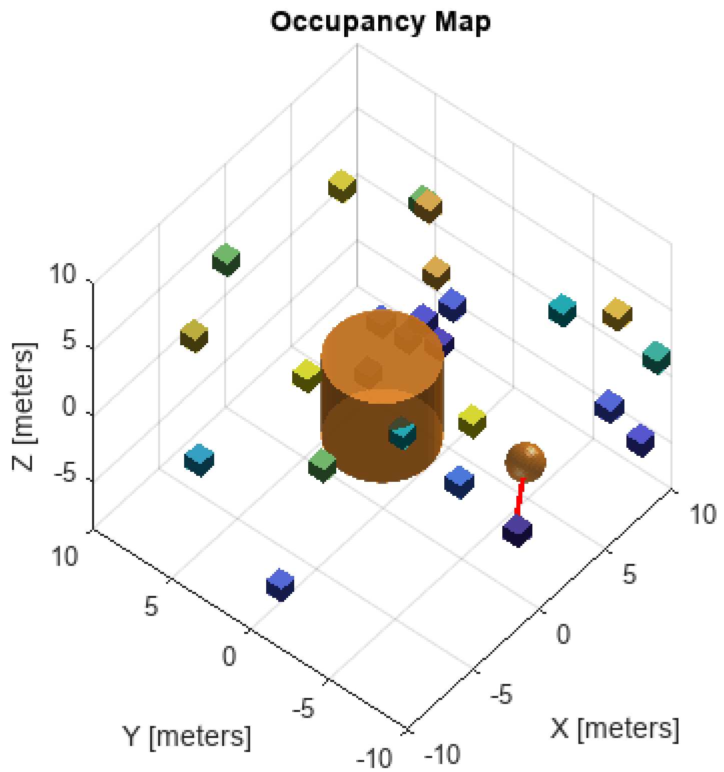
```
npDist = 2.6892
```

```
npWitnesspts = bpResultsSphere.DistanceInfo.WitnessPoints
```

```
npWitnesspts = 3×2

    3.0000    5.2596
   -6.0000   -4.5419
   -7.5000   -7.5000
```

Visualize the occupancy map again and plot line showing the shortest distance between the voxel and sphere. The line between the witness points visually appears accurate after performing the narrow-phase check.

```
exampleHelperPlotCylinderAndSphere(map,cylinder,sphere)
hold on
plot3(npWitnesspts(1,:),npWitnesspts(2,:),npWitnesspts(3,:),LineWidth=2,Color='r')
hold off
```




## Version History

**Introduced in R2022b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`checkMapCollision` | `occupancyMap3D`

# checkOccupancy

Check if locations are free or occupied

## Syntax

```
iOccval = checkOccupancy(map3D,xyz)
```

## Description

`iOccval = checkOccupancy(map3D,xyz)` returns an array of occupancy values specified at the *xyz* locations using the `OccupiedThreshold` and `FreeThreshold` properties of the input `occupancyMap3D` object. Each row is a separate *xyz* location in the map to check the occupancy of. Occupancy values can be obstacle-free (0), occupied (1), or unknown (–1).

## Examples

### Check Occupancy Status and Get Occupancy Values in 3-D Occupancy Map

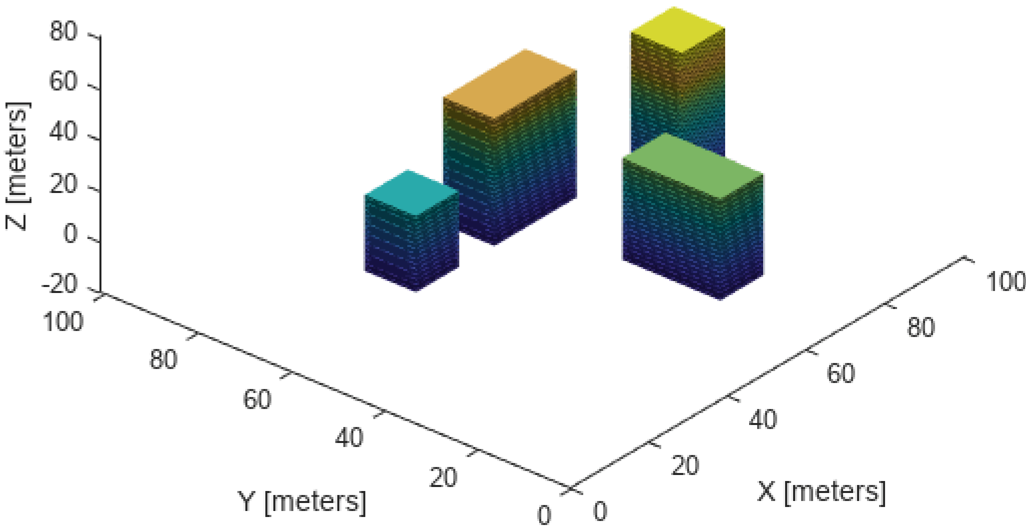
Import a 3-D occupancy map.

```
map3D = importOccupancyMap3D("citymap.ot")
```

```
map3D = 
  occupancyMap3D with properties:

    ProbabilitySaturation: [1.0000e-03 0.9990]
               Resolution: 1
        OccupiedThreshold: 0.6500
            FreeThreshold: 0.2000
```

Display the map.

```
show(map3D)
```




Check the occupancy statuses of different locations and get their occupancy values.

```
iOccVal1 = checkOccupancy(map3D,[50 15 0])
```

```
iOccVal1 = 0
```

```
OccVal1 = getOccupancy(map3D,[50 15 0])
```

```
OccVal1 = 0.0019
```

```
iOccVal2 = checkOccupancy(map3D,[50 15 15])
```

```
iOccVal2 = 1
```

```
OccVal2 = getOccupancy(map3D,[50 15 15])
```

```
OccVal2 = 0.6500
```

```
iOccVal3 = checkOccupancy(map3D,[50 15 45])
```

```
iOccVal3 = -1
```

```
OccVal3 = getOccupancy(map3D,[50 15 45])
```

```
OccVal3 = 0.5000
```

## Input Arguments

**`map3D` — 3-D occupancy map**
`occupancyMap3D` object

3-D occupancy map, specified as an `occupancyMap3D` object.

**`xyz` — World coordinates**
*n*-by-3 matrix

World coordinates, specified as an *n*-by-3 matrix of `[x y z]` points, where *n* is the number of world coordinates.

## Output Arguments

**`iOccval` — Interpreted occupancy values**
column vector

Interpreted occupancy values, returned as a column vector with the same length as `xyz`.

Occupancy values can be obstacle-free (0), occupied (1), or unknown (–1). These values are determined from the actual probability values and the `OccupiedThreshold` and `FreeThreshold` properties of the `map3D` object.

# Version History

**Introduced in R2019b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Classes**
`occupancyMap3D` | `lidarSLAM` | `occupancyMap`

**Functions**
`insertPointCloud` | `inflate` | `setOccupancy` | `show`

# getOccupancy

Get occupancy probability of locations

## Syntax

```
occval = getOccupancy(map3D,xyz)
```

## Description

`occval = getOccupancy(map3D,xyz)` returns an array of probability occupancy values at the specified *xyz* locations in the `occupancyMap3D` object. Values close to 1 represent a high certainty that the cell contains an obstacle. Values close to 0 represent certainty that the cell is not occupied and obstacle-free.

## Examples

### Check Occupancy Status and Get Occupancy Values in 3-D Occupancy Map

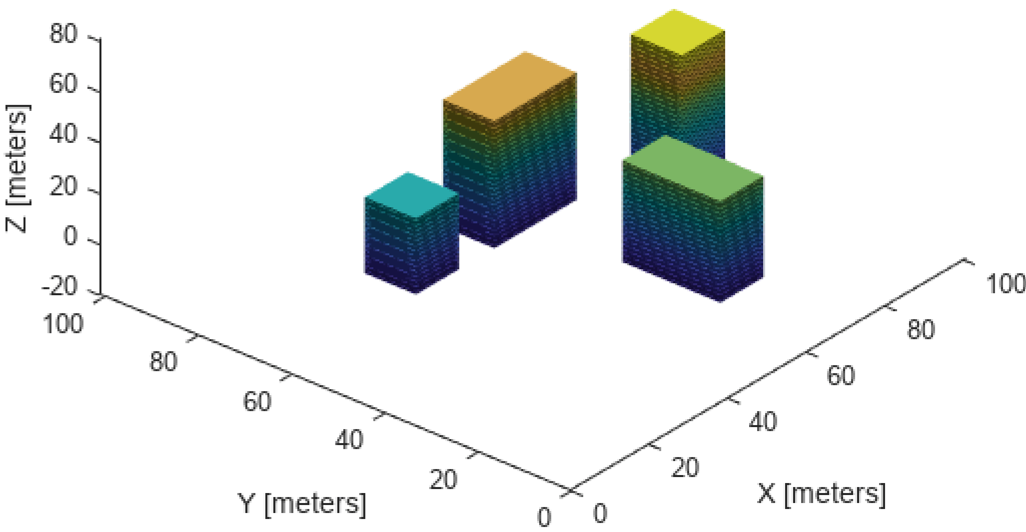
Import a 3-D occupancy map.

```
map3D = importOccupancyMap3D("citymap.ot")
```

```
map3D = 
  occupancyMap3D with properties:

    ProbabilitySaturation: [1.0000e-03 0.9990]
               Resolution: 1
        OccupiedThreshold: 0.6500
            FreeThreshold: 0.2000
```

Display the map.

```
show(map3D)
```




Check the occupancy statuses of different locations and get their occupancy values.

```
iOccVal1 = checkOccupancy(map3D,[50 15 0])
```

```
iOccVal1 = 0
```

```
OccVal1 = getOccupancy(map3D,[50 15 0])
```

```
OccVal1 = 0.0019
```

```
iOccVal2 = checkOccupancy(map3D,[50 15 15])
```

```
iOccVal2 = 1
```

```
OccVal2 = getOccupancy(map3D,[50 15 15])
```

```
OccVal2 = 0.6500
```

```
iOccVal3 = checkOccupancy(map3D,[50 15 45])
```

```
iOccVal3 = -1
```

```
OccVal3 = getOccupancy(map3D,[50 15 45])
```

```
OccVal3 = 0.5000
```

## Input Arguments

**`map3D` — 3-D occupancy map**
`occupancyMap3D` object

3-D occupancy map, specified as an `occupancyMap3D` object.

**`xyz` — World coordinates**
*n*-by-3 matrix

World coordinates, specified as an *n*-by-3 matrix of `[x y z]` points, where *n* is the number of world coordinates.

## Output Arguments

**`occval` — Probability occupancy values**
column vector

Probability occupancy values, returned as a column vector with the same length as `xyz`.

Values close to 0 represent certainty that the cell is not occupied and obstacle-free.

# Version History

**Introduced in R2019b**

## See Also

**Classes**
`occupancyMap3D` | `lidarSLAM` | `occupancyMap`

**Functions**
`insertPointCloud` | `inflate` | `setOccupancy` | `show`

# inflate

Inflate each occupied location

## Syntax

```
inflate(map3D,radius)
```

## Description

`inflate(map3D,radius)` inflates each occupied position of the specified in the input `occupancyMap3D` object by the `radius` specified in meters. `radius` is rounded up to the nearest equivalent cell based on the resolution of the map. This inflation increases the size of the occupied locations in the map.

## Examples

### Get Ray Intersection Points on 3-D Occupancy Map

Import a 3-D occupancy map.

```
map3D = importOccupancyMap3D("citymap.ot")
```

```
map3D = 
  occupancyMap3D with properties:

    ProbabilitySaturation: [1.0000e-03 0.9990]
               Resolution: 1
        OccupiedThreshold: 0.6500
            FreeThreshold: 0.2000
```

Inflate the occupied areas by a radius of 1 m. Display the map.

```
inflate(map3D,1)
show(map3D)
```

Find the intersection points of rays and occupied map cells.

```
numRays = 10;
angles = linspace(-pi/2,pi/2,numRays);
directions = [cos(angles); sin(angles); zeros(1,numRays)]';
sensorPose = [55 40 1 1 0 0 0];
maxrange = 15;
[intersectionPts,isOccupied] = rayIntersection(map3D,sensorPose,directions,maxrange)
```

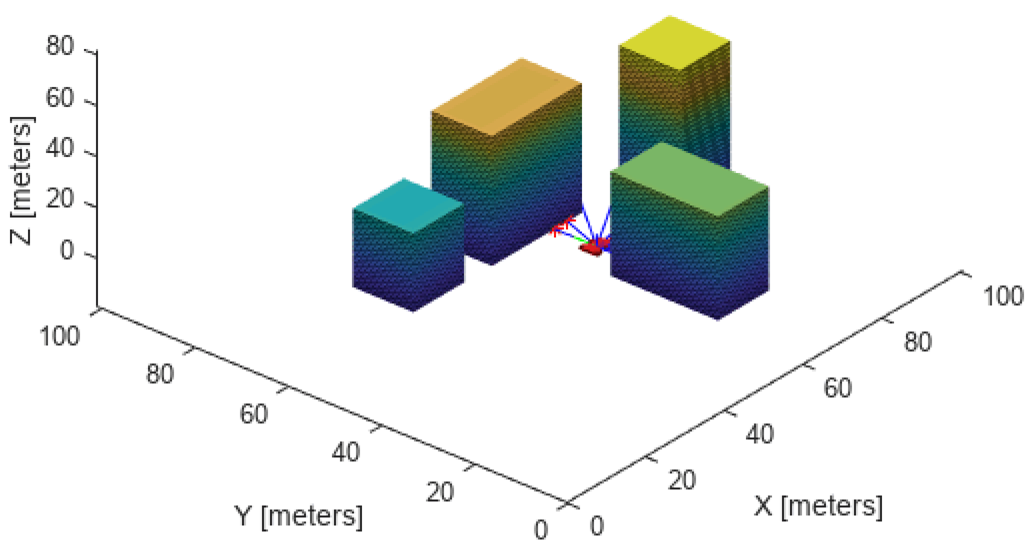
```
intersectionPts = 10×3

   55.0000   32.0000    1.0000
   57.9118   32.0000    1.0000
   61.7128   32.0000    1.0000
   67.9904   32.5000    1.0000
```

```
   69.0000   37.5314    1.0000
   69.0000   42.4686    1.0000
   67.9904   47.5000    1.0000
   64.6418   51.4907    1.0000
   58.2757   49.0000    1.0000
   55.0000   49.0000    1.0000
```

```
isOccupied = 10×1

     1
     1
     1
    -1
     1
     1
    -1
    -1
     1
     1
```

Plot the intersection points and plot rays from the pose to the intersection points.

```
hold on
plotTransforms(sensorPose(1:3),sensorPose(4:end),...
               'FrameSize',5,'MeshFilePath','groundvehicle.stl') % Vehicle sensor pose
for i = 1:numRays
    plot3([sensorPose(1),intersectionPts(i,1)],...
          [sensorPose(2),intersectionPts(i,2)],...
          [sensorPose(3),intersectionPts(i,3)],'-b') % Plot rays
    if isOccupied(i) == 1
        plot3(intersectionPts(i,1),intersectionPts(i,2),intersectionPts(i,3),'*r') % Intersectio
    end
end
```




## Input Arguments

**`map3D` — 3-D occupancy map**
`occupancyMap3D` object

3-D occupancy map, specified as an `occupancyMap3D` object.

**`radius` — Amount to inflate occupied locations**
scalar

Amount to inflate occupied locations, specified as a scalar. `radius` is rounded up to the nearest cell value.

# Version History

**Introduced in R2019b**

## See Also

**Classes**
`occupancyMap3D` | `lidarSLAM` | `occupancyMap`

**Functions**
insertPointCloud | setOccupancy | show

# insertPointCloud

Insert 3-D points or point cloud observation into map

## Syntax

```
insertPointCloud(map3D,pose,points,maxrange)
insertPointCloud(map3D,pose,ptcloud,maxrange)
```

## Description

`insertPointCloud(map3D,pose,points,maxrange)` inserts one or more sensor observations at the given `points` in the occupancy map, `map3D`. Occupied points are updated with an observation of 0.7. All other points between the sensor `pose` and `points` are treated as obstacle-free and updated with an observation of 0.4. Points outside `maxrange` are not updated. `NaN` values are ignored.

`insertPointCloud(map3D,pose,ptcloud,maxrange)` inserts a `ptcloud` object into the map.

## Examples

### Create 3-D Occupancy Map and Inflate Points

The `occupancyMap3D` object stores obstacles in 3-D space, using sensor observations to map an environment. Create a map and add points from a point cloud to identify obstacles. Then inflate the obstacles in the map to ensure safe operating space around obstacles.

Create an `occupancyMap3D` object with a map resolution of 10 cells/meter.

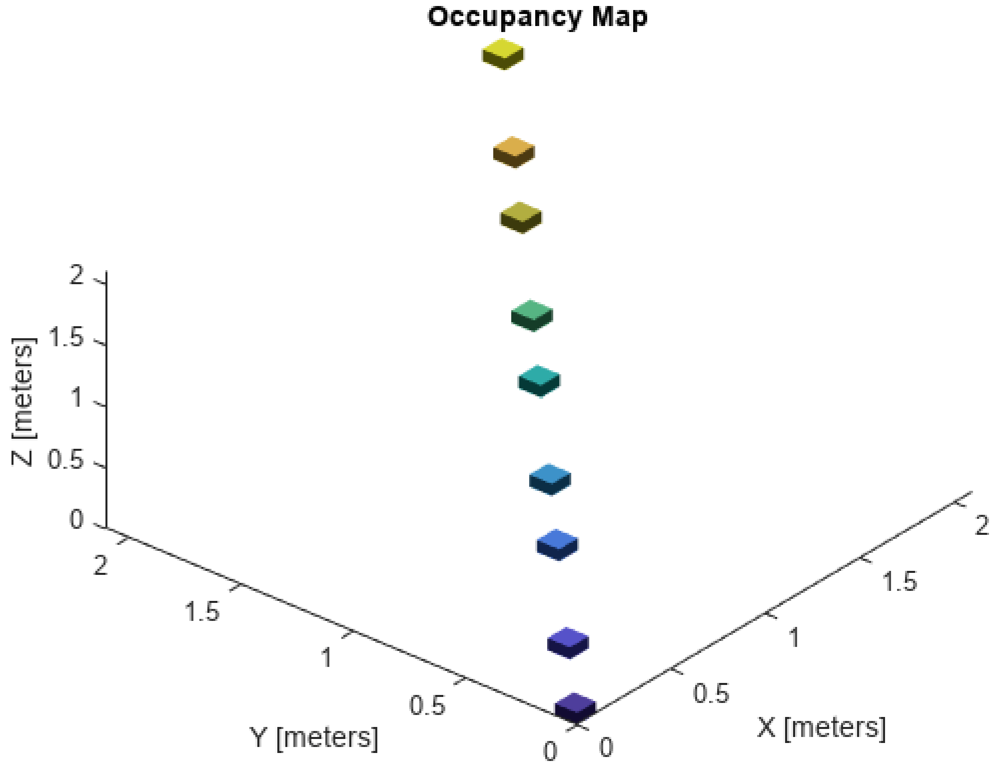
```
map3D = occupancyMap3D(10);
```

Define a set of 3-D points as an observation from a pose `[x y z qw qx qy qz]`. This pose is for the sensor that observes these points and is centered on the origin. Define two sets of points to insert multiple observations.

```
pose = [ 0 0 0 1 0 0 0];

points = repmat((0:0.25:2)', 1, 3);
points2 = [(0:0.25:2)' (2:-0.25:0)' (0:0.25:2)'];
maxRange = 5;
```

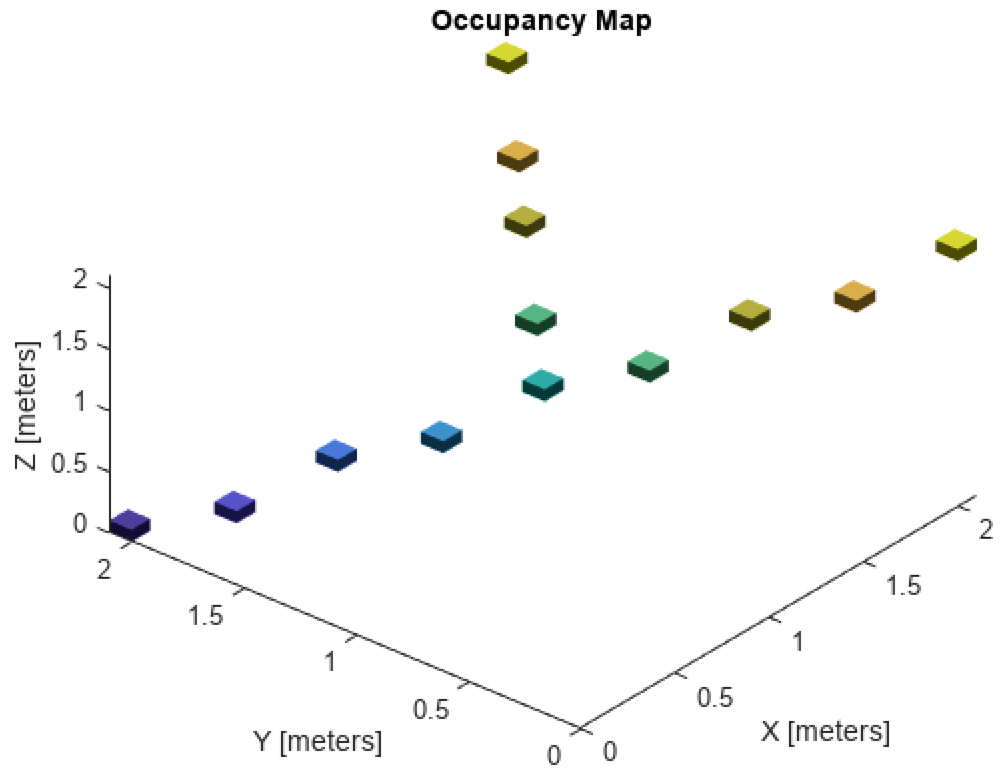
Insert the first set of points using `insertPointCloud`. The function uses the sensor pose and the given points to insert observations into the map. The colors displayed correlate to the height of the point only for illustrative purposes.

```
insertPointCloud(map3D,pose,points,maxRange)
show(map3D)
```



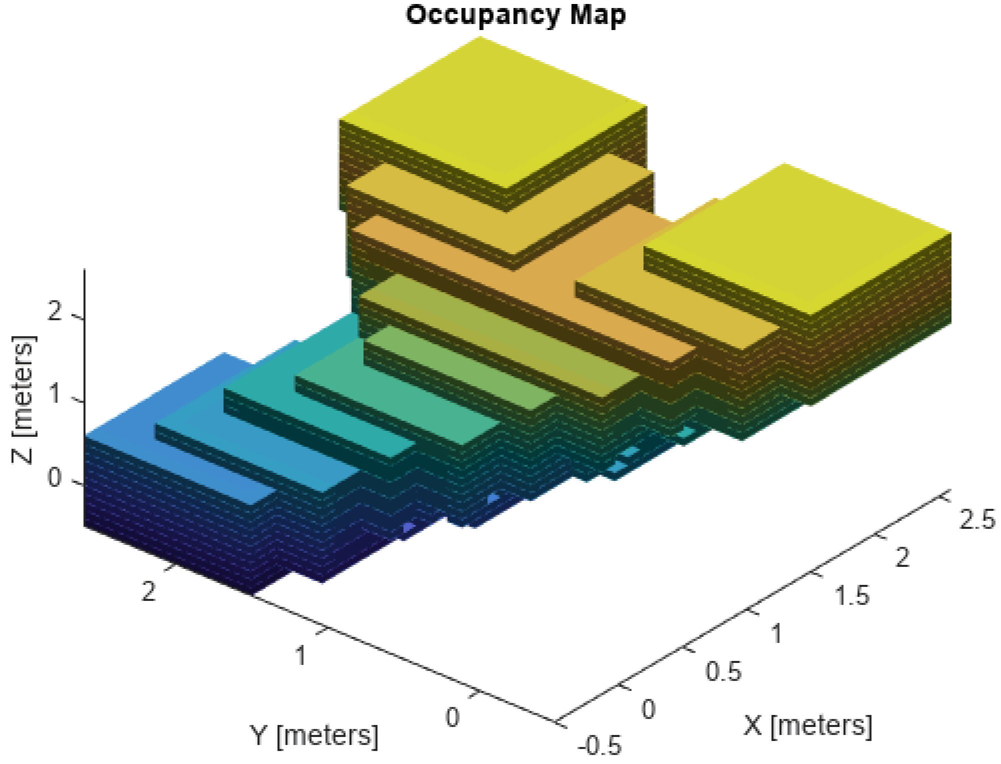

Insert the second set of points. The ray between the sensor pose (origin) and these points overlap points from the previous insertion. Therefore, the free space between the sensor and the new points are updated and marked as free space.

```
insertPointCloud(map3D,pose,points2,maxRange)
show(map3D)
```




Inflate the map to add a buffer zone for safe operation around obstacles. Define the vehicle radius and safety distance and use the sum of these values to define the inflation radius for the map.

```
vehicleRadius = 0.2;
safetyRadius = 0.3;
inflationRadius = vehicleRadius + safetyRadius;
inflate(map3D, inflationRadius);

show(map3D)
```




## Input Arguments

**map3D — 3-D occupancy map**
occupancyMap3D object

3-D occupancy map, specified as a `occupancyMap3D` object.

**points — Points of point cloud**
*n*-by-3 matrix

Points of point cloud in sensor coordinates, specified as an *n*-by-3 matrix of `[x y z]` points, where *n* is the number of points in the point cloud.

**ptcloud — Point cloud reading**
pointCloud object

Point cloud reading, specified as a `pointCloud` object.

**Note** Using `pointCloud` objects requires Computer Vision Toolbox.

**pose — Position and orientation of vehicle**
`[x y z qw qx qy qz]` vector

Position and orientation of vehicle, specified as an `[x y z qw qx qy qz]` vector. The vehicle pose is an *xyz*-position vector with a quaternion orientation vector specified as `[qw qx qy qz]`.

**`maxrange` — Maximum range of sensor**
scalar

Maximum range of point cloud sensor, specified as a scalar. Points outside this range are ignored.

# Version History
**Introduced in R2019b**

## See Also

**Classes**
`occupancyMap3D` | `lidarSLAM` | `occupancyMap`

**Functions**
`inflate` | `setOccupancy` | `show`

# rayIntersection

Find intersection points of rays and occupied map cells

## Syntax

```
[intersectionPts,isOccupied] = rayIntersection(map3D,sensorPose,directions,
maxrange)
[intersectionPts,isOccupied] = rayIntersection(map3D,sensorPose,directions,
maxrange,ignoreUnknown)
```

## Description

`[intersectionPts,isOccupied] = rayIntersection(map3D,sensorPose,directions, maxrange)` returns intersection points of rays in the specified map, `map3D`. Rays emanate from the specified `sensorPose` at the given orientations, `directions`. Intersection points are returned in the world coordinate frame. Use `isOccupied` to determine if the intersection point is at the sensor max range or if it intersects an obstacle.

`[intersectionPts,isOccupied] = rayIntersection(map3D,sensorPose,directions, maxrange,ignoreUnknown)` additionally accepts optional arguments for the sensors max range and whether to ignore unknown values. By default, the rays extend to the map boundary and unknown values are ignored.

## Examples

### Get Ray Intersection Points on 3-D Occupancy Map

Import a 3-D occupancy map.

```
map3D = importOccupancyMap3D("citymap.ot")
```

```
map3D = 
  occupancyMap3D with properties:

    ProbabilitySaturation: [1.0000e-03 0.9990]
               Resolution: 1
        OccupiedThreshold: 0.6500
            FreeThreshold: 0.2000
```

Inflate the occupied areas by a radius of 1 m. Display the map.

```
inflate(map3D,1)
show(map3D)
```

Find the intersection points of rays and occupied map cells.

```
numRays = 10;
angles = linspace(-pi/2,pi/2,numRays);
directions = [cos(angles); sin(angles); zeros(1,numRays)]';
```

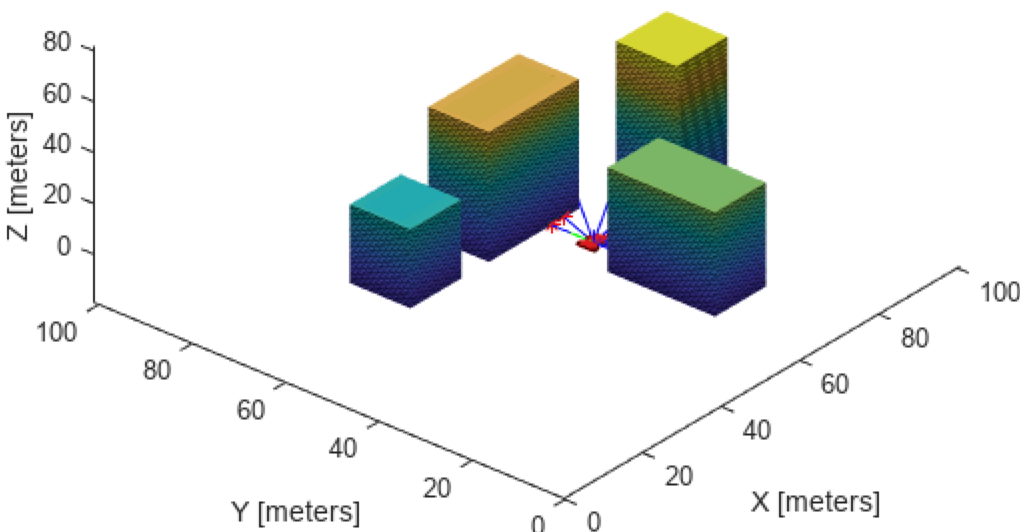
```
sensorPose = [55 40 1 1 0 0 0];
maxrange = 15;
[intersectionPts,isOccupied] = rayIntersection(map3D,sensorPose,directions,maxrange)
```

```
intersectionPts = 10×3

   55.0000   32.0000    1.0000
   57.9118   32.0000    1.0000
   61.7128   32.0000    1.0000
   67.9904   32.5000    1.0000
   69.0000   37.5314    1.0000
   69.0000   42.4686    1.0000
   67.9904   47.5000    1.0000
   64.6418   51.4907    1.0000
   58.2757   49.0000    1.0000
   55.0000   49.0000    1.0000
```

```
isOccupied = 10×1

     1
     1
     1
    -1
     1
     1
    -1
    -1
     1
     1
```

Plot the intersection points and plot rays from the pose to the intersection points.

```
hold on
plotTransforms(sensorPose(1:3),sensorPose(4:end),...
               'FrameSize',5,'MeshFilePath','groundvehicle.stl') % Vehicle sensor pose
for i = 1:numRays
    plot3([sensorPose(1),intersectionPts(i,1)],...
          [sensorPose(2),intersectionPts(i,2)],...
          [sensorPose(3),intersectionPts(i,3)],'-b') % Plot rays
    if isOccupied(i) == 1
        plot3(intersectionPts(i,1),intersectionPts(i,2),intersectionPts(i,3),'*r') % Intersectio
    end
end
```




## Input Arguments

**`map3D` — 3-D occupancy map**
`occupancyMap3D` object

3-D occupancy map, specified as a `occupancyMap3D` object.

**`sensorPose` — Position and orientation of sensor**
`[x y z qw qx qy qz]` vector

Position and orientation of sensor, specified as an `[x y z qw qx qy qz]` vector. The vehicle pose is an *xyz*-position vector with a quaternion orientation vector specified as `[qw qx qy qz]`.

**`directions` — Orientation of rays emanating from sensor**
*n*-by-3 `[dx dy dz]` matrix | *n*-by-2 `[az el]` matrix

Orientation of rays emanating from the sensor relative to the sensor coordinate frame, specified as an *n*-by-3 `[dx dy dz]` matrix or *n*-by-2 `[az el]` matrix.

- `[dx dy dz]` is a directional vector in *xyz*-coordinates.
- `[az el]` is a vector with azimuth angle, `az`, measured from the positive *x* direction to the positive *y* direction, and elevation angle from the *xy*-plane to the positive *z*-direction in sensor coordinate frame.

**maxrange — Maximum range of sensor**
scalar

Maximum range of laser range sensor, specified as a scalar in meters. Range values greater than or equal to maxrange are considered free along the whole length of the ray, up to maxrange.

**ignoreUnknown — Interpret unknown values as free or occupied**
1 (default) | 0

Interpret unknown values in the map as free or occupied specified as 1 or 0. Set this value to 0 to assume unknown values are occupied.

## Output Arguments

**intersectionPts — Intersection points**
*n*-by-3 matrix

Intersection points, returned as *n*-by-3 matrix of [*x* *y* *z*] points in the world frame, where *n* is the length of directions.

**isOccupied — Occupancy status of ray end points**
vector of zeroes and ones

Occupancy status of ray end points, returned as a vector of zeroes and ones. Use isOccupied to determine if the intersection point is at the sensor max range or if it intersects an obstacle.

# Version History

**Introduced in R2020a**

## See Also

**Classes**
occupancyMap3D | lidarSLAM | occupancyMap

**Functions**
insertPointCloud | inflate | setOccupancy | show

# setOccupancy

Set occupancy probability of locations

## Syntax

```
setOccupancy(map3D,xyz,occval)
```

## Description

`setOccupancy(map3D,xyz,occval)` assigns the occupancy values to each specified `xyz` coordinate in the 3-D occupancy map.

## Examples

### Create and Export 3-D Occupancy Map

Create an `occupancyMap3D` object.

```
map3D = occupancyMap3D;
```

Create a ground plane and set occupancy values to 0.

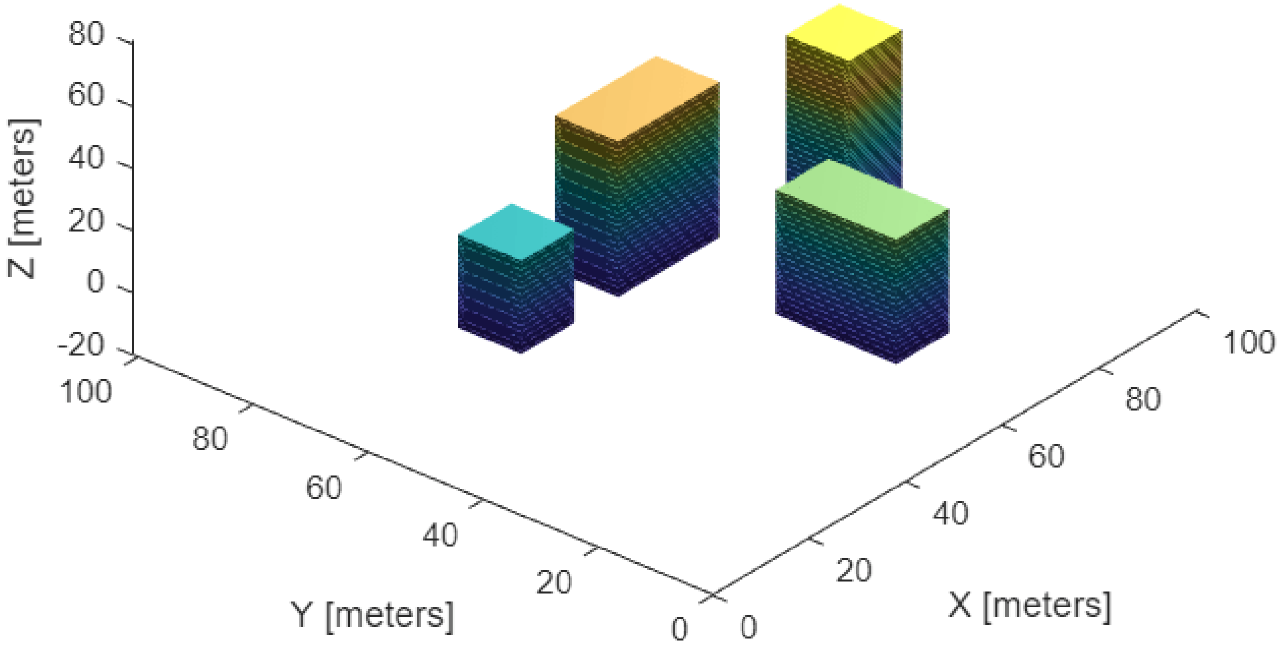
```
[xGround,yGround,zGround] = meshgrid(0:100,0:100,0);
xyzGround = [xGround(:) yGround(:) zGround(:)];
occval = 0;
setOccupancy(map3D,xyzGround,occval)
```

Create obstacles in specific world locations of the map.

```
[xBuilding1,yBuilding1,zBuilding1] = meshgrid(20:30,50:60,0:30);
[xBuilding2,yBuilding2,zBuilding2] = meshgrid(50:60,10:30,0:40);
[xBuilding3,yBuilding3,zBuilding3] = meshgrid(40:60,50:60,0:50);
[xBuilding4,yBuilding4,zBuilding4] = meshgrid(70:80,35:45,0:60);

xyzBuildings = [xBuilding1(:) yBuilding1(:) zBuilding1(:);...
                xBuilding2(:) yBuilding2(:) zBuilding2(:);...
                xBuilding3(:) yBuilding3(:) zBuilding3(:);...
                xBuilding4(:) yBuilding4(:) zBuilding4(:)];
```

Update the obstacles with new probability values and display the map.

```
obs = 0.65;
updateOccupancy(map3D,xyzBuildings,obs)
show(map3D)
```




Check if the map file named `citymap.ot` already exist in the current directory and delete it before creating the map file.

```
if exist("citymap.ot",'file')
    delete("citymap.ot")
end
```

Export the map as an octree file.

```
filePath = fullfile(pwd,"citymap.ot");
exportOccupancyMap3D(map3D,filePath)
```

## Input Arguments

**map3D — 3-D occupancy map**
`occupancyMap3D` object

3-D occupancy map, specified as an `occupancyMap3D` object.

**`xyz` — World coordinates**
*n*-by-3 matrix

World coordinates, specified as an *n*-by-3 matrix of `[x y z]` points, where *n* is the number of world coordinates.

**`occval` — Probability occupancy values**
scalar | column vector

Probability occupancy values, specified as a scalar or a column vector with the same length as `xyz`. A scalar input is applied to all coordinates in `xyz`.

Values close to 0 represent certainty that the cell is not occupied and obstacle-free.

# Version History

**Introduced in R2019b**

## See Also

**Classes**
`occupancyMap3D` | `lidarSLAM` | `occupancyMap`

**Functions**
`insertPointCloud` | `inflate` | `show`

# show

Display 3-D occupancy map

## Syntax

```
axes = show(map3D)
show(map3D,Name=Value)
```

## Description

`axes = show(map3D)` displays the occupancy map, `map3D`, in the current axes, with the axes labels representing the world coordinates.

The function displays the 3-D environment using 3-D voxels for areas with occupancy values greater than the `OccupiedThreshold` property value specified in `map3D`. The color of the 3-D plot is strictly height-based.

`show(map3D,Name=Value)` specifies options using one or more name-value arguments.

## Examples

### Get Ray Intersection Points on 3-D Occupancy Map

Import a 3-D occupancy map.

```
map3D = importOccupancyMap3D("citymap.ot")
```

```
map3D = 
  occupancyMap3D with properties:

    ProbabilitySaturation: [1.0000e-03 0.9990]
               Resolution: 1
        OccupiedThreshold: 0.6500
            FreeThreshold: 0.2000
```

Inflate the occupied areas by a radius of 1 m. Display the map.

```
inflate(map3D,1)
show(map3D)
```

Find the intersection points of rays and occupied map cells.

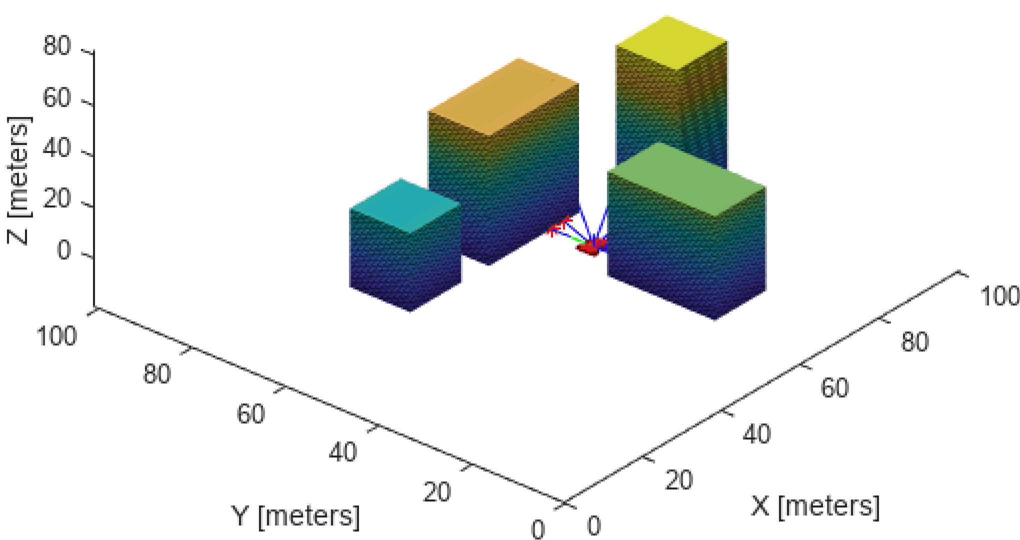
```
numRays = 10;
angles = linspace(-pi/2,pi/2,numRays);
directions = [cos(angles); sin(angles); zeros(1,numRays)]';
sensorPose = [55 40 1 1 0 0 0];
maxrange = 15;
[intersectionPts,isOccupied] = rayIntersection(map3D,sensorPose,directions,maxrange)
```

```
intersectionPts = 10×3
```

```
   55.0000   32.0000    1.0000
   57.9118   32.0000    1.0000
   61.7128   32.0000    1.0000
   67.9904   32.5000    1.0000
   69.0000   37.5314    1.0000
   69.0000   42.4686    1.0000
   67.9904   47.5000    1.0000
   64.6418   51.4907    1.0000
   58.2757   49.0000    1.0000
   55.0000   49.0000    1.0000

isOccupied = 10×1

     1
     1
     1
    -1
     1
     1
    -1
    -1
     1
     1
```

Plot the intersection points and plot rays from the pose to the intersection points.

```
hold on
plotTransforms(sensorPose(1:3),sensorPose(4:end),...
               'FrameSize',5,'MeshFilePath','groundvehicle.stl') % Vehicle sensor pose
for i = 1:numRays
    plot3([sensorPose(1),intersectionPts(i,1)],...
          [sensorPose(2),intersectionPts(i,2)],...
          [sensorPose(3),intersectionPts(i,3)],'-b') % Plot rays
    if isOccupied(i) == 1
        plot3(intersectionPts(i,1),intersectionPts(i,2),intersectionPts(i,3),'*r') % Intersectio
    end
end
```



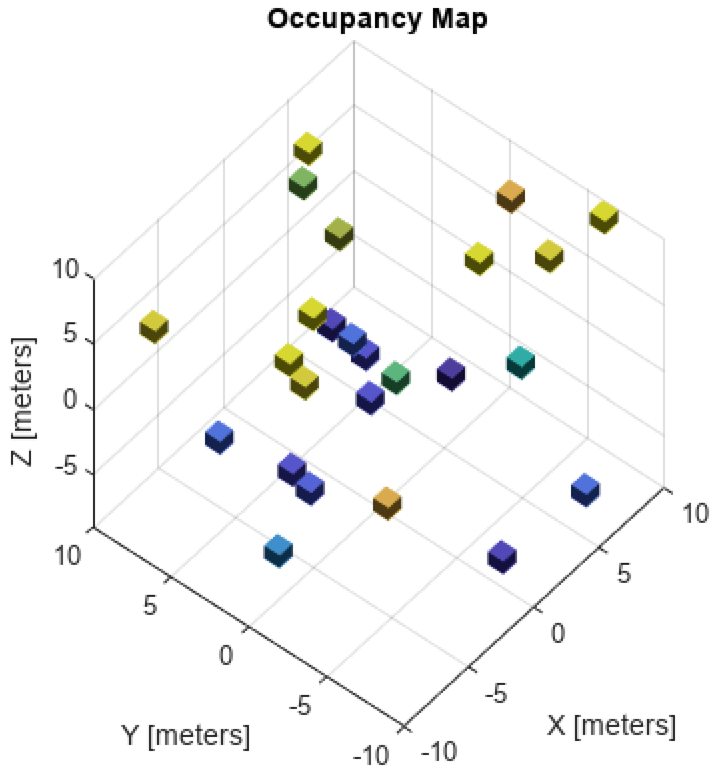

#### Visualize 3-D Occupancy Maps with Varying Search Depths

Create a 3-D occupancy map and set 25 random coordinates in the occupancy map as occupied.

```
map = occupancyMap3D;
rng(0);
for i = 1:25
    pt = (rand(1,3)-.5)*20;
    map.setOccupancy(pt,1);
end
```

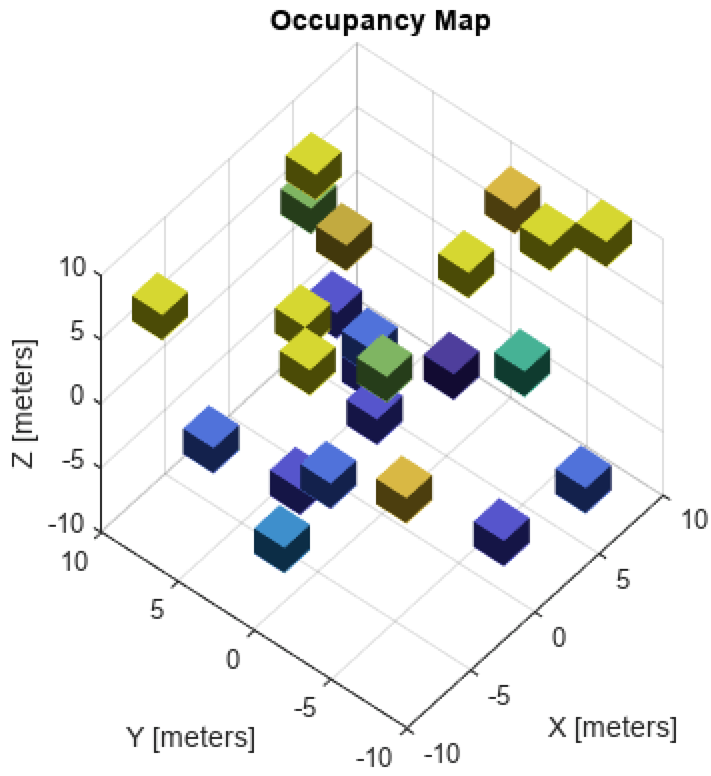
Visualize the voxels with the default search depth value, 16.

```
show(map)
axis equal
grid on
```

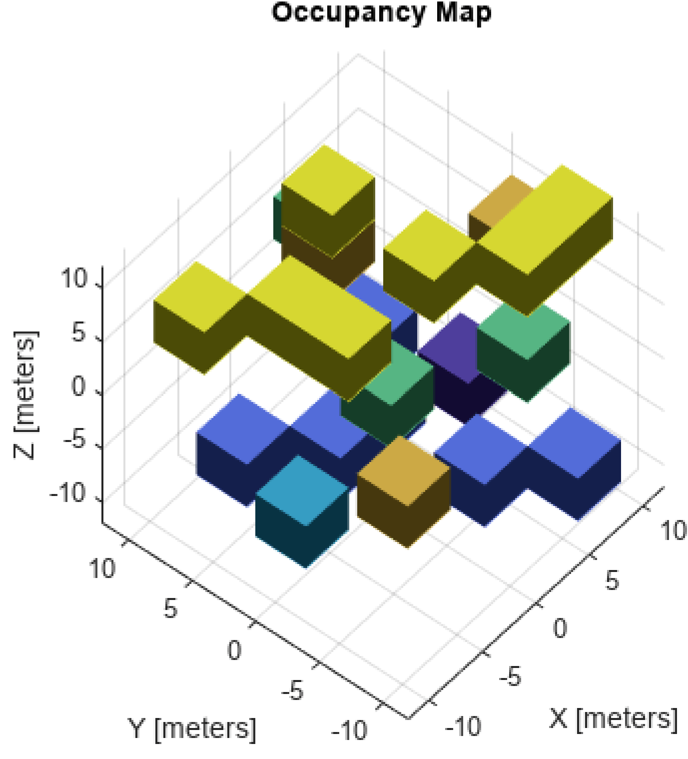



Decrease the search depth in increments of 1 and notice that the resolution drops as you decrease the search depth.

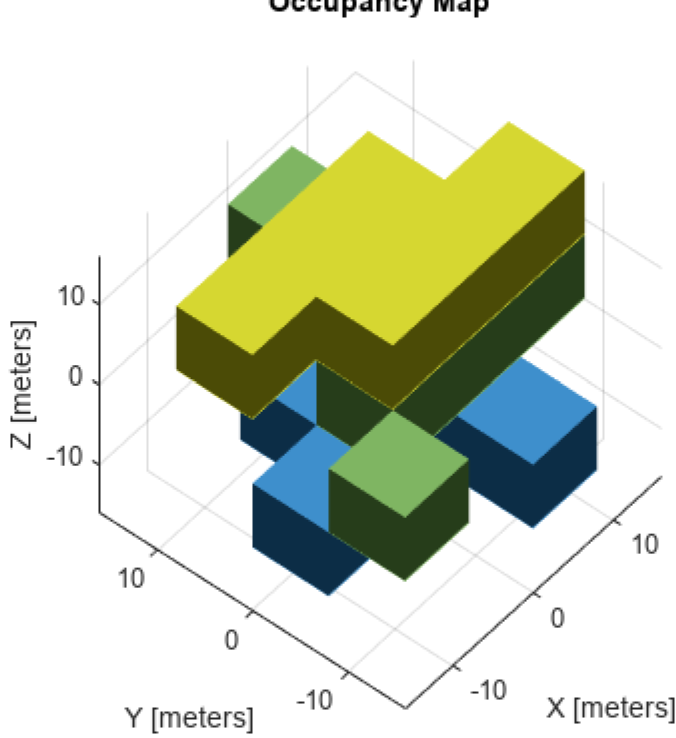
```
show(map,SearchDepth=15)
axis equal
grid on
```




```
show(map,SearchDepth=14)
axis equal
grid on
```




```
show(map,SearchDepth=13)
axis equal
grid on
```




## Input Arguments

**map3D — 3-D occupancy map**
occupancyMap3D object

3-D occupancy map, specified as an occupancyMap3D object.

### Name-Value Pair Arguments

Specify optional pairs of arguments as Name1=Value1,...,NameN=ValueN, where Name is the argument name and Value is the corresponding value. Name-value arguments must appear after other arguments, but the order of the pairs does not matter.

*Before R2021a, use commas to separate each name and value, and enclose* Name *in quotes.*

Example: show(map,SearchDepth=14)

**Parent — Axes used to plot the map**
Axes object | UIAxes object

Axes used to plot the map, specified as either an Axes or UIAxes object. See axes or uiaxes.

**SearchDepth — Voxel search depth**
16 (default) | integer in the range [0,16]

Voxel search depth, specified as an integer in the range [0,16], which determines the level-of-detail at which the map is displayed. The maximum depth is 16, corresponding to voxels whose edge length is equal to 1/map.Resolution. Each level above the maximum depth doubles this minimum voxel size.

## Output Arguments

**axes — Axes handle for map**
Axes object | UIAxes object

Axes handle for map, returned as either an Axes or UIAxesobject. See axes or uiaxes.

# Version History

**Introduced in R2019b**

## See Also

**Classes**
occupancyMap3D | lidarSLAM | occupancyMap

**Functions**
insertPointCloud | setOccupancy

# updateOccupancy

Update occupancy probability at locations

## Syntax

```
updateOccupancy(map3D,xyz,obs)
```

## Description

`updateOccupancy(map3D,xyz,obs)` probabilistically integrates the observation values, `obs`, to each specified `xyz` coordinate in the `occupancyMap3D` object, `map3D`.

## Examples

### Create and Export 3-D Occupancy Map

Create an `occupancyMap3D` object.

```
map3D = occupancyMap3D;
```

Create a ground plane and set occupancy values to 0.

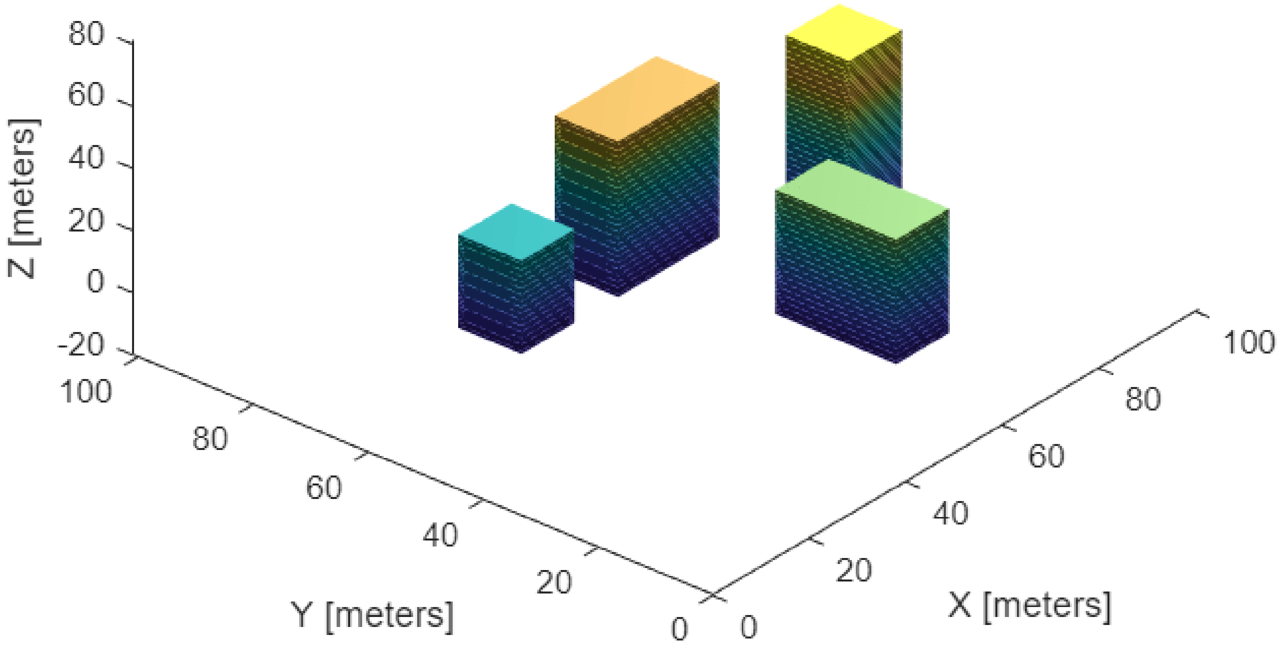
```
[xGround,yGround,zGround] = meshgrid(0:100,0:100,0);
xyzGround = [xGround(:) yGround(:) zGround(:)];
occval = 0;
setOccupancy(map3D,xyzGround,occval)
```

Create obstacles in specific world locations of the map.

```
[xBuilding1,yBuilding1,zBuilding1] = meshgrid(20:30,50:60,0:30);
[xBuilding2,yBuilding2,zBuilding2] = meshgrid(50:60,10:30,0:40);
[xBuilding3,yBuilding3,zBuilding3] = meshgrid(40:60,50:60,0:50);
[xBuilding4,yBuilding4,zBuilding4] = meshgrid(70:80,35:45,0:60);

xyzBuildings = [xBuilding1(:) yBuilding1(:) zBuilding1(:);...
                xBuilding2(:) yBuilding2(:) zBuilding2(:);...
                xBuilding3(:) yBuilding3(:) zBuilding3(:);...
                xBuilding4(:) yBuilding4(:) zBuilding4(:)];
```

Update the obstacles with new probability values and display the map.

```
obs = 0.65;
updateOccupancy(map3D,xyzBuildings,obs)
show(map3D)
```




Check if the map file named `citymap.ot` already exist in the current directory and delete it before creating the map file.

```
if exist("citymap.ot",'file')
    delete("citymap.ot")
end
```

Export the map as an octree file.

```
filePath = fullfile(pwd,"citymap.ot");
exportOccupancyMap3D(map3D,filePath)
```

## Input Arguments

**map3D — 3-D occupancy map**
`occupancyMap3D` object

3-D occupancy map, specified as an `occupancyMap3D` object.

**xyz — World coordinates**
*n*-by-3 matrix

World coordinates, specified as an *n*-by-3 matrix of `[x y z]` points, where *n* is the number of world coordinates.

**obs — Probability observation values**
numeric scalar | logical scalar | *n*-by-1 column vector

Probability observation values, specified as a numeric or logical scalar, or as an *n*-by-1 column vector with the same size as `xyz`.

`obs` values can be from 0 to 1, but if `obs` is a logical array, the function uses the default observation values of 0.7 (`true`) and 0.4 (`false`). If `obs` is a numeric or logical scalar, the value is applied to all coordinates in `xyz`.

# Version History

**Introduced in R2019b**

## See Also

**Classes**
`occupancyMap3D` | `lidarSLAM` | `occupancyMap`

**Functions**
`insertPointCloud` | `inflate` | `setOccupancy` | `show`

# odometryMotionModel

Create an odometry motion model

## Description

`odometryMotionModel` creates an odometry motion model object for differential drive vehicles. This object contains specific motion model parameters. You can use this object to specify the motion model parameters in the `monteCarloLocalization` object.

This motion model assumes that the vehicle makes pure rotation and translation motions to travel from one location to the other. The model propagates points for either forward or backwards motion based on these motion patterns. The elements of the `Noise` property refer to the variance in the motion. To see the effect of changing the noise parameters, use `showNoiseDistribution`.

## Creation

### Syntax

`omm = odometryMotionModel`

#### Description

`omm = odometryMotionModel` creates an odometry motion model object for differential drive vehicles.

### Properties

**`Noise` — Gaussian noise for vehicle motion**
`[0.2 0.2 0.2 0.2]` (default) | 4-element vector

Gaussian noise for vehicle motion, specified as a 4-element vector. This property represents the variance parameters for Gaussian noise applied to vehicle motion. The elements of the vector correspond to the following errors in order:

- Rotational error due to rotational motion
- Rotational error due to translational motion
- Translational error due to translation motion
- Translational error due to rotational motion

**Type — Type of the odometry motion model**
`'DifferentialDrive'` (default)

This property is read-only.

Type of the odometry motion model, returned as `'DifferentialDrive'`. This read-only property indicates the type of odometry motion model being used by the object.

## Object Functions

showNoiseDistribution Display noise parameter effects

## Examples

### Predict Poses Based On An Odometry Motion Model

This example shows how to use the `odometryMotionModel` class to predict the pose of a vehicle. An `odometryMotionModel` object contains the motion model parameters for a differential drive vehicle. Use the object to predict the pose of a vehicle based on its current and previous poses and the motion model parameters.

Create odometry motion model object.

```
motionModel = odometryMotionModel;
```

Define previous poses and the current odometry reading. Each pose prediction corresponds to a row in `previousPoses` vector.

```
previousPoses =  rand(10,3);
currentOdom = [0.1 0.1 0.1];
```

The first call to the object initializes values and returns the previous poses as the current poses.

```
currentPoses = motionModel(previousPoses, currentOdom);
```

Subsequent calls to the object with updated odometry poses returns the predicted poses based on the motion model.

```
currentOdom = currentOdom + [0.1 0.1 0.05];
predPoses = motionModel(previousPoses, currentOdom);
```

### Show Noise Distribution Effects for Odometry Motion Model

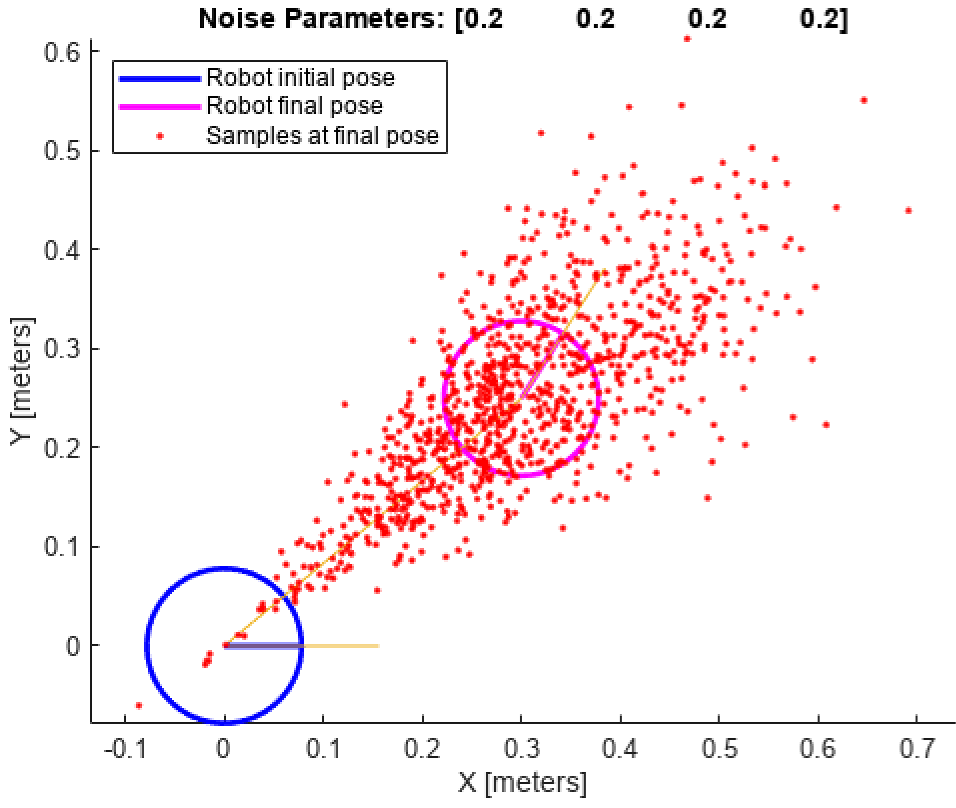
This example shows how to visualize the effect of different noise parameters on the `odometryMotionModel` class. An `odometryMotionModel` object contains the motion model noise parameters for a differential drive vehicle. Use `showNoiseDistribution` to visualize how changing these values affect the distribution of predicted poses.

Create a motion model object.

```
motionModel = odometryMotionModel;
```

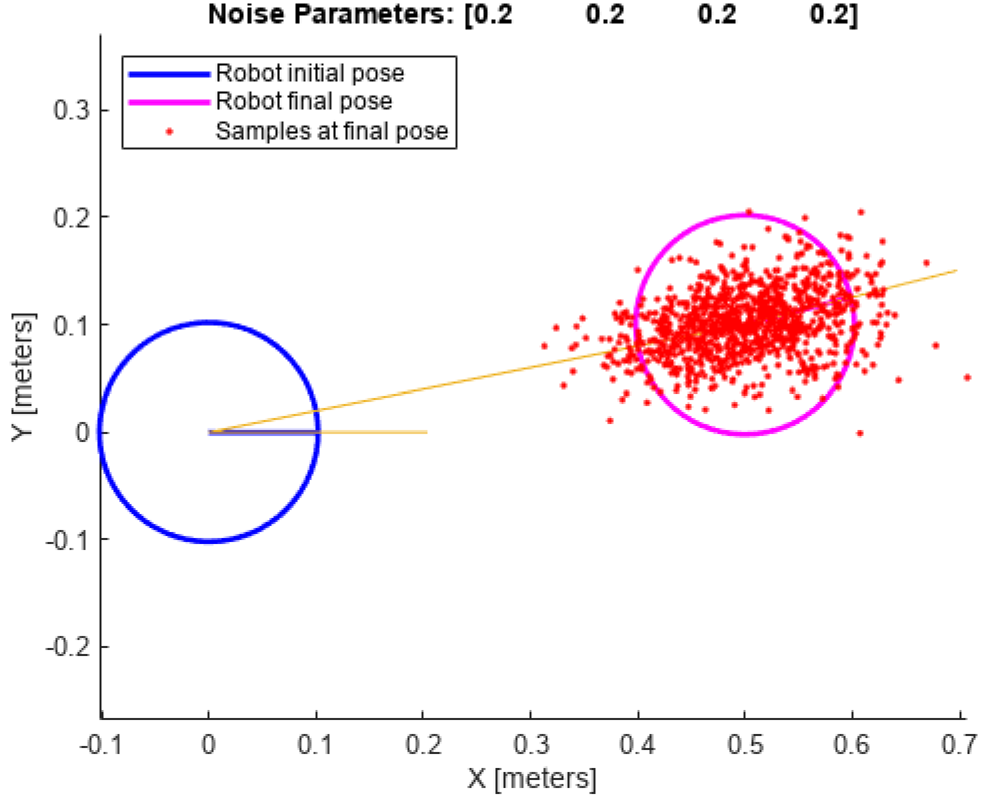
Show the distribution of particles with the existing noise parameters. Each particle is a hypothesis for the predicted pose.

```
showNoiseDistribution(motionModel);
```



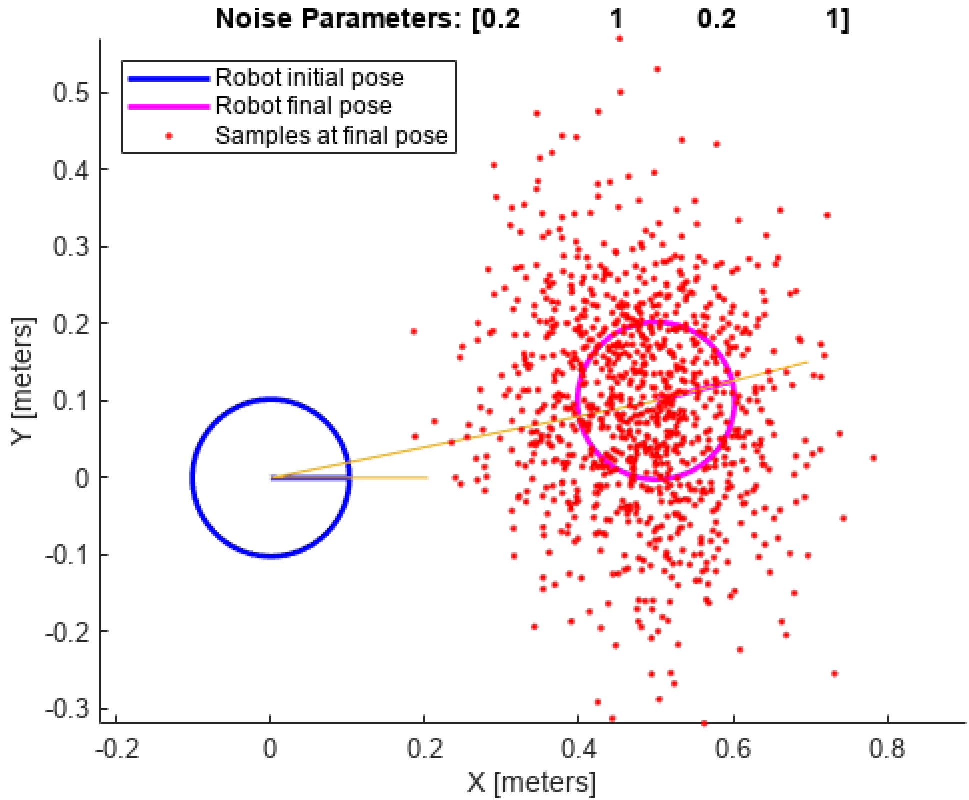

Show the distribution with a specified odometry pose change and number of samples. The change in odometry is used as the final pose with hypotheses distributed around based on the `Noise` parameters.

```
showNoiseDistribution(motionModel, ...
            'OdometryPoseChange', [0.5 0.1 0.25], ...
            'NumSamples', 1000);
```




Change the `Noise` parameters and visualize the effects. Use the same odometry pose change and number of samples.

```
motionModel.Noise = [0.2 1 0.2 1];

showNoiseDistribution(motionModel, ...
            'OdometryPoseChange', [0.5 0.1 0.25], ...
            'NumSamples', 1000);
```




## Limitations

If you make changes to your motion model after using it with the `monteCarloLocalization` object, call `release` on that object beforehand. For example:

```
mcl = monteCarloLocalization;
[isUpdated,pose,covariance] = mcl(ranges,angles);
release(mcl)
mcl.MotionModel.Noise = [0.25 0.25 0.4 0.4];
```

# Version History

**Introduced in R2019b**

## References

[1] Thrun, Sebatian, Wolfram Burgard, and Dieter Fox. *Probabilistic Robotics*. MIT Press, 2005.

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`monteCarloLocalization` | `likelihoodFieldSensorModel`

### Topics

"Localize TurtleBot Using Monte Carlo Localization Algorithm"

# showNoiseDistribution

Display noise parameter effects

## Syntax

```
showNoiseDistribution(ommObj)
showNoiseDistribution(ommObj)
showNoiseDistribution(ommObj,Name,Value)
```

## Description

`showNoiseDistribution(ommObj)` shows the noise distribution for a default odometry pose update, number of samples and the current noise parameters on the input object.

`axes` = `showNoiseDistribution(ommObj)` shows the noise distribution and returns the axes handle.

`showNoiseDistribution(ommObj,Name,Value)` provides additional options specified by one or more `Name,Value` pairs. Name is the property name and Value is the corresponding value. Name must appear inside single quotes (`' '`). You can specify several name-value pair arguments in any order as `Name1,Value1,...,NameN,ValueN`. Properties not specified retain their default values.

## Examples

### Show Noise Distribution Effects for Odometry Motion Model

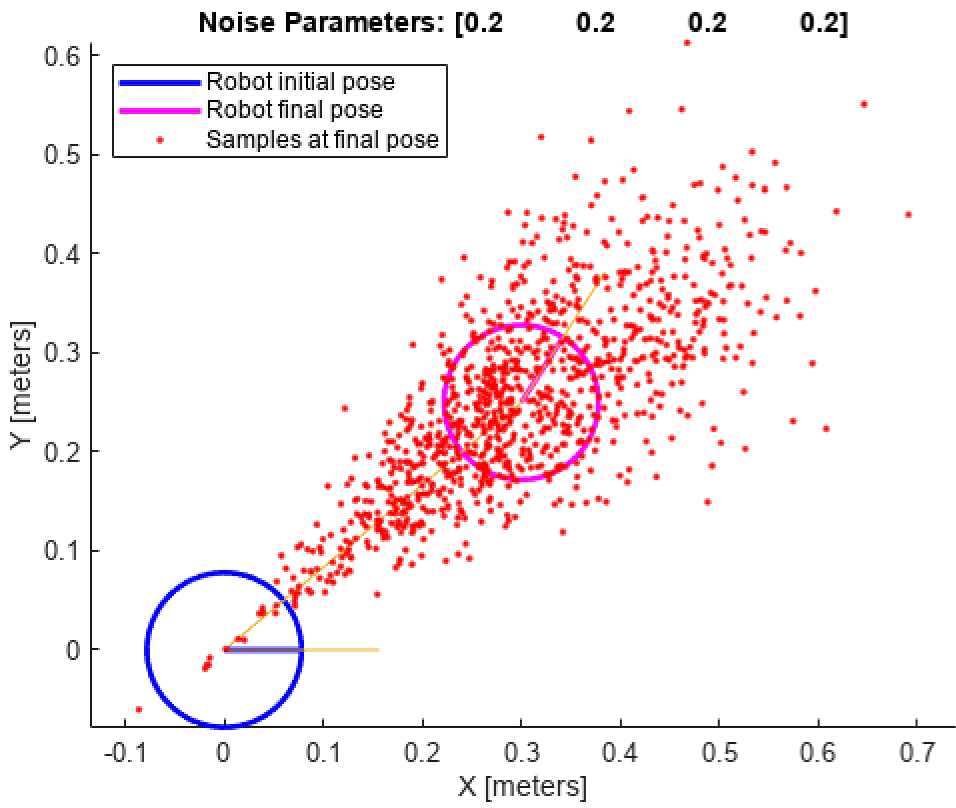
This example shows how to visualize the effect of different noise parameters on the `odometryMotionModel` class. An `odometryMotionModel` object contains the motion model noise parameters for a differential drive vehicle. Use `showNoiseDistribution` to visualize how changing these values affect the distribution of predicted poses.

Create a motion model object.

```
motionModel = odometryMotionModel;
```

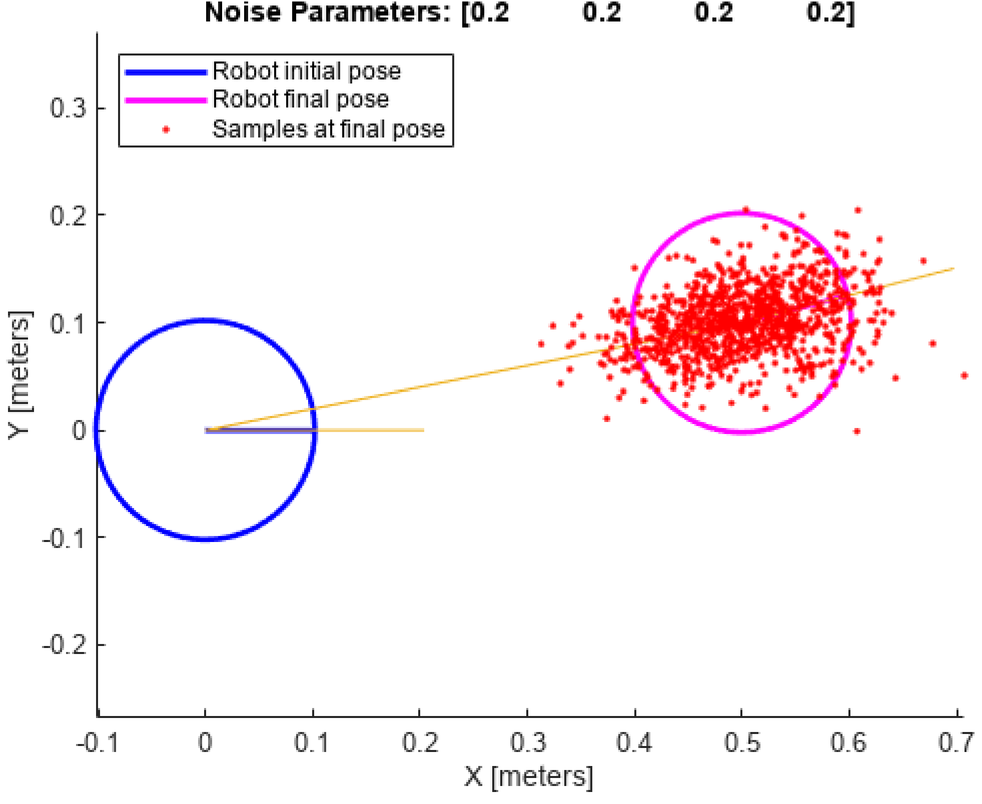
Show the distribution of particles with the existing noise parameters. Each particle is a hypothesis for the predicted pose.

```
showNoiseDistribution(motionModel);
```



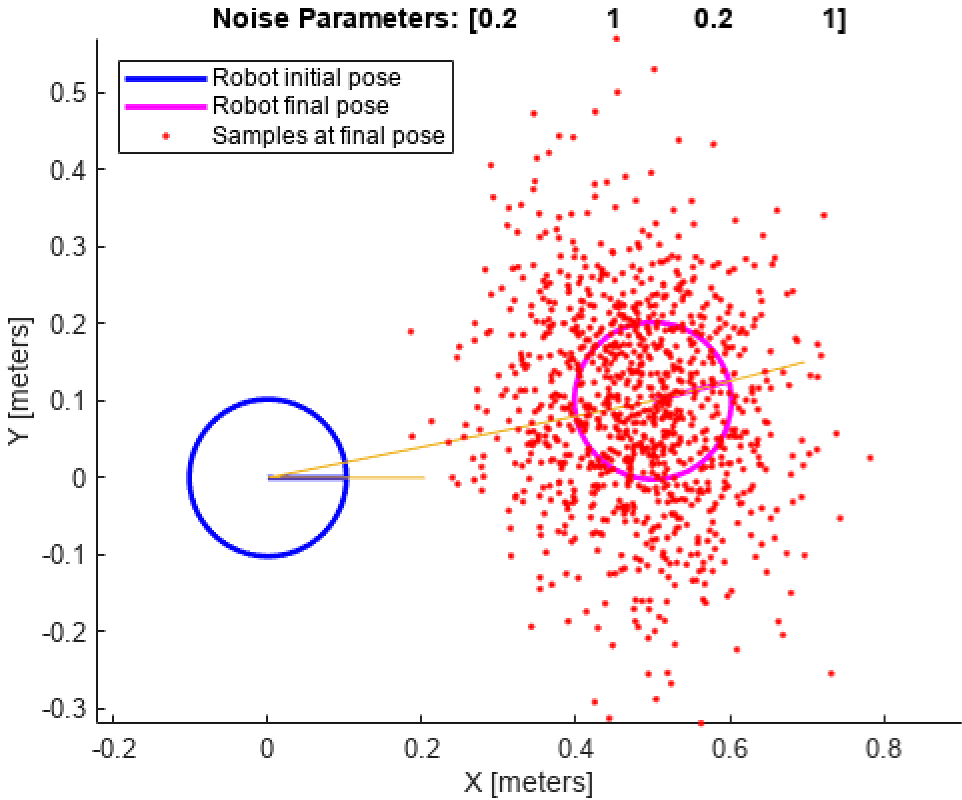

Show the distribution with a specified odometry pose change and number of samples. The change in odometry is used as the final pose with hypotheses distributed around based on the `Noise` parameters.

```
showNoiseDistribution(motionModel, ...
            'OdometryPoseChange', [0.5 0.1 0.25], ...
            'NumSamples', 1000);
```




Change the `Noise` parameters and visualize the effects. Use the same odometry pose change and number of samples.

```
motionModel.Noise = [0.2 1 0.2 1];

showNoiseDistribution(motionModel, ...
            'OdometryPoseChange', [0.5 0.1 0.25], ...
            'NumSamples', 1000);
```




## Input Arguments

**`ommObj` — `odometryMotionModel` object**
handle

`odometryMotionModel` object, specified as a handle. Create this object using `odometryMotionModel`.

### Name-Value Pair Arguments

Specify optional pairs of arguments as `Name1=Value1,...,NameN=ValueN`, where `Name` is the argument name and `Value` is the corresponding value. Name-value arguments must appear after other arguments, but the order of the pairs does not matter.

*Before R2021a, use commas to separate each name and value, and enclose* `Name` *in quotes.*

Example: `'OdometryPoseChange',[1 1 pi]`

**`OdometryPoseChange` — Change in odometry**
three-element vector

Change in odometry of the robot, specified as a comma-separated pair consisting of `'OdometryPoseChange'` and a three-element vector, `[x y theta]`.

**`NumSamples` — Number of particles to display**
scalar

Number of particles to display, specified as a comma-separated pair consisting of `'NumSamples'` and a scalar.

**`Parent` — Axes to plot the map**
`Axes` object | `UIAxes` object

Axes to plot the map, specified as a comma-separated pair consisting of `'Parent'` and either an `Axes` or `UIAxes` object. See `axes` or `uiaxes`.

# Version History
**Introduced in R2019b**

## See Also
`monteCarloLocalization` | `odometryMotionModel` | `likelihoodFieldSensorModel`

# optimizePathOptions

Create optimization options for optimizePath function

## Description

Optimization options are grouped into four categories:

- **Trajectory Parameters** — Specify the desired robot motion throughout the path.
- **Obstacle Parameters** — Specify the distances which dictate the influence of obstacle on the path.
- **Solver Parameters** — Specify the options for solver used to optimize the path.
- **Weights** — Specify the cost function weights.

---

**Note** At a very high level, two primary operations happen inside `optimizePath` function:

1. **Path Adjustment** — Increase (interpolate) or decrease (de-interpolate) poses in the path.
2. **Optimization** — Minimize the cost of the path by invoking the solver (Levenberg–Marquardt).

NumIteration property determines how many times Step 1 and 2 will be executed in a loop. MaxSolverIteration property determines the maximum iterations for Levenberg–Marquardt every time it is invoked in Step 2. For the default values, **Path Adjustment** and **Optimization** (Solver invocation) will happen four times, and at each invocation the solver will iterate a maximum of 15 times.

---

## Creation

### Syntax

`options = optimizePathOptions`

#### Description

`options = optimizePathOptions` creates a set of default optimization options for `optimizePath` function.

### Properties

#### Trajectory Parameters

**`MaxPathStates` — Maximum number of poses allowed in path**
`200` (default) | integer greater than or equal to 3

Maximum number of poses allowed in the path, specified as an integer greater than or equal to 3.

Example: `options.MaxPathStates = 100`

Data Types: `single` | `double`

**`ReferenceDeltaTime` — Travel time between two consecutive poses**
`0.3` (default) | positive scalar

Travel time between two consecutive poses, specified as a positive scalar in seconds. This parameter along with MaxVelocity impacts the interpolation distance between poses. Increase this value to have lesser number of poses and reduce it to have higher number of poses in the output path.

Example: `options.ReferenceDeltaTime = 0.5`

Data Types: `single` | `double`

**`MinTurningRadius` — Minimum turning radius in path**
`1` (default) | positive scalar

Minimum turning radius in the path, specified as a positive scalar in meters. Note that this is a soft constraint and may be ignored based on the value of WeightMinTurningRadius parameter with respect to other weights.

Example: `options.MinTurningRadius = 1.5`

Data Types: `single` | `double`

**`MaxVelocity` — Maximum velocity along path**
`0.4` (default) | positive scalar

Maximum velocity along the path, specified as a positive scalar in meters per second. Note that this is a soft constraint and may be ignored based on the value of WeightVelocity parameter with respect to other weights.

Example: `options.MaxVelocity = 0.5`

Data Types: `single` | `double`

**`MaxAngularVelocity` — Maximum angular velocity along path**
`0.3` (default) | positive scalar

Maximum angular velocity along the path, specified as a positive scalar in radians per second. Note that this is a soft constraint and may be ignored based on the value of WeightAngularVelocity parameter with respect to other weights.

Example: `options.MaxAngularVelocity = 0.5`

Data Types: `single` | `double`

**`MaxAcceleration` — Maximum acceleration along path**
`0.5` (default) | positive scalar

Maximum acceleration along the path, specified as a positive scalar in meters per second squared. Note that this is a soft constraint and may be ignored based on the value of WeightAcceleration parameter with respect to other weights.

Example: `options.MaxAcceleration = 0.6`

Data Types: `single` | `double`

**`MaxAngularAcceleration` — Maximum angular acceleration along path**
`0.5` (default) | positive scalar

Maximum angular acceleration along path, specified as a positive scalar in radians per second squared. Note that this is a soft constraint and may be ignored based on the value of WeightAngularAcceleration parameter with respect to other weights.

Example: `options.MaxAngularAcceleration = 0.6`

Data Types: `single` | `double`

#### Obstacle Parameters

### `ObstacleSafetyMargin` — Safety distance from obstacles
`0.5` (default) | positive scalar

Safety distance from the obstacles, specified as a positive scalar in meters. Note that this is a soft constraint and may be ignored based on the value of WeightObstacles parameter with respect to other weights.

Example: `options.ObstacleSafetyMargin = 0.6`

Data Types: `single` | `double`

### `ObstacleCutOffDistance` — Obstacle cutoff distance
`2.5` (default) | positive scalar

Obstacle cutoff distance, specified as a positive scalar in meters. The path optimizer ignores obstacles beyond the cutoff distance.

Example: `options.ObstacleCutOffDistance = 1.5`

Data Types: `single` | `double`

### `ObstacleInclusionDistance` — Obstacle inclusion distance
`0.75` (default) | positive scalar

Obstacle inclusion distance, specified as a positive scalar in meters. The path optimizer considers all obstacles within the inclusion distance, but only the closest obstacle on the left and on the right between the inclusion and cutoff distances.

Example: `options.ObstacleInclusionDistance = 0.5`

Data Types: `single` | `double`

#### Solver Parameters

### `NumIteration` — Number of solver invocations
`4` (default) | positive integer

Number of solver invocations, specified as a positive integer. This value also specifies the number of times interpolation occurs during optimization.

Example: `options.NumIteration = 5`

Data Types: `single` | `double`

### `MaxSolverIteration` — Maximum number of iterations for each solver invocation
`15` (default) | positive integer

Maximum number of iterations for each solver invocation, specified as a positive integer.

Example: `options.MaxSolverIteration = 12`

Data Types: `single` | `double`

**Weights**

#### `WeightTime` — Cost function weight for time
`10` (default) | nonnegative scalar

Cost function weight for time, specified as a nonnegative scalar. To lower the travel time, increase this weight value.

Example: `options.WeightTime = 12`

Data Types: `single` | `double`

#### `WeightSmoothness` — Cost function weight for nonholonomic motion
`1000` (default) | nonnegative scalar

Cost function weight for nonholonomic motion, specified as a nonnegative scalar. To obtain smoother path, increase this weight value.

Example: `options.WeightSmoothness = 500`

Data Types: `single` | `double`

#### `WeightMinTurningRadius` — Cost function weight for complying with minimum turning radius
`10` (default) | nonnegative scalar

Cost function weight for complying with minimum turning radius, specified as a nonnegative scalar. To ensure the turning radius is above minimum turning radius, increase this weight value.

Example: `options.WeightMinTurningRadius = 15`

Data Types: `single` | `double`

#### `WeightVelocity` — Cost function weight for velocity
`100` (default) | nonnegative scalar

Cost function weight for velocity, specified as a nonnegative scalar. To maintain the velocity below MaxVelocity, increase this weight value.

Example: `options.WeightVelocity = 120`

Data Types: `single` | `double`

#### `WeightAngularVelocity` — Cost function weight for angular velocity
`10` (default) | nonnegative scalar

Cost function weight for angular velocity, specified as a nonnegative scalar. To maintain the angular velocity below MaxAngularVelocity, increase this weight value.

Example: `options.WeightAngularVelocity = 15`

Data Types: `single` | `double`

#### `WeightAcceleration` — Cost function weight for acceleration
`10` (default) | nonnegative scalar

Cost function weight for acceleration, specified as a nonnegative scalar. To maintain the acceleration below MaxAcceleration, increase this weight value.

Example: `options.WeightAcceleration = 15`

Data Types: `single` | `double`

**`WeightAngularAcceleration` — Cost function weight for angular acceleration**
`10` (default) | nonnegative scalar

Cost function weight for angular acceleration, specified as a nonnegative scalar. To maintain the angular acceleration below MaxAngularAcceleration, increase this weight value.

Example: `options.WeightAngularAcceleration = 15`

Data Types: `single` | `double`

**`WeightObstacles` — Cost function weight for maintaining safe distance from obstacles**
`50` (default) | nonnegative scalar

Cost function weight for maintaining safe distance from obstacles, specified as a nonnegative scalar. To maintain the safe distance from obstacles, increase this weight value.

Example: `options.WeightObstacles = 60`

Data Types: `single` | `double`

## Examples

### Optimize Planned Path

#### Setup Environment

Load a map into the workspace.

```
map = load("exampleMaps.mat").complexMap;
```

Create a binary occupancy map.

```
map = binaryOccupancyMap(map);
```

Create a state validator object.

```
stateValidator = validatorOccupancyMap;
```

Assign the map to the state validator object.

```
stateValidator.Map = map;
```

Set the validation distance for the validator.

```
stateValidator.ValidationDistance = 0.01;
```

#### Plan Path

Initialize the `plannerHybridAStar` object with the state validator object. Specify the `MinTurningRadius` property of the planner as 2 meters.

```
planner = plannerHybridAStar(stateValidator,MinTurningRadius=2);
```

Define start and goal poses as [*x y theta*] vectors. *x* and *y* specify the position in meters, and *theta* specifies the orientation angle in radians.

```
start = [6 3 pi/2];
goal = [32 32 0];
```

Plan a path from the start pose to the goal pose.

```
path = plan(planner,start,goal);
inpath = path.States;
```

**Optimize Path**

Configure options for optimization.

```
options = optimizePathOptions
```

```
options = 
optimizePathOptions

   Trajectory Parameters
                MaxPathStates: 200
           ReferenceDeltaTime: 0.3000
             MinTurningRadius: 1
                  MaxVelocity: 0.4000
           MaxAngularVelocity: 0.3000
              MaxAcceleration: 0.5000
       MaxAngularAcceleration: 0.5000

   Obstacle Parameters
         ObstacleSafetyMargin: 0.5000
       ObstacleCutOffDistance: 2.5000
    ObstacleInclusionDistance: 0.7500

   Solver Parameters
                 NumIteration: 4
           MaxSolverIteration: 15

   Weights
                   WeightTime: 10
             WeightSmoothness: 1000
       WeightMinTurningRadius: 10
               WeightVelocity: 100
        WeightAngularVelocity: 10
           WeightAcceleration: 10
    WeightAngularAcceleration: 10
              WeightObstacles: 50
```

Set the minimum turning radius value as same as in the planner.

```
options.MinTurningRadius = 2;
```

Specify the maximum number of poses allowed in the optimized path.

```
options.MaxPathStates = size(inpath,1) * 3;
```

Maintain a safe distance of `0.75` meters from the obstacles.

```
options.ObstacleSafetyMargin = 0.75;
```

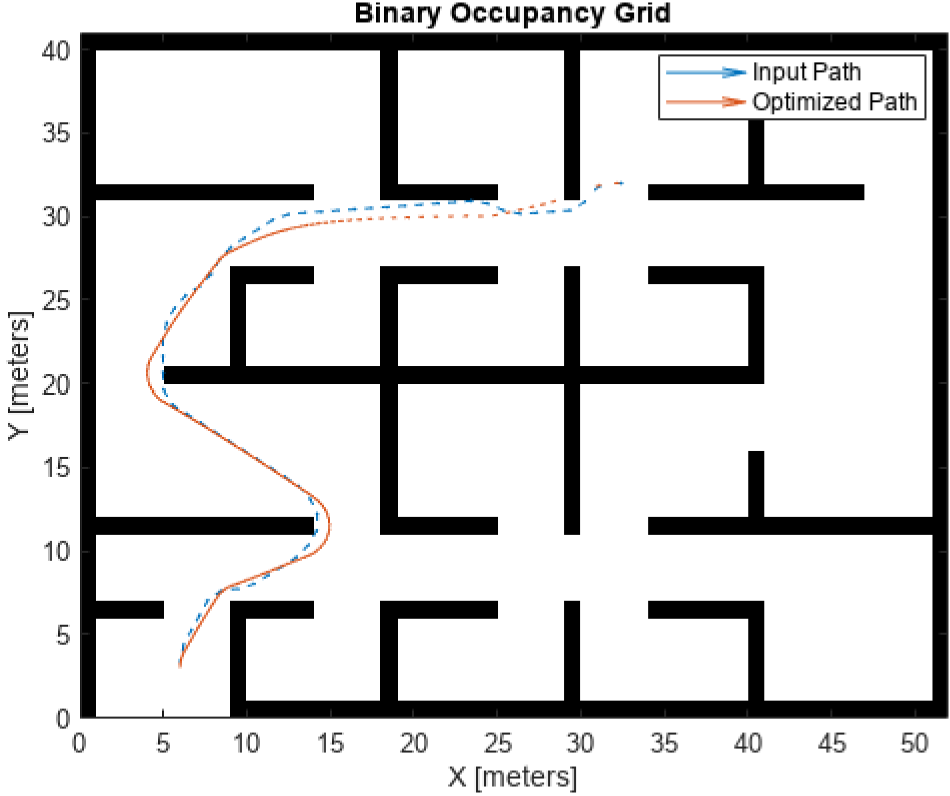
Optimize the path generated by the planner.

```
optpath = optimizePath(inpath,map,options);
```

**Visualize**

Visualize input path and optimized path in the map.

```
show(map)
hold on
quiver(inpath(:,1),inpath(:,2),cos(inpath(:,3)),sin(inpath(:,3)),0.1);
quiver(optpath(:,1),optpath(:,2),cos(optpath(:,3)),sin(optpath(:,3)),0.1);
legend("Input Path","Optimized Path")
```




# Version History

**Introduced in R2022a**

## References

[1] Rosmann, Christoph, Frank Hoffmann, and Torsten Bertram. “Kinodynamic Trajectory Optimization and Control for Car-like Robots.” In *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 5681–86. Vancouver, BC: IEEE, 2017. https://doi.org/10.1109/IROS.2017.8206458.

## Extended Capabilities

### C/C++ Code Generation
Generate C and C++ code using MATLAB® Coder™.

## See Also
`optimizePath`

# pathmetrics

Information for path metrics

## Description

The pathmetrics object holds information for computing path metrics. Use object functions to calculate smoothness, clearance, and path validity based on a set of poses and the associated map environment.

## Creation

### Syntax

```
pathMetricsObj = pathmetrics(path)
pathMetricsObj = pathmetrics(path,validator)
```

#### Description

pathMetricsObj = pathmetrics(path) creates an object based on the input navPath object. The state validator is assumed to be a validatorOccupancyMap object, if the state space of the navPath object is a stateSpaceSE2, stateSpaceDubins, or stateSpaceReedsShepp object. Otherwise, The state validator is assumed to be a validatorOccupancyMap3D object, if the state space of the navPath object is a stateSpaceSE3 object. The path input sets the value of the "Path" on page 2-0 property.

pathMetricsObj = pathmetrics(path,validator) creates an object based on the input navPath object and associated state validator for checking the path validity. The validator input sets the value of the "StateValidator" on page 2-0 property.

## Properties

**Path — Path data structure**
navPath object

Path data structure, specified as a navPath object is the path whose metric is to be calculated.

**StateValidator — Validator for states on path**
validatorOccupancyMap object | validatorVehicleCostmap object | validatorOccupancyMap3D object

Validator for states on path, specified either as a validatorOccupancyMap, validatorVehicleCostmap, or validatorOccupancyMap3D object.

For 2-D state spaces, The default state validator is validatorOccupancyMap(stateSpaceSE2,binaryOccupancyMap(10)).

For 3-D state spaces, The default state validator is validatorOccupancyMap3D(stateSpaceSE3).

## Object Functions

| | |
|---|---|
| clearance | Minimum clearance of path |
| isPathValid | Determine if planned path is obstacle free |
| show | Visualize path metrics in map environment |
| smoothness | Smoothness of path |

## Examples

### Compute Path Metrics

Compute smoothness, clearance, and validity of a planned path based on a set of poses and the associated map environment.

#### Load and Assign Map to State Validator

Create an occupancy map from an example map and set the map resolution.

```
load exampleMaps.mat; % simpleMap
mapResolution = 1; % cells/meter
map = occupancyMap(simpleMap,mapResolution);
```

Create a Dubins state space.

```
statespace = stateSpaceDubins;
```

Create a state validator based on occupancy map to store the parameters and states in the Dubins state space.

```
statevalidator = validatorOccupancyMap(statespace);
```

Assign the map to the validator.

```
statevalidator.Map = map;
```

Set the validation distance for the validator.

```
statevalidator.ValidationDistance = 0.01;
```

Update the state space bounds to be the same as the map limits.

```
statespace.StateBounds = [map.XWorldLimits;map.YWorldLimits;[-pi pi]];
```

#### Plan Path

Create an RRT* path planner and allow further optimization.

```
planner = plannerRRTStar(statespace,statevalidator);
planner.ContinueAfterGoalReached = true;
```

Reduce the maximum number of iterations and increase the maximum connection distance.

```
planner.MaxIterations = 2500;
planner.MaxConnectionDistance = 0.3;
```

Define start and goal states for the path planner as [*x, y, theta*] vectors. *x* and *y* are the Cartesian coordinates, and *theta* is the orientation angle.

```
start = [2.5, 2.5, 0]; % [meters, meters, radians]
goal = [22.5, 8.75, 0];
```

Plan a path from the start state to the goal state. The plan function returns a `navPath` object.

```
rng(100,'twister') % repeatable result
[path,solutionInfo] = plan(planner,start,goal);
```

**Compute and Visualize Path Metrics**

Create a path metrics object.

```
pathMetricsObj = pathmetrics(path,statevalidator);
```

Check path validity. The result is `1 (true)` if the planned path is obstacle free. `0 (false)` indicates an invalid path.

```
isPathValid(pathMetricsObj)
```

```
ans = logical
   1
```

Calculate the minimum clearance of the path.

```
clearance(pathMetricsObj)
```

```
ans = 1.4142
```

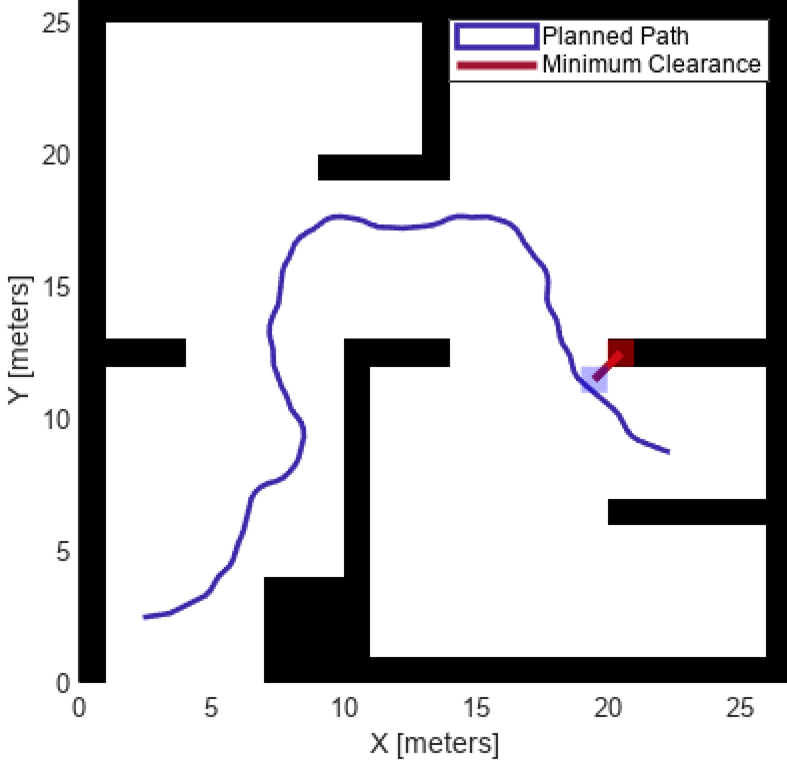
Evaluate the smoothness of the path. Values close to `0` indicate a smoother path. Straight-line paths return a value of `0`.

```
smoothness(pathMetricsObj)
```

```
ans = 1.7318
```

Visualize the minimum clearance of the path.

```
show(pathMetricsObj)
legend('Planned Path','Minimum Clearance')
```



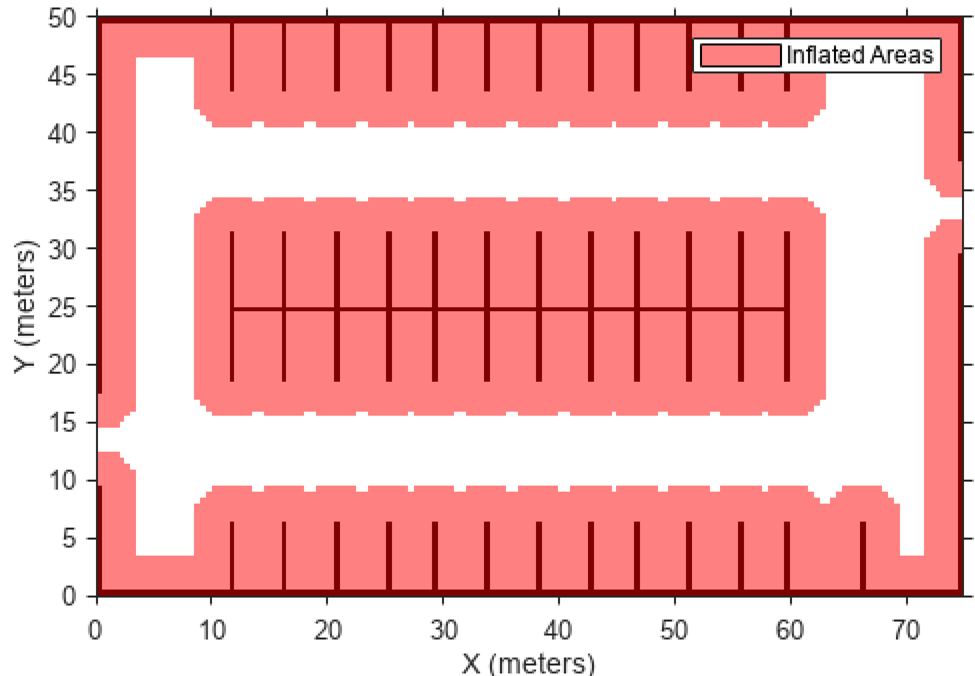

### Vehicle Path Planning and Metrics Computation in a 2-D Costmap Environment

Plan a vehicle path through a parking lot using the RRT* algorithm. Compute and visualize the smoothness, clearance, and validity of the planned path.

#### Load and Assign Map to State Validator

Load a costmap of a parking lot. Plot the costmap to see the parking lot and the inflated areas that the vehicle should avoid.

```
load parkingLotCostmap.mat;
costmap = parkingLotCostmap;
plot(costmap)
xlabel('X (meters)')
ylabel('Y (meters)')
```




Create a `stateSpaceDubins` object and increase the minimum turing radius to 4 meters.

```
statespace = stateSpaceDubins;
statespace.MinTurningRadius = 4; % meters
```

Create a `validatorVehicleCostmap` object using the created state space.

```
statevalidator = validatorVehicleCostmap(statespace);
```

Assign the parking lot costmap to the state validator object.

```
statevalidator.Map = costmap;
```

**Plan Path**

Define start and goal poses for the vehicle as [*x*, *y*, Θ] vectors. World units for the (*x*,*y*) locations are in meters. World units for the orientation angles Θ are in degrees.

```
startPose = [5, 5, 90]; % [meters, meters, degrees]
goalPose = [40, 38, 180]; % [meters, meters, degrees]
```

Use a `pathPlannerRRT` (Automated Driving Toolbox) object and the `plan` (Automated Driving Toolbox) function to plan the vehicle path from the start pose to the goal pose.

```
planner = pathPlannerRRT(costmap);
refPath = plan(planner,startPose,goalPose);
```

Interpolate along the path at every one meter. Convert the orientation angles from degrees to radians.

```
poses = zeros(size(refPath.PathSegments,2)+1,3);
poses(1,:) = refPath.StartPose;
for i = 1:size(refPath.PathSegments,2)
    poses(i+1,:) = refPath.PathSegments(i).GoalPose;
end
poses(:,3) = deg2rad(poses(:,3));
```

Create a `navPath` object using the Dubins state space object and the states specified by `poses`.

```
path = navPath(statespace,poses);
```

**Compute and Visualize Path Metrics**

Create a `pathmetrics` object.

```
pathMetricsObj = pathmetrics(path,statevalidator);
```

Check path validity. The result is `1` (`true`) if the planned path is obstacle free. `0` (`false`) indicates an invalid path.

```
isPathValid(pathMetricsObj)
```

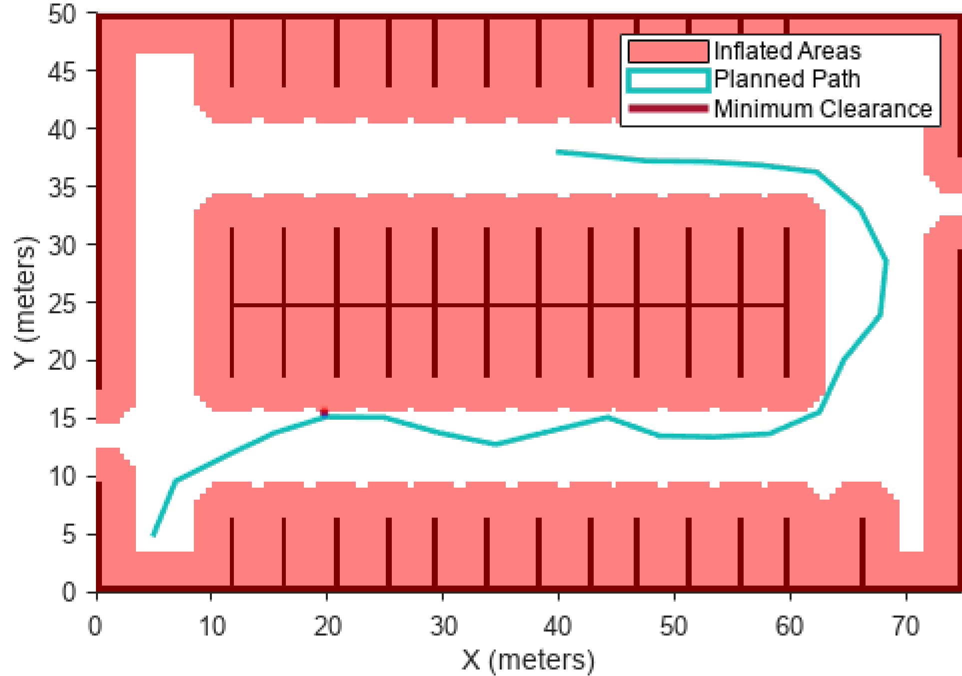
```
ans = logical
   1
```

Compute and visualize the minimum `clearance` of the path.

```
clearance(pathMetricsObj)
```

```
ans = 0.5000
```

```
show(pathMetricsObj)
legend('Inflated Areas','Planned Path','Minimum Clearance')
xlabel('X (meters)')
ylabel('Y (meters)')
```

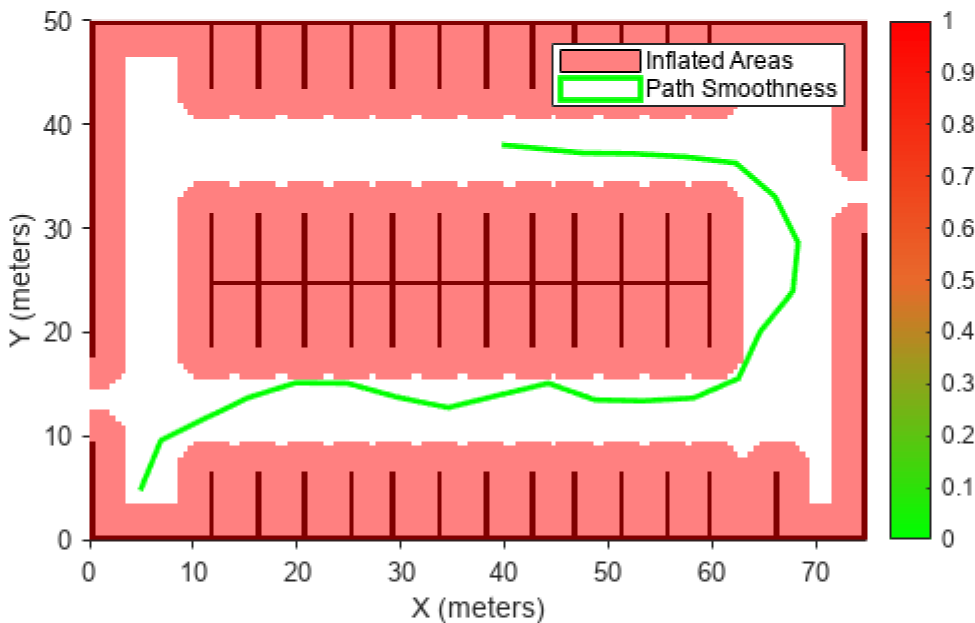



Compute and visualize the `smoothness` of the path. Values close to `0` indicate a smoother path. Straight-line paths return a value of `0`.

```
smoothness(pathMetricsObj)
```

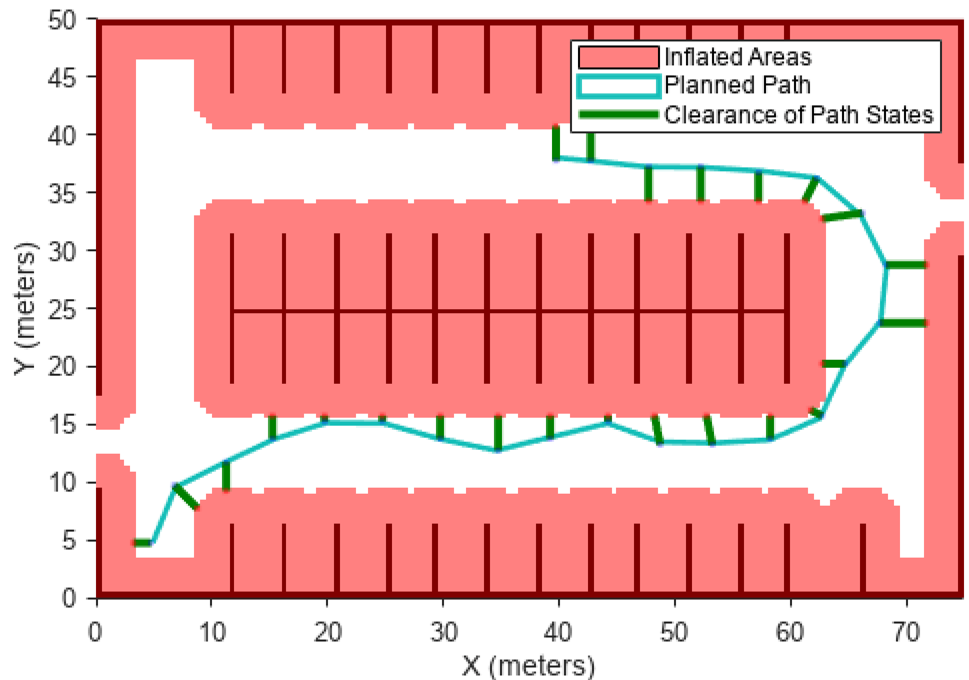
```
ans = 0.0842
```

```
show(pathMetricsObj,'Metrics',{'Smoothness'})
legend('Inflated Areas','Path Smoothness')
xlabel('X (meters)')
ylabel('Y (meters)')
```




Visualize the clearance for each state of the path.

```
show(pathMetricsObj,'Metrics',{'StatesClearance'})
legend('Inflated Areas','Planned Path','Clearance of Path States')
xlabel('X (meters)')
ylabel('Y (meters)')
```




**Path Planning and Metrics Computation in 3-D Environment**

Plan a path through a city block using the RRT algorithm. Compute and visualize the smoothness, clearance, and validity of the planned path.

**Load and Assign Map to State Validator**

Load a 3-D occupancy map of a city block into the workspace. Specify the threshold to consider cells as obstacle-free.

```
mapData = load("dMapCityBlock.mat");
omap = mapData.omap;
omap.FreeThreshold = 0.5;
```

Inflate the occupancy map to add a buffer zone for safe operation around the obstacles.

```
inflate(omap,1)
```

Create an SE(3) state space object with bounds for state variables.

```
ss = stateSpaceSE3([0 220;0 220;0 100;inf inf;inf inf;inf inf;inf inf]);
```

Create a 3-D occupancy map state validator using the created state space. Assign the occupancy map to the state validator object. Specify the sampling distance interval.

```
sv = validatorOccupancyMap3D(ss, ...
     Map = omap, ...
     ValidationDistance = 0.1);
```

#### Plan Path

Create a RRT path planner with increased maximum connection distance and reduced maximum number of iterations. Specify a custom goal function that determines that a path reaches the goal if the Euclidean distance to the target is below a threshold of 1 meter.

```
planner = plannerRRT(ss,sv, ...
          MaxConnectionDistance = 50, ...
          MaxIterations = 1000, ...
          GoalReachedFcn = @(~,s,g)(norm(s(1:3)-g(1:3))<1), ...
          GoalBias = 0.1);
```

Specify start and goal poses.

```
start = [50 180 25 0.7 0.2 0 0.1];
goal = [150 33 35 0.3 0 0.1 0.6];
```

Configure the random number generator for repeatable result.

```
rng(1,"twister")
```

Plan the path.

```
[pthObj,solnInfo] = plan(planner,start,goal);
```

#### Compute and Visualize Path Metrics

Create a path metrics object.

```
pathMetricsObj = pathmetrics(pthObj,sv);
```

Check path validity. The result is `1 (true)` if the planned path is obstacle free. `0 (false)` indicates an invalid path.

```
isPathValid(pathMetricsObj)
```

```
ans = logical
   1
```

Calculate the minimum clearance of the path.

```
clearance(pathMetricsObj)
```

```
ans = 10
```

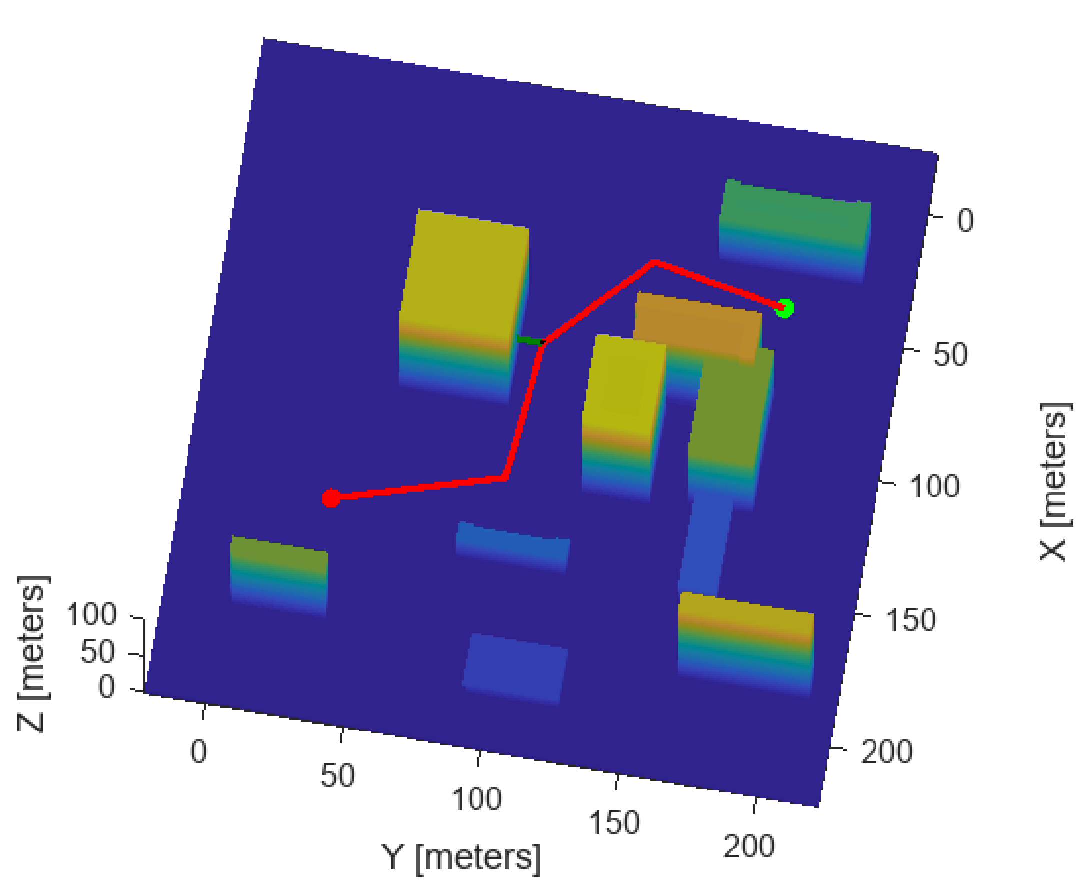
Evaluate the smoothness of the path. Values close to `0` indicate a smoother path. Straight-line paths return a value of `0`.

```
smoothness(pathMetricsObj)
```

```
ans = 0.0011
```

Visualize the minimum clearance of the path.

```
show(pathMetricsObj)
axis equal
view([100 75])
hold on
% Start state
scatter3(start(1,1),start(1,2),start(1,3),"g","filled")
% Goal state
scatter3(goal(1,1),goal(1,2),goal(1,3),"r","filled")
% Path
plot3(pthObj.States(:,1),pthObj.States(:,2),pthObj.States(:,3), ...
      "r-",LineWidth=2)
```




## Version History
**Introduced in R2019b**

## See Also

**Objects**
navPath | validatorOccupancyMap | validatorVehicleCostmap | validatorOccupancyMap3D

# clearance

Minimum clearance of path

## Syntax

```
clearance(pathMetricsObj)
clearance(pathMetricsObj,'Type','states')
```

## Description

`clearance(pathMetricsObj)` returns the minimum clearance of the path. Clearance is measured as the minimum distance between grid cell centers of states on the path and obstacles in the specified map environment.

**Note** The computed clearance is accurate up to `sqrt(2)` times grid map cell size.

`clearance(pathMetricsObj,'Type','states')` returns the set of minimum distances for each state of the path, in the form of an *n*-by-1 vector, where *n* is the number of states.

## Examples

### Compute Path Metrics

Compute smoothness, clearance, and validity of a planned path based on a set of poses and the associated map environment.

#### Load and Assign Map to State Validator

Create an occupancy map from an example map and set the map resolution.

```
load exampleMaps.mat; % simpleMap
mapResolution = 1; % cells/meter
map = occupancyMap(simpleMap,mapResolution);
```

Create a Dubins state space.

```
statespace = stateSpaceDubins;
```

Create a state validator based on occupancy map to store the parameters and states in the Dubins state space.

```
statevalidator = validatorOccupancyMap(statespace);
```

Assign the map to the validator.

```
statevalidator.Map = map;
```

Set the validation distance for the validator.

```
statevalidator.ValidationDistance = 0.01;
```

Update the state space bounds to be the same as the map limits.

```
statespace.StateBounds = [map.XWorldLimits;map.YWorldLimits;[-pi pi]];
```

#### Plan Path

Create an RRT* path planner and allow further optimization.

```
planner = plannerRRTStar(statespace,statevalidator);
planner.ContinueAfterGoalReached = true;
```

Reduce the maximum number of iterations and increase the maximum connection distance.

```
planner.MaxIterations = 2500;
planner.MaxConnectionDistance = 0.3;
```

Define start and goal states for the path planner as [*x, y, theta*] vectors. *x* and *y* are the Cartesian coordinates, and *theta* is the orientation angle.

```
start = [2.5, 2.5, 0]; % [meters, meters, radians]
goal = [22.5, 8.75, 0];
```

Plan a path from the start state to the goal state. The plan function returns a `navPath` object.

```
rng(100,'twister') % repeatable result
[path,solutionInfo] = plan(planner,start,goal);
```

#### Compute and Visualize Path Metrics

Create a path metrics object.

```
pathMetricsObj = pathmetrics(path,statevalidator);
```

Check path validity. The result is `1 (true)` if the planned path is obstacle free. `0 (false)` indicates an invalid path.

```
isPathValid(pathMetricsObj)
```

```
ans = logical
   1
```

Calculate the minimum clearance of the path.

```
clearance(pathMetricsObj)
```

```
ans = 1.4142
```

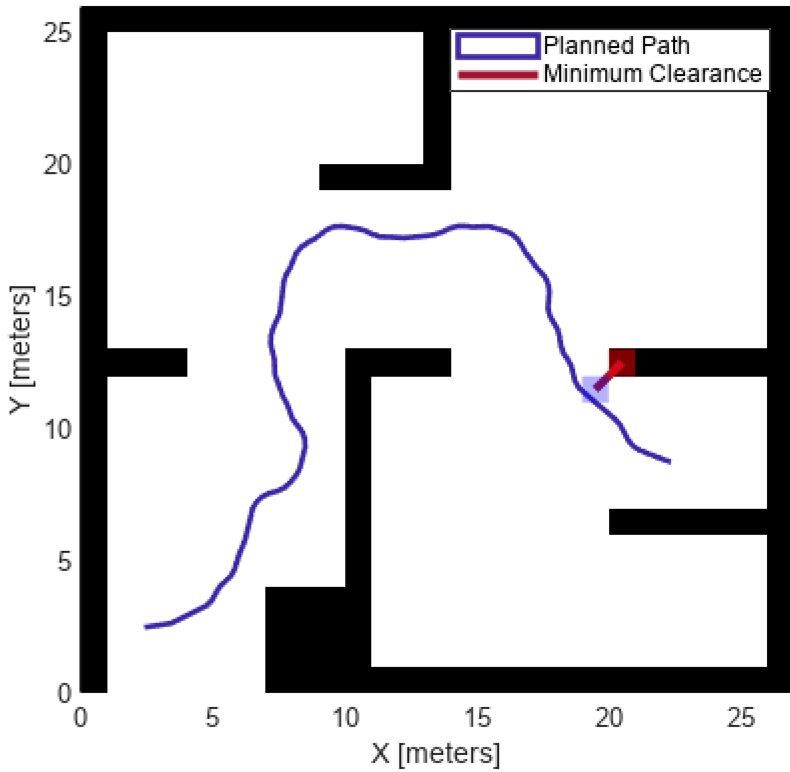
Evaluate the smoothness of the path. Values close to `0` indicate a smoother path. Straight-line paths return a value of `0`.

```
smoothness(pathMetricsObj)
```

```
ans = 1.7318
```

Visualize the minimum clearance of the path.

```
show(pathMetricsObj)
legend('Planned Path','Minimum Clearance')
```



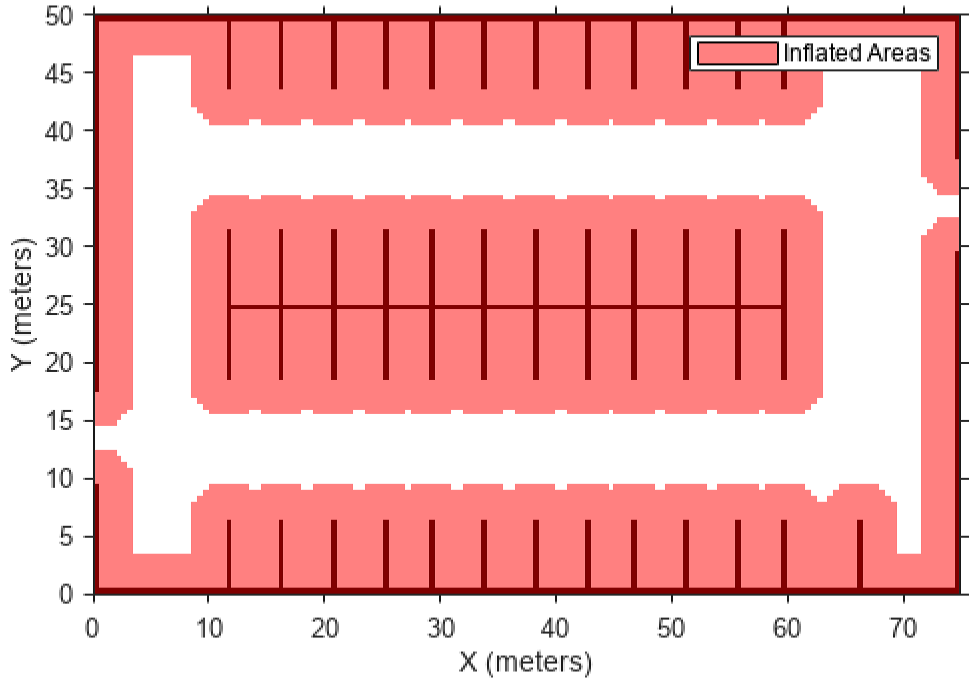

**Vehicle Path Planning and Metrics Computation in a 2-D Costmap Environment**

Plan a vehicle path through a parking lot using the RRT* algorithm. Compute and visualize the smoothness, clearance, and validity of the planned path.

**Load and Assign Map to State Validator**

Load a costmap of a parking lot. Plot the costmap to see the parking lot and the inflated areas that the vehicle should avoid.

```
load parkingLotCostmap.mat;
costmap = parkingLotCostmap;
plot(costmap)
xlabel('X (meters)')
ylabel('Y (meters)')
```




Create a `stateSpaceDubins` object and increase the minimum turing radius to 4 meters.

```
statespace = stateSpaceDubins;
statespace.MinTurningRadius = 4; % meters
```

Create a `validatorVehicleCostmap` object using the created state space.

```
statevalidator = validatorVehicleCostmap(statespace);
```

Assign the parking lot costmap to the state validator object.

```
statevalidator.Map = costmap;
```

**Plan Path**

Define start and goal poses for the vehicle as [*x*, *y*, Θ] vectors. World units for the (*x*,*y*) locations are in meters. World units for the orientation angles Θ are in degrees.

```
startPose = [5, 5, 90]; % [meters, meters, degrees]
goalPose = [40, 38, 180]; % [meters, meters, degrees]
```

Use a `pathPlannerRRT` (Automated Driving Toolbox) object and the `plan` (Automated Driving Toolbox) function to plan the vehicle path from the start pose to the goal pose.

```
planner = pathPlannerRRT(costmap);
refPath = plan(planner,startPose,goalPose);
```

Interpolate along the path at every one meter. Convert the orientation angles from degrees to radians.

```
poses = zeros(size(refPath.PathSegments,2)+1,3);
poses(1,:) = refPath.StartPose;
for i = 1:size(refPath.PathSegments,2)
    poses(i+1,:) = refPath.PathSegments(i).GoalPose;
end
poses(:,3) = deg2rad(poses(:,3));
```

Create a `navPath` object using the Dubins state space object and the states specified by `poses`.

```
path = navPath(statespace,poses);
```

#### Compute and Visualize Path Metrics

Create a `pathmetrics` object.

```
pathMetricsObj = pathmetrics(path,statevalidator);
```

Check path validity. The result is `1` (`true`) if the planned path is obstacle free. `0` (`false`) indicates an invalid path.

```
isPathValid(pathMetricsObj)
```

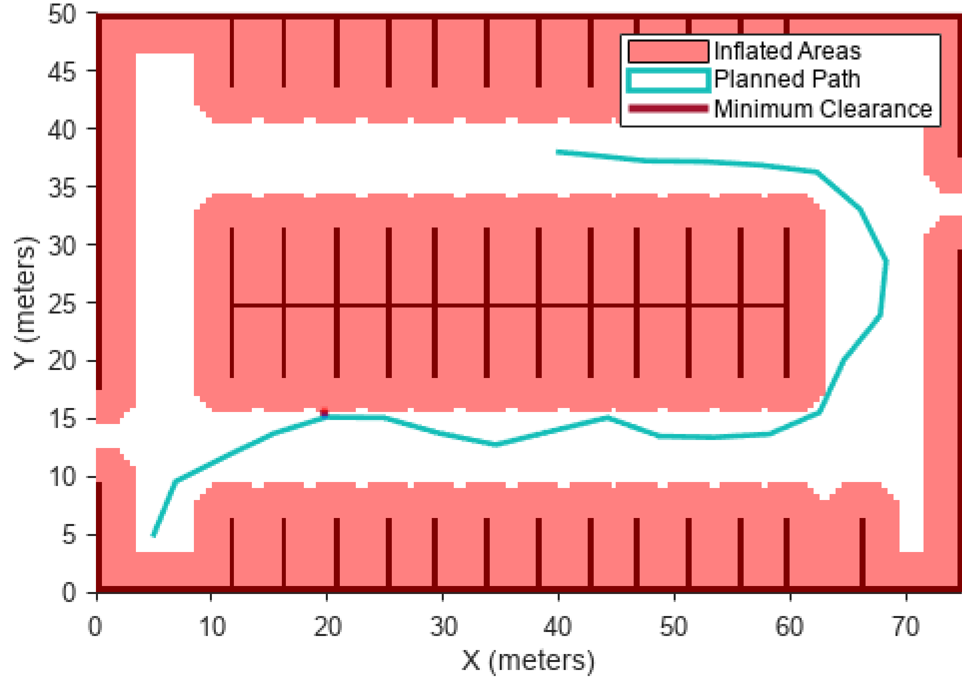
```
ans = logical
   1
```

Compute and visualize the minimum `clearance` of the path.

```
clearance(pathMetricsObj)
```

```
ans = 0.5000
```

```
show(pathMetricsObj)
legend('Inflated Areas','Planned Path','Minimum Clearance')
xlabel('X (meters)')
ylabel('Y (meters)')
```

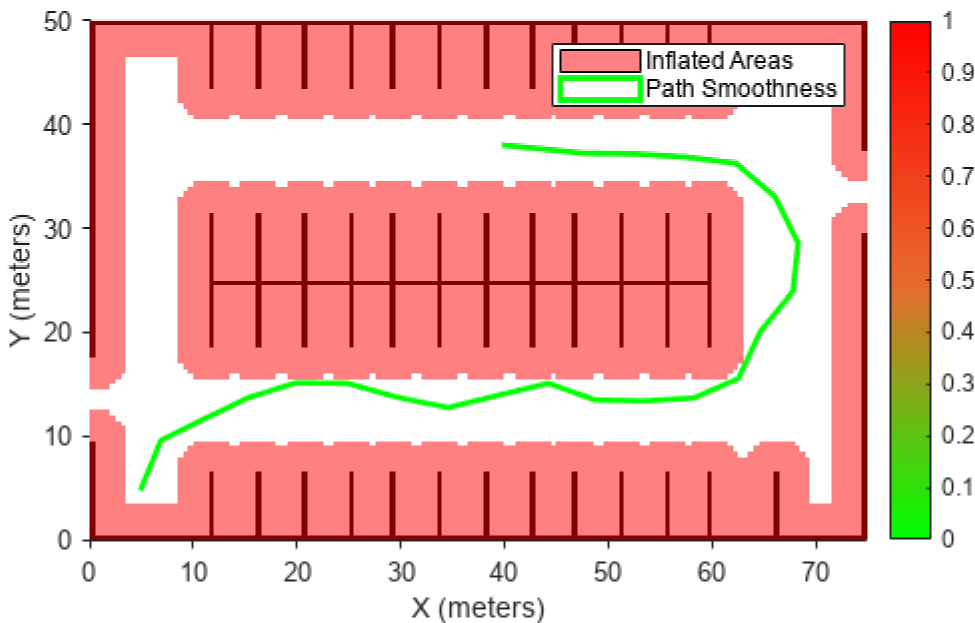



Compute and visualize the `smoothness` of the path. Values close to `0` indicate a smoother path. Straight-line paths return a value of `0`.

```
smoothness(pathMetricsObj)
```

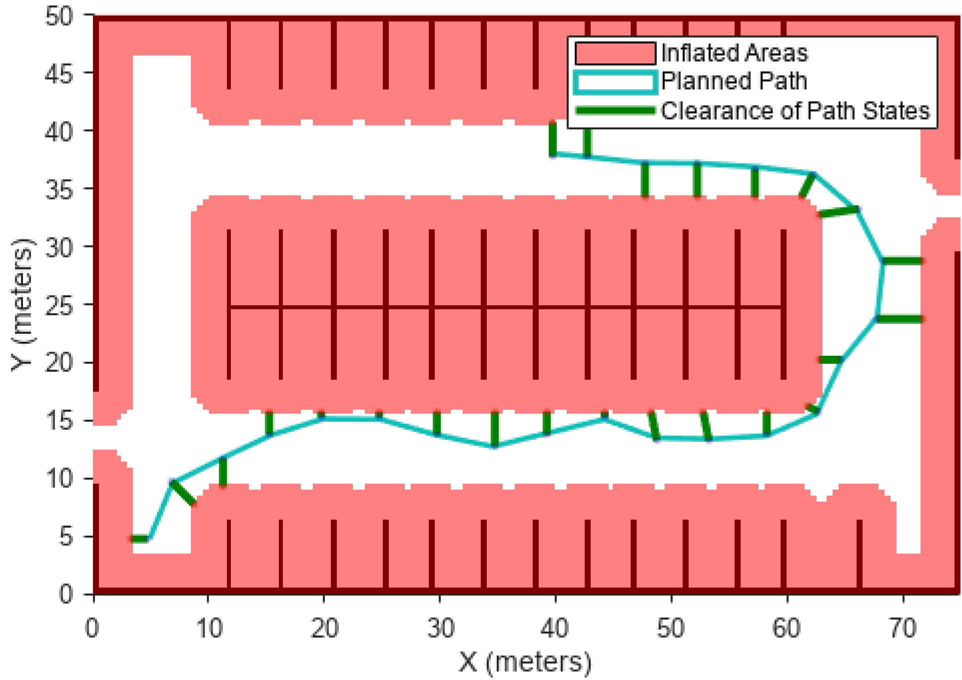
```
ans = 0.0842
```

```
show(pathMetricsObj,'Metrics',{'Smoothness'})
legend('Inflated Areas','Path Smoothness')
xlabel('X (meters)')
ylabel('Y (meters)')
```




Visualize the clearance for each state of the path.

```
show(pathMetricsObj,'Metrics',{'StatesClearance'})
legend('Inflated Areas','Planned Path','Clearance of Path States')
xlabel('X (meters)')
ylabel('Y (meters)')
```




**Path Planning and Metrics Computation in 3-D Environment**

Plan a path through a city block using the RRT algorithm. Compute and visualize the smoothness, clearance, and validity of the planned path.

**Load and Assign Map to State Validator**

Load a 3-D occupancy map of a city block into the workspace. Specify the threshold to consider cells as obstacle-free.

```
mapData = load("dMapCityBlock.mat");
omap = mapData.omap;
omap.FreeThreshold = 0.5;
```

Inflate the occupancy map to add a buffer zone for safe operation around the obstacles.

```
inflate(omap,1)
```

Create an SE(3) state space object with bounds for state variables.

```
ss = stateSpaceSE3([0 220;0 220;0 100;inf inf;inf inf;inf inf;inf inf]);
```

Create a 3-D occupancy map state validator using the created state space. Assign the occupancy map to the state validator object. Specify the sampling distance interval.

```
sv = validatorOccupancyMap3D(ss, ...
     Map = omap, ...
     ValidationDistance = 0.1);
```

#### Plan Path

Create a RRT path planner with increased maximum connection distance and reduced maximum number of iterations. Specify a custom goal function that determines that a path reaches the goal if the Euclidean distance to the target is below a threshold of 1 meter.

```
planner = plannerRRT(ss,sv, ...
          MaxConnectionDistance = 50, ...
          MaxIterations = 1000, ...
          GoalReachedFcn = @(~,s,g)(norm(s(1:3)-g(1:3))<1), ...
          GoalBias = 0.1);
```

Specify start and goal poses.

```
start = [50 180 25 0.7 0.2 0 0.1];
goal = [150 33 35 0.3 0 0.1 0.6];
```

Configure the random number generator for repeatable result.

```
rng(1,"twister")
```

Plan the path.

```
[pthObj,solnInfo] = plan(planner,start,goal);
```

#### Compute and Visualize Path Metrics

Create a path metrics object.

```
pathMetricsObj = pathmetrics(pthObj,sv);
```

Check path validity. The result is `1 (true)` if the planned path is obstacle free. `0 (false)` indicates an invalid path.

```
isPathValid(pathMetricsObj)
```

```
ans = logical
   1
```

Calculate the minimum clearance of the path.

```
clearance(pathMetricsObj)
```

```
ans = 10
```

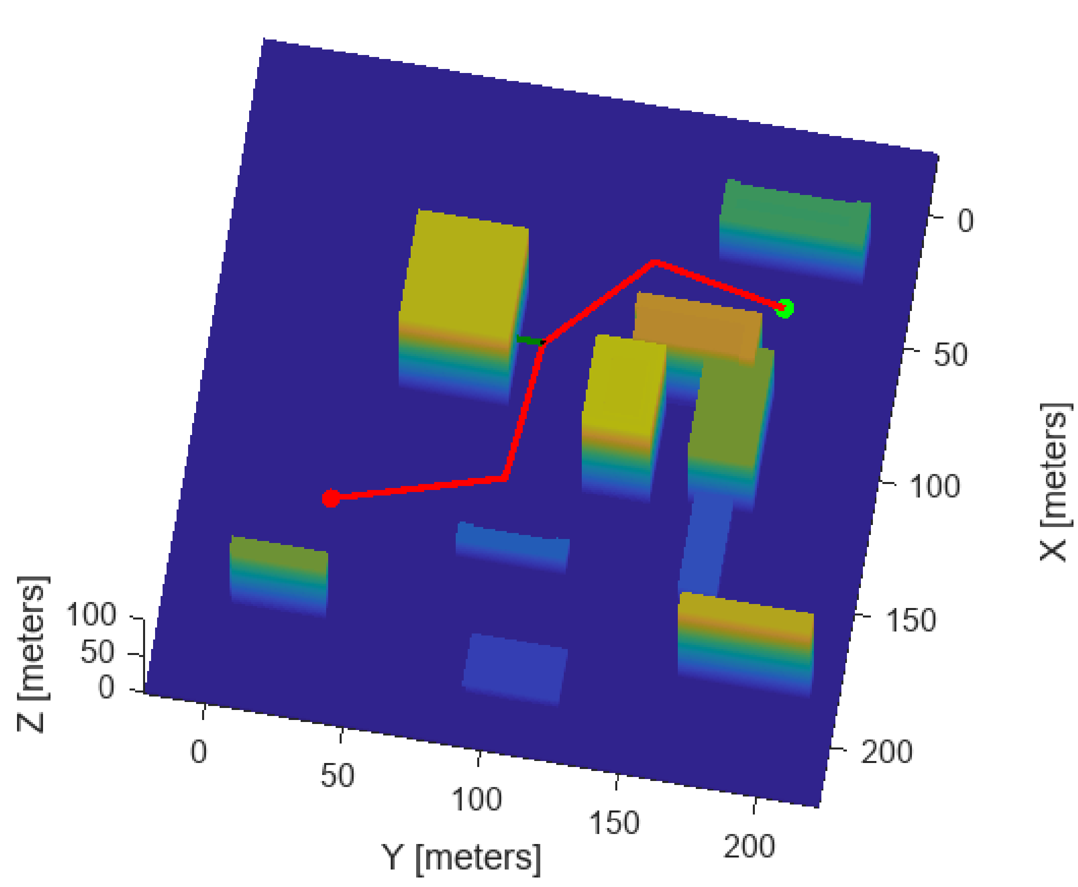
Evaluate the smoothness of the path. Values close to `0` indicate a smoother path. Straight-line paths return a value of `0`.

```
smoothness(pathMetricsObj)
```

```
ans = 0.0011
```

Visualize the minimum clearance of the path.

```
show(pathMetricsObj)
axis equal
view([100 75])
hold on
% Start state
scatter3(start(1,1),start(1,2),start(1,3),"g","filled")
% Goal state
scatter3(goal(1,1),goal(1,2),goal(1,3),"r","filled")
% Path
plot3(pthObj.States(:,1),pthObj.States(:,2),pthObj.States(:,3), ...
      "r-",LineWidth=2)
```




## Input Arguments

**`pathMetricsObj` — Information for path metrics**
`pathmetrics` object

Information for path metrics, specified as a `pathmetrics` object.

## Version History

**Introduced in R2019b**

## See Also

**Objects**
`pathmetrics`

**Functions**
`isPathValid` | `show` | `smoothness`

# isPathValid

Determine if planned path is obstacle free

## Syntax

`isPathValid(pathMetricsObj)`

## Description

`isPathValid(pathMetricsObj)` returns either a logical `1 (true)` if the planned path is obstacle free or a logical `0 (false)` if the path is invalid.

## Examples

### Compute Path Metrics

Compute smoothness, clearance, and validity of a planned path based on a set of poses and the associated map environment.

#### Load and Assign Map to State Validator

Create an occupancy map from an example map and set the map resolution.

```
load exampleMaps.mat; % simpleMap
mapResolution = 1; % cells/meter
map = occupancyMap(simpleMap,mapResolution);
```

Create a Dubins state space.

```
statespace = stateSpaceDubins;
```

Create a state validator based on occupancy map to store the parameters and states in the Dubins state space.

```
statevalidator = validatorOccupancyMap(statespace);
```

Assign the map to the validator.

```
statevalidator.Map = map;
```

Set the validation distance for the validator.

```
statevalidator.ValidationDistance = 0.01;
```

Update the state space bounds to be the same as the map limits.

```
statespace.StateBounds = [map.XWorldLimits;map.YWorldLimits;[-pi pi]];
```

#### Plan Path

Create an RRT* path planner and allow further optimization.

```
planner = plannerRRTStar(statespace,statevalidator);
planner.ContinueAfterGoalReached = true;
```

Reduce the maximum number of iterations and increase the maximum connection distance.

```
planner.MaxIterations = 2500;
planner.MaxConnectionDistance = 0.3;
```

Define start and goal states for the path planner as [*x*, *y*, *theta*] vectors. *x* and *y* are the Cartesian coordinates, and *theta* is the orientation angle.

```
start = [2.5, 2.5, 0]; % [meters, meters, radians]
goal = [22.5, 8.75, 0];
```

Plan a path from the start state to the goal state. The plan function returns a `navPath` object.

```
rng(100,'twister') % repeatable result
[path,solutionInfo] = plan(planner,start,goal);
```

### Compute and Visualize Path Metrics

Create a path metrics object.

```
pathMetricsObj = pathmetrics(path,statevalidator);
```

Check path validity. The result is `1 (true)` if the planned path is obstacle free. `0 (false)` indicates an invalid path.

```
isPathValid(pathMetricsObj)
```

```
ans = logical
   1
```

Calculate the minimum clearance of the path.

```
clearance(pathMetricsObj)
```

```
ans = 1.4142
```

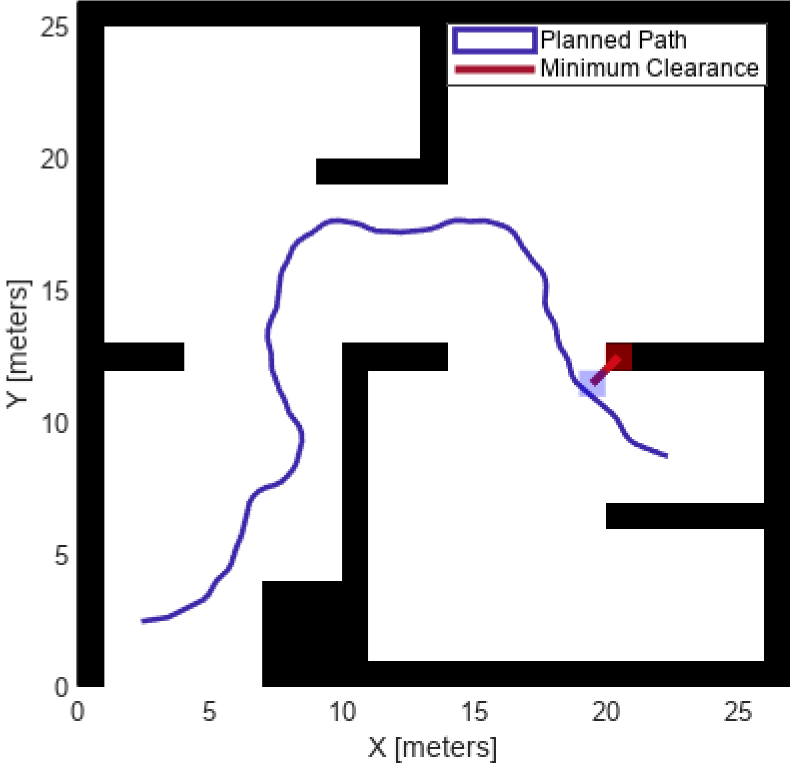
Evaluate the smoothness of the path. Values close to `0` indicate a smoother path. Straight-line paths return a value of `0`.

```
smoothness(pathMetricsObj)
```

```
ans = 1.7318
```

Visualize the minimum clearance of the path.

```
show(pathMetricsObj)
legend('Planned Path','Minimum Clearance')
```



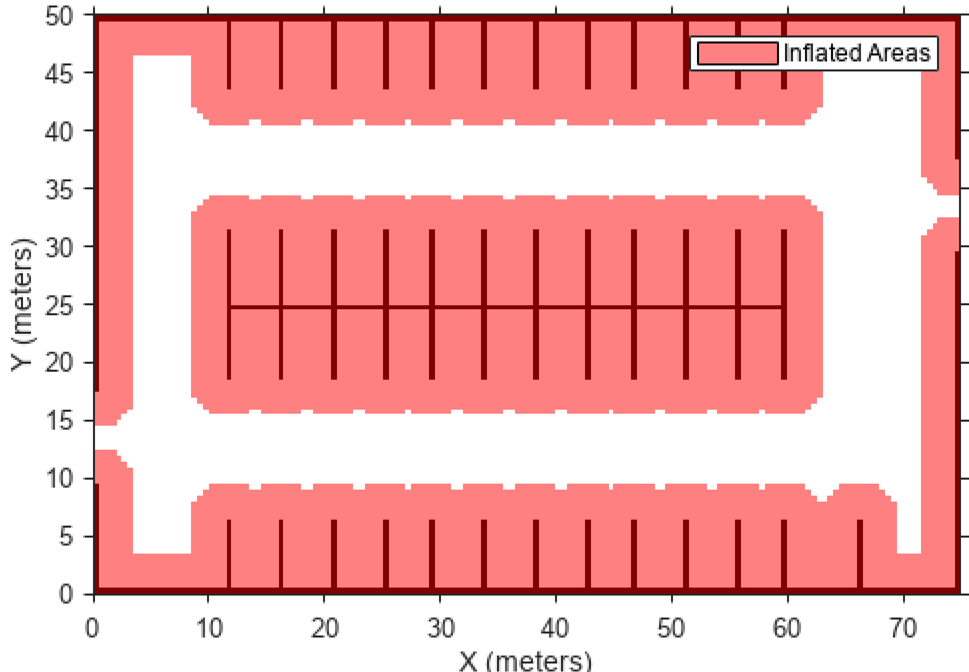

#### Vehicle Path Planning and Metrics Computation in a 2-D Costmap Environment

Plan a vehicle path through a parking lot using the RRT* algorithm. Compute and visualize the smoothness, clearance, and validity of the planned path.

#### Load and Assign Map to State Validator

Load a costmap of a parking lot. Plot the costmap to see the parking lot and the inflated areas that the vehicle should avoid.

```
load parkingLotCostmap.mat;
costmap = parkingLotCostmap;
plot(costmap)
xlabel('X (meters)')
ylabel('Y (meters)')
```




Create a `stateSpaceDubins` object and increase the minimum turing radius to 4 meters.

```
statespace = stateSpaceDubins;
statespace.MinTurningRadius = 4; % meters
```

Create a `validatorVehicleCostmap` object using the created state space.

```
statevalidator = validatorVehicleCostmap(statespace);
```

Assign the parking lot costmap to the state validator object.

```
statevalidator.Map = costmap;
```

**Plan Path**

Define start and goal poses for the vehicle as [*x*, *y*, Θ] vectors. World units for the (*x*,*y*) locations are in meters. World units for the orientation angles Θ are in degrees.

```
startPose = [5, 5, 90]; % [meters, meters, degrees]
goalPose = [40, 38, 180]; % [meters, meters, degrees]
```

Use a `pathPlannerRRT` (Automated Driving Toolbox) object and the `plan` (Automated Driving Toolbox) function to plan the vehicle path from the start pose to the goal pose.

```
planner = pathPlannerRRT(costmap);
refPath = plan(planner,startPose,goalPose);
```

Interpolate along the path at every one meter. Convert the orientation angles from degrees to radians.

```
poses = zeros(size(refPath.PathSegments,2)+1,3);
poses(1,:) = refPath.StartPose;
for i = 1:size(refPath.PathSegments,2)
    poses(i+1,:) = refPath.PathSegments(i).GoalPose;
end
poses(:,3) = deg2rad(poses(:,3));
```

Create a `navPath` object using the Dubins state space object and the states specified by `poses`.

```
path = navPath(statespace,poses);
```

### Compute and Visualize Path Metrics

Create a `pathmetrics` object.

```
pathMetricsObj = pathmetrics(path,statevalidator);
```

Check path validity. The result is `1` (`true`) if the planned path is obstacle free. `0` (`false`) indicates an invalid path.

```
isPathValid(pathMetricsObj)
```

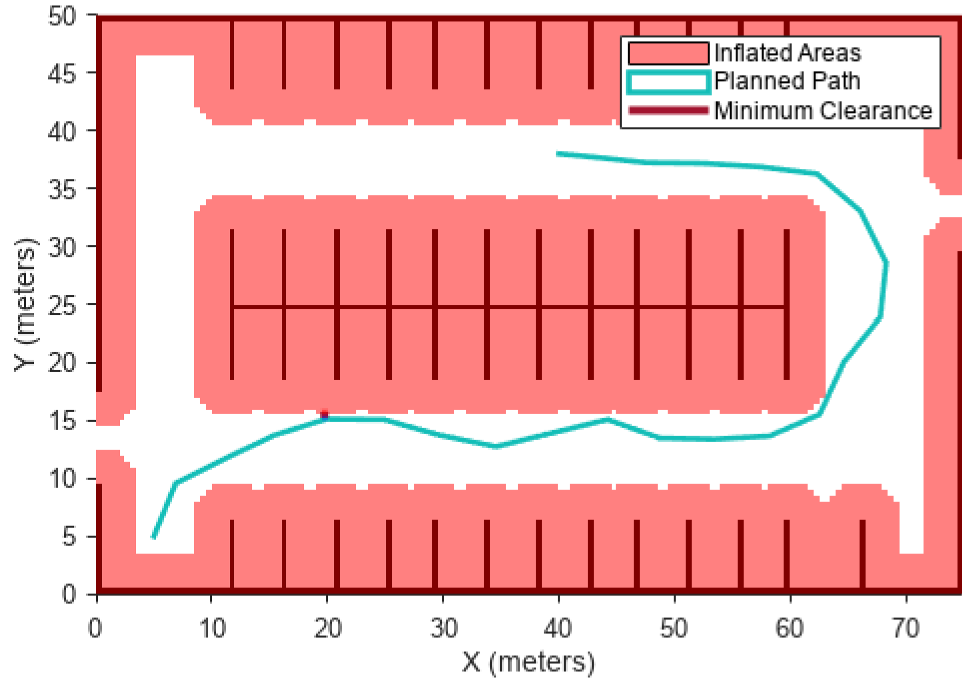
```
ans = logical
   1
```

Compute and visualize the minimum `clearance` of the path.

```
clearance(pathMetricsObj)
```

```
ans = 0.5000
```

```
show(pathMetricsObj)
legend('Inflated Areas','Planned Path','Minimum Clearance')
xlabel('X (meters)')
ylabel('Y (meters)')
```

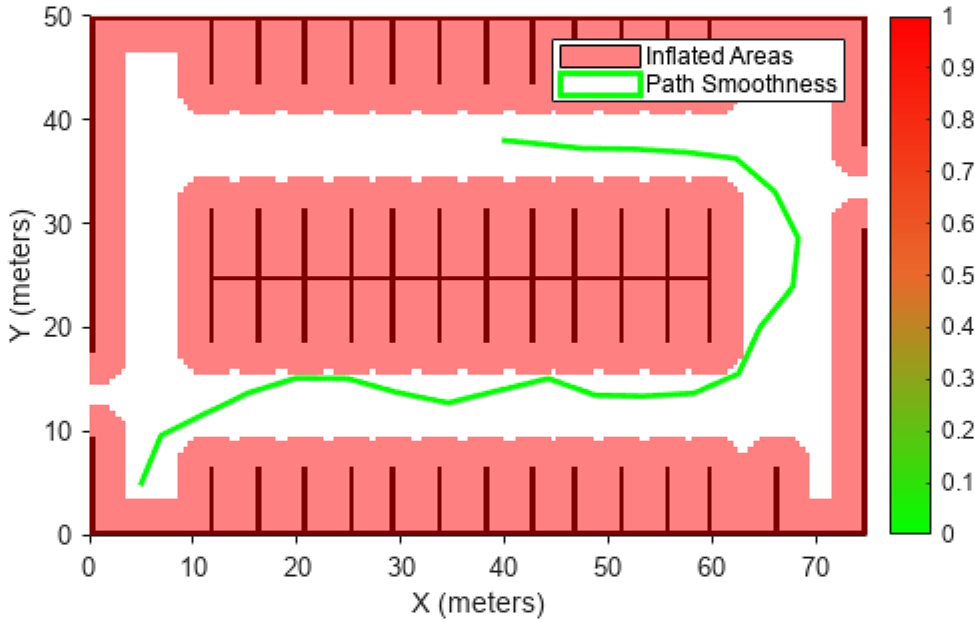



Compute and visualize the `smoothness` of the path. Values close to `0` indicate a smoother path. Straight-line paths return a value of `0`.

```
smoothness(pathMetricsObj)
```

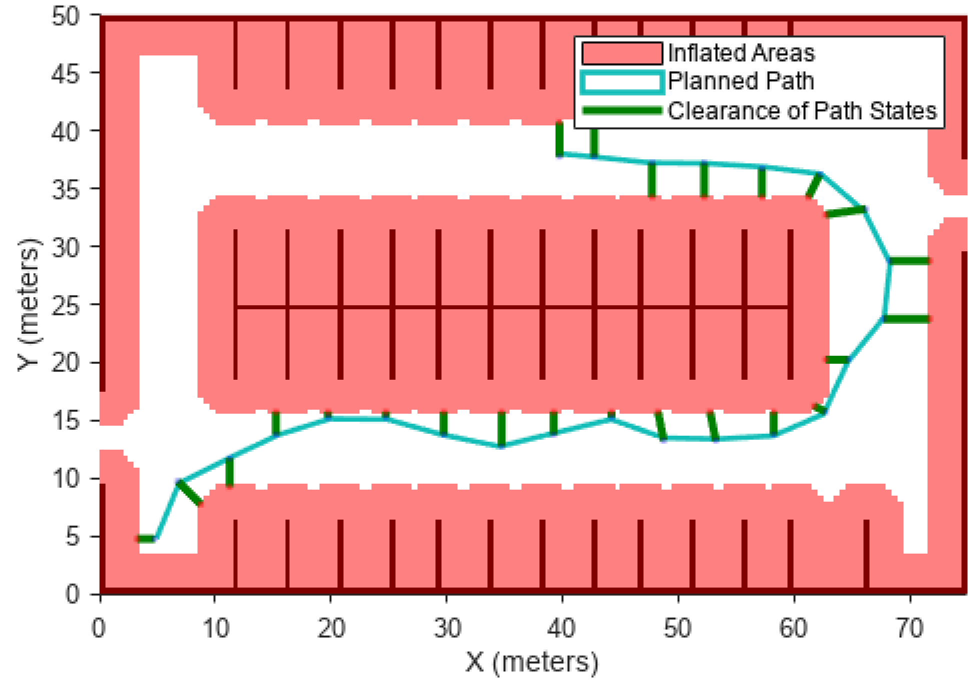
```
ans = 0.0842
```

```
show(pathMetricsObj,'Metrics',{'Smoothness'})
legend('Inflated Areas','Path Smoothness')
xlabel('X (meters)')
ylabel('Y (meters)')
```




Visualize the clearance for each state of the path.

```
show(pathMetricsObj,'Metrics',{'StatesClearance'})
legend('Inflated Areas','Planned Path','Clearance of Path States')
xlabel('X (meters)')
ylabel('Y (meters)')
```




**Path Planning and Metrics Computation in 3-D Environment**

Plan a path through a city block using the RRT algorithm. Compute and visualize the smoothness, clearance, and validity of the planned path.

**Load and Assign Map to State Validator**

Load a 3-D occupancy map of a city block into the workspace. Specify the threshold to consider cells as obstacle-free.

```
mapData = load("dMapCityBlock.mat");
omap = mapData.omap;
omap.FreeThreshold = 0.5;
```

Inflate the occupancy map to add a buffer zone for safe operation around the obstacles.

```
inflate(omap,1)
```

Create an SE(3) state space object with bounds for state variables.

```
ss = stateSpaceSE3([0 220;0 220;0 100;inf inf;inf inf;inf inf;inf inf]);
```

Create a 3-D occupancy map state validator using the created state space. Assign the occupancy map to the state validator object. Specify the sampling distance interval.

```
sv = validatorOccupancyMap3D(ss, ...
     Map = omap, ...
     ValidationDistance = 0.1);
```

#### Plan Path

Create a RRT path planner with increased maximum connection distance and reduced maximum number of iterations. Specify a custom goal function that determines that a path reaches the goal if the Euclidean distance to the target is below a threshold of 1 meter.

```
planner = plannerRRT(ss,sv, ...
          MaxConnectionDistance = 50, ...
          MaxIterations = 1000, ...
          GoalReachedFcn = @(~,s,g)(norm(s(1:3)-g(1:3))<1), ...
          GoalBias = 0.1);
```

Specify start and goal poses.

```
start = [50 180 25 0.7 0.2 0 0.1];
goal = [150 33 35 0.3 0 0.1 0.6];
```

Configure the random number generator for repeatable result.

```
rng(1,"twister")
```

Plan the path.

```
[pthObj,solnInfo] = plan(planner,start,goal);
```

#### Compute and Visualize Path Metrics

Create a path metrics object.

```
pathMetricsObj = pathmetrics(pthObj,sv);
```

Check path validity. The result is `1 (true)` if the planned path is obstacle free. `0 (false)` indicates an invalid path.

```
isPathValid(pathMetricsObj)
```

```
ans = logical
   1
```

Calculate the minimum clearance of the path.

```
clearance(pathMetricsObj)
```

```
ans = 10
```

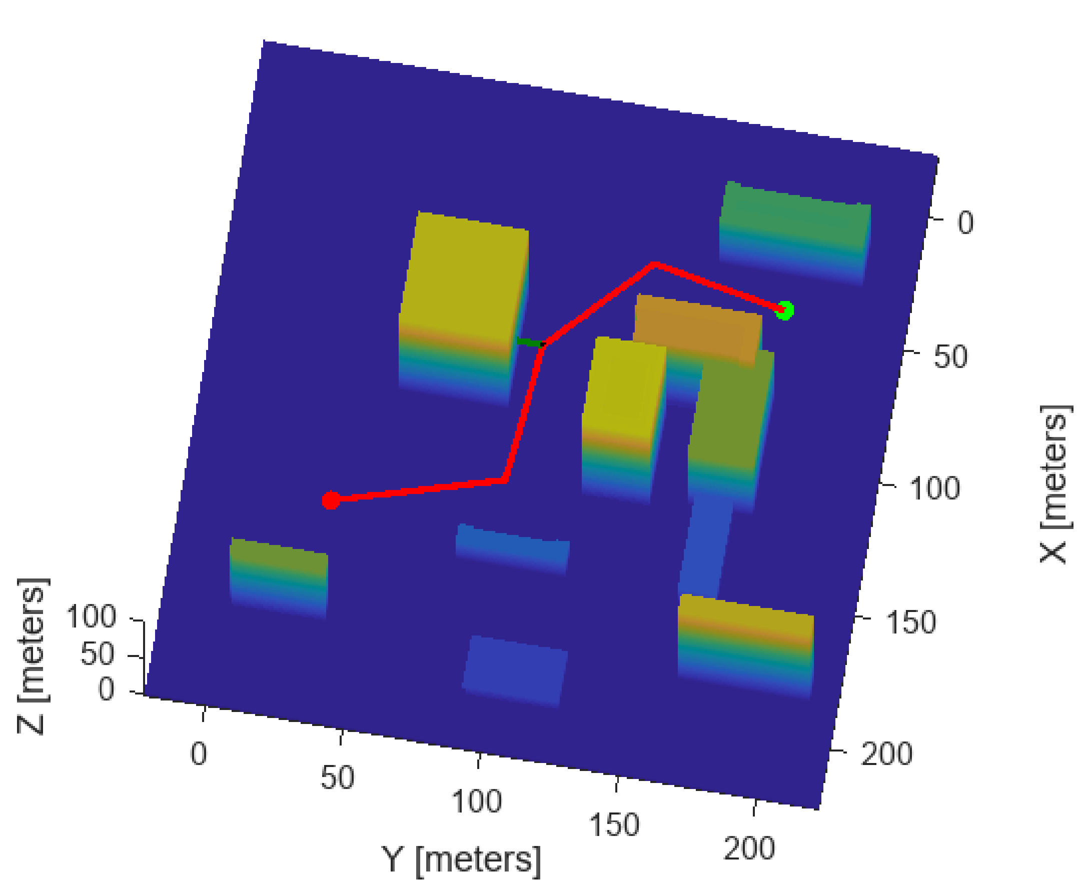
Evaluate the smoothness of the path. Values close to `0` indicate a smoother path. Straight-line paths return a value of `0`.

```
smoothness(pathMetricsObj)
```

```
ans = 0.0011
```

Visualize the minimum clearance of the path.

```
show(pathMetricsObj)
axis equal
view([100 75])
hold on
% Start state
scatter3(start(1,1),start(1,2),start(1,3),"g","filled")
% Goal state
scatter3(goal(1,1),goal(1,2),goal(1,3),"r","filled")
% Path
plot3(pthObj.States(:,1),pthObj.States(:,2),pthObj.States(:,3), ...
      "r-",LineWidth=2)
```




## Input Arguments

**pathMetricsObj — Information for path metrics**
pathmetrics object

Information for path metrics, specified as a `pathmetrics` object.

## Version History

**Introduced in R2019b**

## See Also

**Objects**
`pathmetrics`

**Functions**
`clearance` | `show` | `smoothness`

# show

Visualize path metrics in map environment

## Syntax

```
show(pathMetricsObj)
show(pathMetricsObj,Name,Value)
axHandle = show(pathMetricsObj)
```

## Description

`show(pathMetricsObj)` plots the path in the map environment with the minimum clearance.

`show(pathMetricsObj,Name,Value)` specifies additional options using one or more name-value pair arguments.

`axHandle = show(pathMetricsObj)` outputs the axes handle of the figure used to plot the path.

## Examples

### Compute Path Metrics

Compute smoothness, clearance, and validity of a planned path based on a set of poses and the associated map environment.

#### Load and Assign Map to State Validator

Create an occupancy map from an example map and set the map resolution.

```
load exampleMaps.mat; % simpleMap
mapResolution = 1; % cells/meter
map = occupancyMap(simpleMap,mapResolution);
```

Create a Dubins state space.

```
statespace = stateSpaceDubins;
```

Create a state validator based on occupancy map to store the parameters and states in the Dubins state space.

```
statevalidator = validatorOccupancyMap(statespace);
```

Assign the map to the validator.

```
statevalidator.Map = map;
```

Set the validation distance for the validator.

```
statevalidator.ValidationDistance = 0.01;
```

Update the state space bounds to be the same as the map limits.

```
statespace.StateBounds = [map.XWorldLimits;map.YWorldLimits;[-pi pi]];
```

### Plan Path

Create an RRT* path planner and allow further optimization.

```
planner = plannerRRTStar(statespace,statevalidator);
planner.ContinueAfterGoalReached = true;
```

Reduce the maximum number of iterations and increase the maximum connection distance.

```
planner.MaxIterations = 2500;
planner.MaxConnectionDistance = 0.3;
```

Define start and goal states for the path planner as `[`*x, y, theta*`]` vectors. *x* and *y* are the Cartesian coordinates, and *theta* is the orientation angle.

```
start = [2.5, 2.5, 0]; % [meters, meters, radians]
goal = [22.5, 8.75, 0];
```

Plan a path from the start state to the goal state. The plan function returns a `navPath` object.

```
rng(100,'twister') % repeatable result
[path,solutionInfo] = plan(planner,start,goal);
```

### Compute and Visualize Path Metrics

Create a path metrics object.

```
pathMetricsObj = pathmetrics(path,statevalidator);
```

Check path validity. The result is `1 (true)` if the planned path is obstacle free. `0 (false)` indicates an invalid path.

```
isPathValid(pathMetricsObj)
```

```
ans = logical
   1
```

Calculate the minimum clearance of the path.

```
clearance(pathMetricsObj)
```

```
ans = 1.4142
```

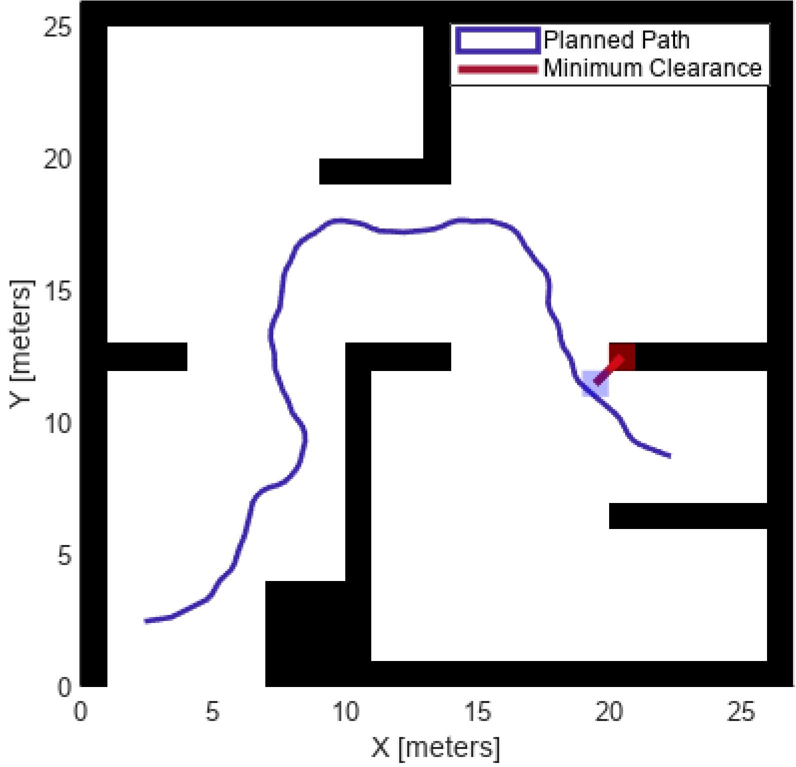
Evaluate the smoothness of the path. Values close to `0` indicate a smoother path. Straight-line paths return a value of `0`.

```
smoothness(pathMetricsObj)
```

```
ans = 1.7318
```

Visualize the minimum clearance of the path.

```
show(pathMetricsObj)
legend('Planned Path','Minimum Clearance')
```



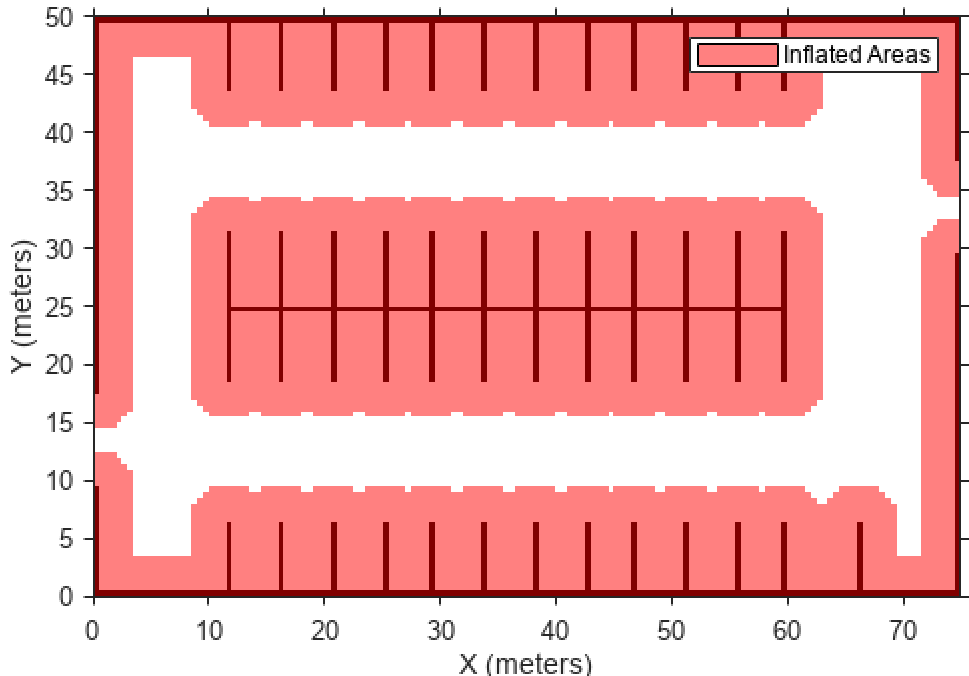

### Vehicle Path Planning and Metrics Computation in a 2-D Costmap Environment

Plan a vehicle path through a parking lot using the RRT* algorithm. Compute and visualize the smoothness, clearance, and validity of the planned path.

#### Load and Assign Map to State Validator

Load a costmap of a parking lot. Plot the costmap to see the parking lot and the inflated areas that the vehicle should avoid.

```
load parkingLotCostmap.mat;
costmap = parkingLotCostmap;
plot(costmap)
xlabel('X (meters)')
ylabel('Y (meters)')
```




Create a `stateSpaceDubins` object and increase the minimum turing radius to 4 meters.

```
statespace = stateSpaceDubins;
statespace.MinTurningRadius = 4; % meters
```

Create a `validatorVehicleCostmap` object using the created state space.

```
statevalidator = validatorVehicleCostmap(statespace);
```

Assign the parking lot costmap to the state validator object.

```
statevalidator.Map = costmap;
```

**Plan Path**

Define start and goal poses for the vehicle as [*x*, *y*, Θ] vectors. World units for the (*x*,*y*) locations are in meters. World units for the orientation angles Θ are in degrees.

```
startPose = [5, 5, 90]; % [meters, meters, degrees]
goalPose = [40, 38, 180]; % [meters, meters, degrees]
```

Use a `pathPlannerRRT` (Automated Driving Toolbox) object and the `plan` (Automated Driving Toolbox) function to plan the vehicle path from the start pose to the goal pose.

```
planner = pathPlannerRRT(costmap);
refPath = plan(planner,startPose,goalPose);
```

Interpolate along the path at every one meter. Convert the orientation angles from degrees to radians.

```
poses = zeros(size(refPath.PathSegments,2)+1,3);
poses(1,:) = refPath.StartPose;
for i = 1:size(refPath.PathSegments,2)
    poses(i+1,:) = refPath.PathSegments(i).GoalPose;
end
poses(:,3) = deg2rad(poses(:,3));
```

Create a `navPath` object using the Dubins state space object and the states specified by `poses`.

```
path = navPath(statespace,poses);
```

#### Compute and Visualize Path Metrics

Create a `pathmetrics` object.

```
pathMetricsObj = pathmetrics(path,statevalidator);
```

Check path validity. The result is `1` (`true`) if the planned path is obstacle free. `0` (`false`) indicates an invalid path.

```
isPathValid(pathMetricsObj)
```

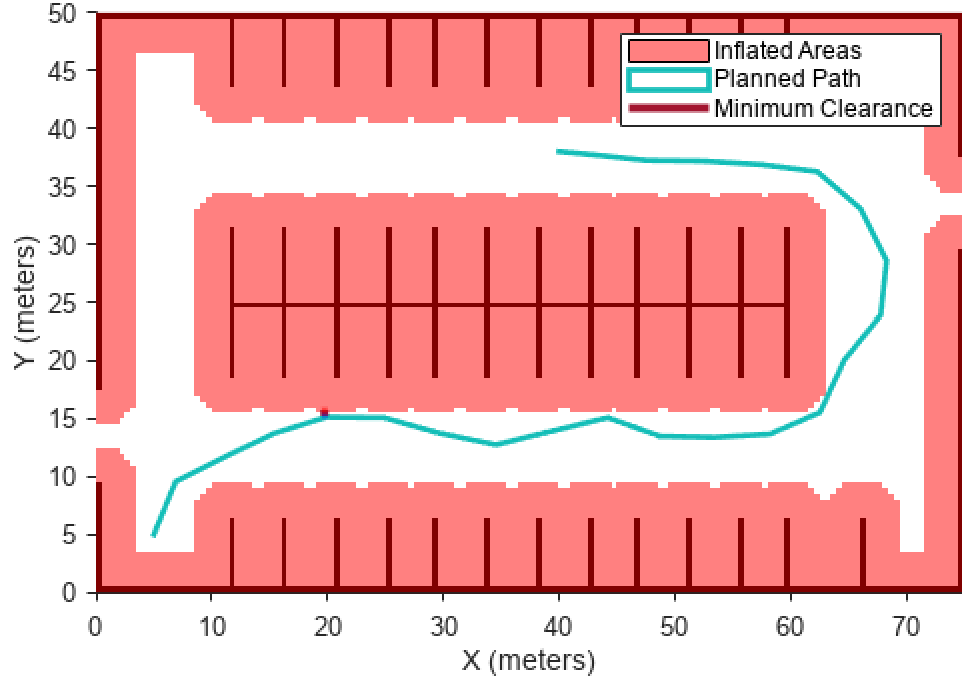
```
ans = logical
   1
```

Compute and visualize the minimum `clearance` of the path.

```
clearance(pathMetricsObj)
```

```
ans = 0.5000
```

```
show(pathMetricsObj)
legend('Inflated Areas','Planned Path','Minimum Clearance')
xlabel('X (meters)')
ylabel('Y (meters)')
```

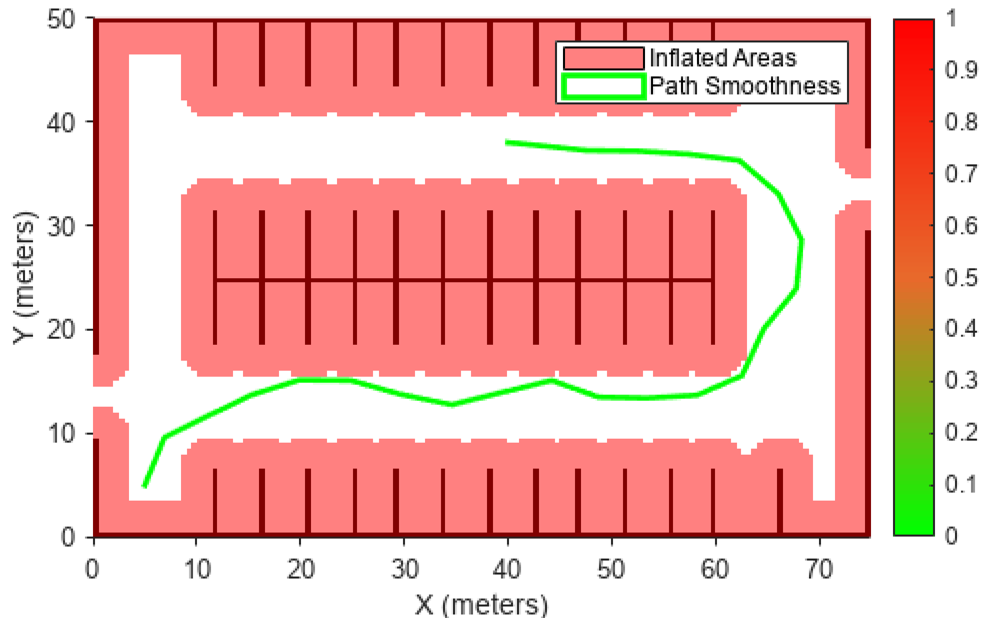



Compute and visualize the `smoothness` of the path. Values close to `0` indicate a smoother path. Straight-line paths return a value of `0`.

```
smoothness(pathMetricsObj)
```

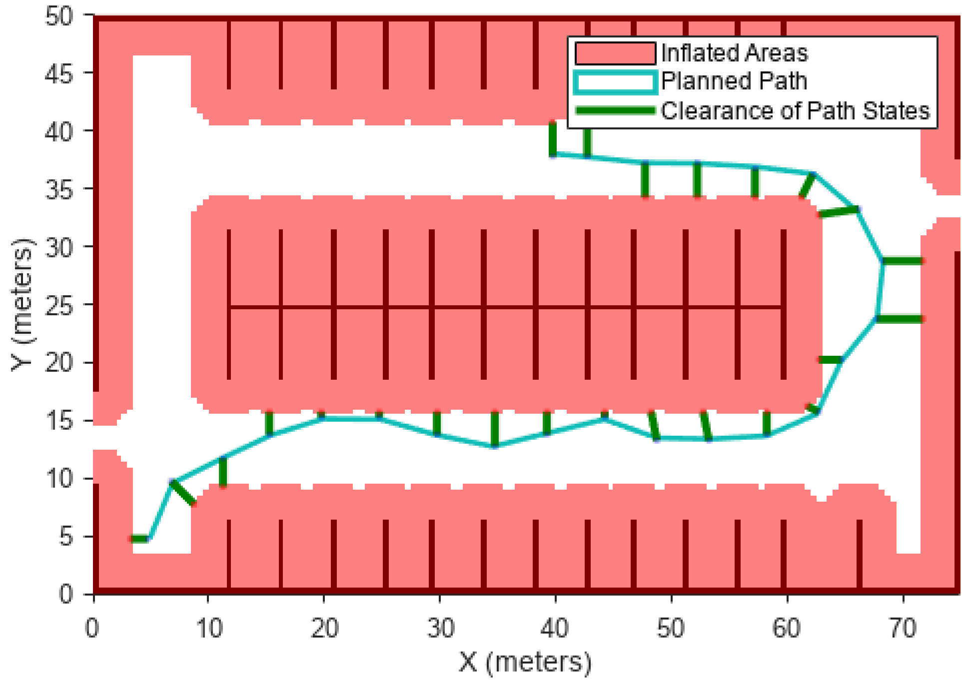
```
ans = 0.0842
```

```
show(pathMetricsObj,'Metrics',{'Smoothness'})
legend('Inflated Areas','Path Smoothness')
xlabel('X (meters)')
ylabel('Y (meters)')
```




Visualize the clearance for each state of the path.

```
show(pathMetricsObj,'Metrics',{'StatesClearance'})
legend('Inflated Areas','Planned Path','Clearance of Path States')
xlabel('X (meters)')
ylabel('Y (meters)')
```




**Path Planning and Metrics Computation in 3-D Environment**

Plan a path through a city block using the RRT algorithm. Compute and visualize the smoothness, clearance, and validity of the planned path.

**Load and Assign Map to State Validator**

Load a 3-D occupancy map of a city block into the workspace. Specify the threshold to consider cells as obstacle-free.

```
mapData = load("dMapCityBlock.mat");
omap = mapData.omap;
omap.FreeThreshold = 0.5;
```

Inflate the occupancy map to add a buffer zone for safe operation around the obstacles.

```
inflate(omap,1)
```

Create an SE(3) state space object with bounds for state variables.

```
ss = stateSpaceSE3([0 220;0 220;0 100;inf inf;inf inf;inf inf;inf inf]);
```

Create a 3-D occupancy map state validator using the created state space. Assign the occupancy map to the state validator object. Specify the sampling distance interval.

```
sv = validatorOccupancyMap3D(ss, ...
     Map = omap, ...
     ValidationDistance = 0.1);
```

**Plan Path**

Create a RRT path planner with increased maximum connection distance and reduced maximum number of iterations. Specify a custom goal function that determines that a path reaches the goal if the Euclidean distance to the target is below a threshold of 1 meter.

```
planner = plannerRRT(ss,sv, ...
          MaxConnectionDistance = 50, ...
          MaxIterations = 1000, ...
          GoalReachedFcn = @(~,s,g)(norm(s(1:3)-g(1:3))<1), ...
          GoalBias = 0.1);
```

Specify start and goal poses.

```
start = [50 180 25 0.7 0.2 0 0.1];
goal = [150 33 35 0.3 0 0.1 0.6];
```

Configure the random number generator for repeatable result.

```
rng(1,"twister")
```

Plan the path.

```
[pthObj,solnInfo] = plan(planner,start,goal);
```

**Compute and Visualize Path Metrics**

Create a path metrics object.

```
pathMetricsObj = pathmetrics(pthObj,sv);
```

Check path validity. The result is `1 (true)` if the planned path is obstacle free. `0 (false)` indicates an invalid path.

```
isPathValid(pathMetricsObj)
```

```
ans = logical
   1
```

Calculate the minimum clearance of the path.

```
clearance(pathMetricsObj)
```

```
ans = 10
```

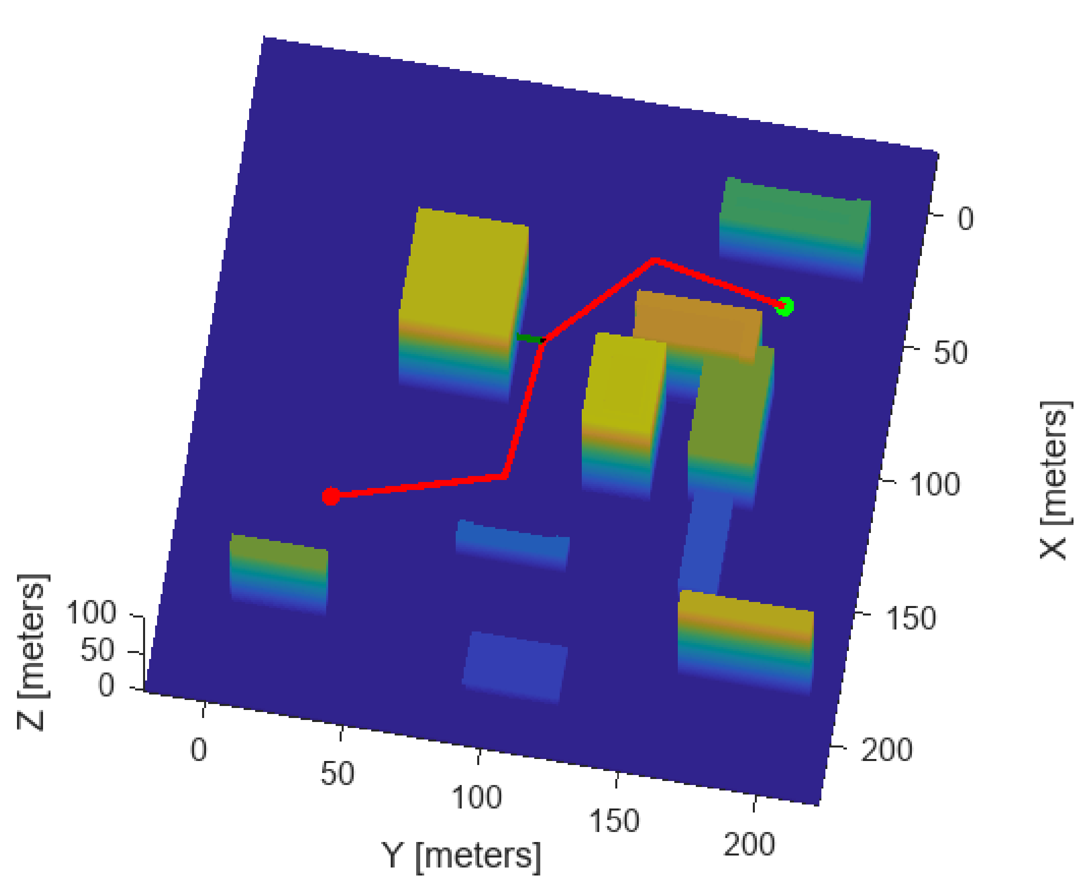
Evaluate the smoothness of the path. Values close to `0` indicate a smoother path. Straight-line paths return a value of `0`.

```
smoothness(pathMetricsObj)
```

```
ans = 0.0011
```

Visualize the minimum clearance of the path.

```
show(pathMetricsObj)
axis equal
view([100 75])
hold on
% Start state
scatter3(start(1,1),start(1,2),start(1,3),"g","filled")
% Goal state
scatter3(goal(1,1),goal(1,2),goal(1,3),"r","filled")
% Path
plot3(pthObj.States(:,1),pthObj.States(:,2),pthObj.States(:,3), ...
      "r-",LineWidth=2)
```




## Input Arguments

**`pathMetricsObj` — Information for path metrics**
`pathmetrics` object

Information for path metrics, specified as a `pathmetrics` object.

#### Name-Value Pair Arguments

Specify optional pairs of arguments as `Name1=Value1,...,NameN=ValueN`, where `Name` is the argument name and `Value` is the corresponding value. Name-value arguments must appear after other arguments, but the order of the pairs does not matter.

*Before R2021a, use commas to separate each name and value, and enclose* `Name` *in quotes.*

Example: `'Parent',axHandle`

**`Parent` — Axes used to plot path**
`Axes` object | `UIAxes` object

Axes used to plot path, specified as the comma-separated pair consisting of `'Parent'` and either an `axes` or `uiaxes` object. If you do not specify `Parent`, a new figure is created.

Example: `show(pathMetricsObj,'Parent',axHandle)`

**`Metrics` — Display metrics option**
`"MinClearance"` (default) | string | cell array of strings

Display metrics option, specified as the comma-separated pair consisting of `'Metrics'` and a string or cell array with any combination of these values:

- `"MinClearance"` — Display minimum clearance of path.
- `"StatesClearance"` — Display clearance of path states.
- `"Smoothness"` — Display path smoothness.

Example: `show(pathMetricsObj,'Metrics',"Smoothness")`

Example: `show(pathMetricsObj,'Metrics',{"Smoothness","StatesClearance"})`

Data Types: `cell` | `string`

### Output Arguments

**`axHandle` — Axes used to plot path**
`Axes` object | `UIAxes` object

Axes used to plot path, returned as either an `axes` or `uiaxes` object.

## Version History

**Introduced in R2019b**

### See Also

**Objects**
`pathmetrics`

**Functions**
`clearance` | `isPathValid` | `smoothness`

# smoothness

Smoothness of path

## Syntax

```
smoothness(pathMetricsObj)
smoothness(pathMetricsObj,'Type','segments')
```

## Description

`smoothness(pathMetricsObj)` evaluates the smoothness of the planned path. Values close to `0` indicate a smoother path. Straight-line paths return a value of `0`.

`smoothness(pathMetricsObj,'Type','segments')` returns individual smoothness calculations between each set of three poses on the path, in the form of a ($n$–2)-element vector, where $n$ is the number of poses.

## Examples

### Compute Path Metrics

Compute smoothness, clearance, and validity of a planned path based on a set of poses and the associated map environment.

#### Load and Assign Map to State Validator

Create an occupancy map from an example map and set the map resolution.

```
load exampleMaps.mat; % simpleMap
mapResolution = 1; % cells/meter
map = occupancyMap(simpleMap,mapResolution);
```

Create a Dubins state space.

```
statespace = stateSpaceDubins;
```

Create a state validator based on occupancy map to store the parameters and states in the Dubins state space.

```
statevalidator = validatorOccupancyMap(statespace);
```

Assign the map to the validator.

```
statevalidator.Map = map;
```

Set the validation distance for the validator.

```
statevalidator.ValidationDistance = 0.01;
```

Update the state space bounds to be the same as the map limits.

```
statespace.StateBounds = [map.XWorldLimits;map.YWorldLimits;[-pi pi]];
```

#### Plan Path

Create an RRT* path planner and allow further optimization.

```
planner = plannerRRTStar(statespace,statevalidator);
planner.ContinueAfterGoalReached = true;
```

Reduce the maximum number of iterations and increase the maximum connection distance.

```
planner.MaxIterations = 2500;
planner.MaxConnectionDistance = 0.3;
```

Define start and goal states for the path planner as [*x*, *y*, *theta*] vectors. *x* and *y* are the Cartesian coordinates, and *theta* is the orientation angle.

```
start = [2.5, 2.5, 0]; % [meters, meters, radians]
goal = [22.5, 8.75, 0];
```

Plan a path from the start state to the goal state. The plan function returns a `navPath` object.

```
rng(100,'twister') % repeatable result
[path,solutionInfo] = plan(planner,start,goal);
```

#### Compute and Visualize Path Metrics

Create a path metrics object.

```
pathMetricsObj = pathmetrics(path,statevalidator);
```

Check path validity. The result is `1 (true)` if the planned path is obstacle free. `0 (false)` indicates an invalid path.

```
isPathValid(pathMetricsObj)
```

```
ans = logical
   1
```

Calculate the minimum clearance of the path.

```
clearance(pathMetricsObj)
```

```
ans = 1.4142
```

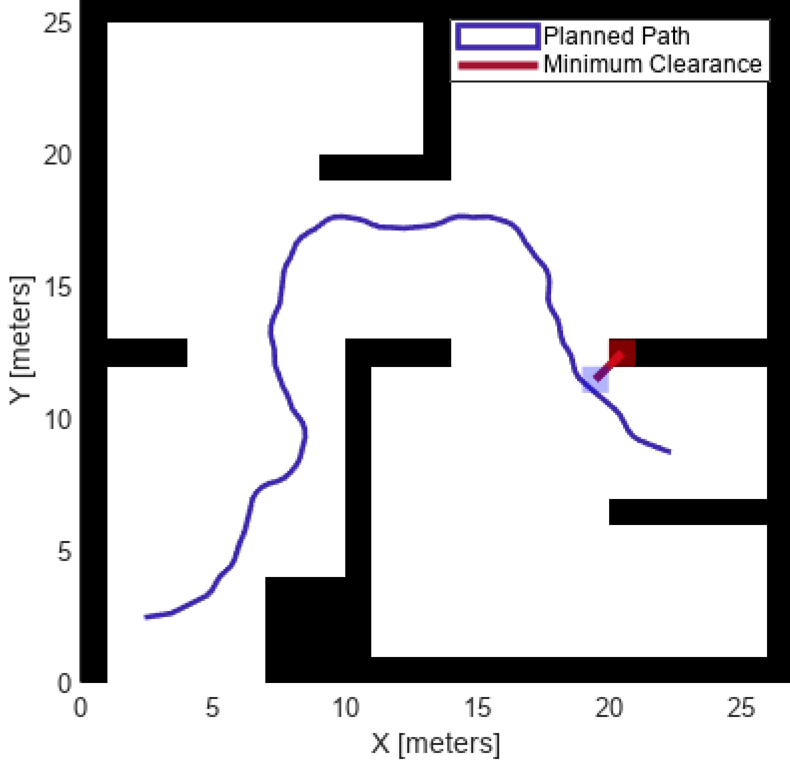
Evaluate the smoothness of the path. Values close to `0` indicate a smoother path. Straight-line paths return a value of `0`.

```
smoothness(pathMetricsObj)
```

```
ans = 1.7318
```

Visualize the minimum clearance of the path.

```
show(pathMetricsObj)
legend('Planned Path','Minimum Clearance')
```



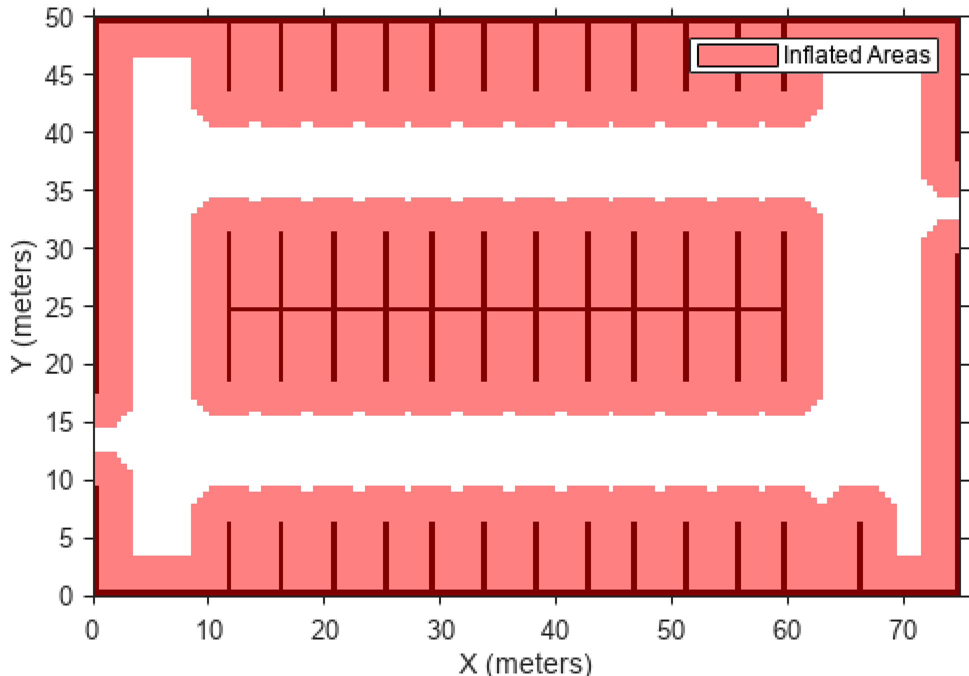

#### Vehicle Path Planning and Metrics Computation in a 2-D Costmap Environment

Plan a vehicle path through a parking lot using the RRT* algorithm. Compute and visualize the smoothness, clearance, and validity of the planned path.

#### Load and Assign Map to State Validator

Load a costmap of a parking lot. Plot the costmap to see the parking lot and the inflated areas that the vehicle should avoid.

```
load parkingLotCostmap.mat;
costmap = parkingLotCostmap;
plot(costmap)
xlabel('X (meters)')
ylabel('Y (meters)')
```




Create a `stateSpaceDubins` object and increase the minimum turing radius to 4 meters.

```
statespace = stateSpaceDubins;
statespace.MinTurningRadius = 4; % meters
```

Create a `validatorVehicleCostmap` object using the created state space.

```
statevalidator = validatorVehicleCostmap(statespace);
```

Assign the parking lot costmap to the state validator object.

```
statevalidator.Map = costmap;
```

**Plan Path**

Define start and goal poses for the vehicle as [*x*, *y*, Θ] vectors. World units for the (*x*,*y*) locations are in meters. World units for the orientation angles Θ are in degrees.

```
startPose = [5, 5, 90]; % [meters, meters, degrees]
goalPose = [40, 38, 180]; % [meters, meters, degrees]
```

Use a `pathPlannerRRT` (Automated Driving Toolbox) object and the `plan` (Automated Driving Toolbox) function to plan the vehicle path from the start pose to the goal pose.

```
planner = pathPlannerRRT(costmap);
refPath = plan(planner,startPose,goalPose);
```

Interpolate along the path at every one meter. Convert the orientation angles from degrees to radians.

```
poses = zeros(size(refPath.PathSegments,2)+1,3);
poses(1,:) = refPath.StartPose;
for i = 1:size(refPath.PathSegments,2)
    poses(i+1,:) = refPath.PathSegments(i).GoalPose;
end
poses(:,3) = deg2rad(poses(:,3));
```

Create a `navPath` object using the Dubins state space object and the states specified by `poses`.

```
path = navPath(statespace,poses);
```

**Compute and Visualize Path Metrics**

Create a `pathmetrics` object.

```
pathMetricsObj = pathmetrics(path,statevalidator);
```

Check path validity. The result is `1` (`true`) if the planned path is obstacle free. `0` (`false`) indicates an invalid path.

```
isPathValid(pathMetricsObj)
```

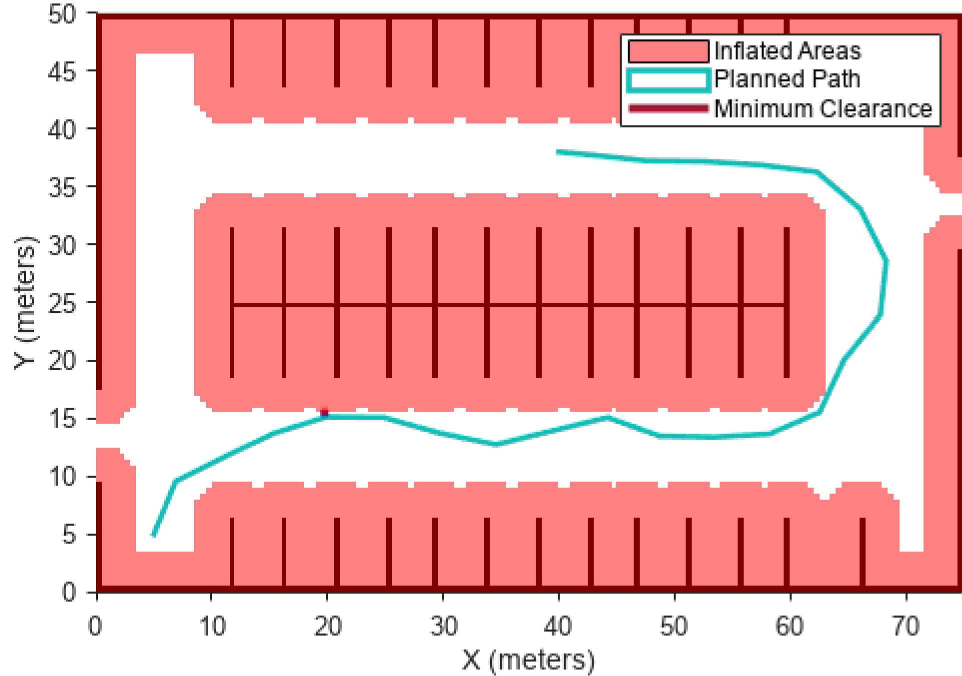
```
ans = logical
   1
```

Compute and visualize the minimum `clearance` of the path.

```
clearance(pathMetricsObj)
```

```
ans = 0.5000
```

```
show(pathMetricsObj)
legend('Inflated Areas','Planned Path','Minimum Clearance')
xlabel('X (meters)')
ylabel('Y (meters)')
```

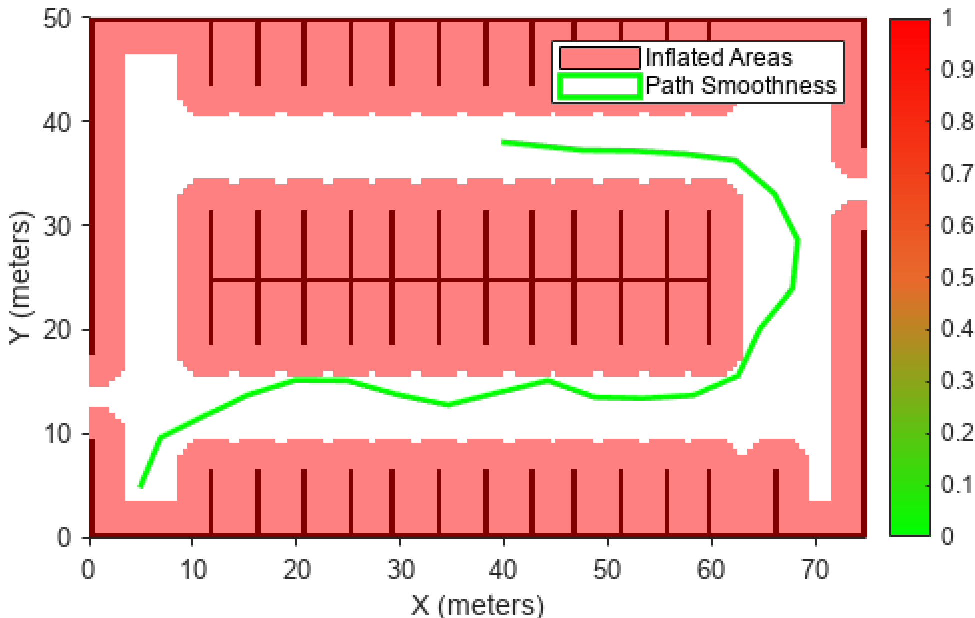



Compute and visualize the `smoothness` of the path. Values close to `0` indicate a smoother path. Straight-line paths return a value of `0`.

```
smoothness(pathMetricsObj)
```

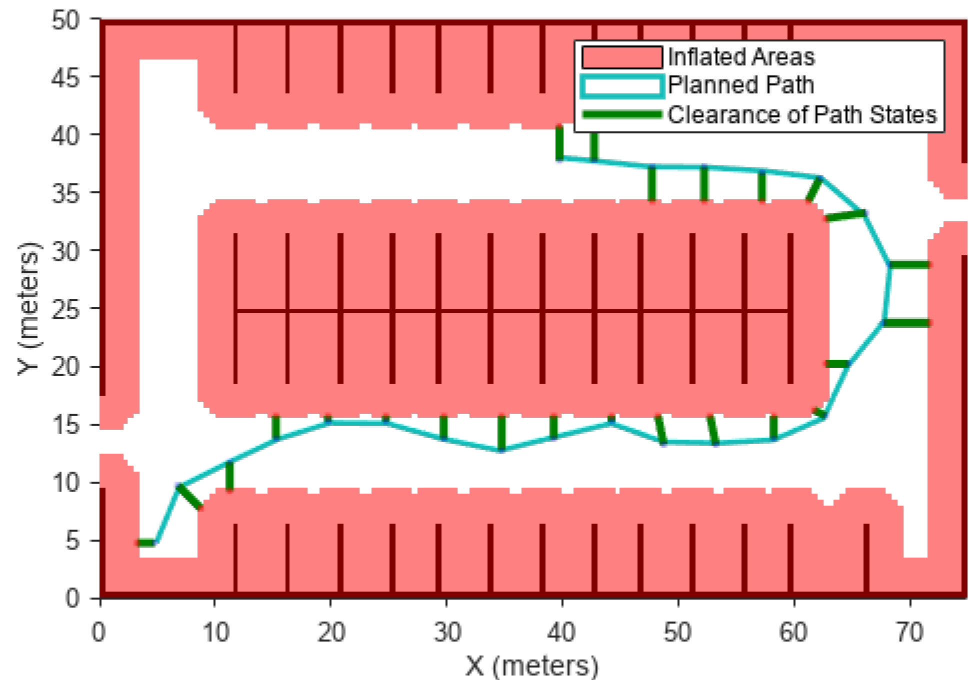
```
ans = 0.0842
```

```
show(pathMetricsObj,'Metrics',{'Smoothness'})
legend('Inflated Areas','Path Smoothness')
xlabel('X (meters)')
ylabel('Y (meters)')
```




Visualize the clearance for each state of the path.

```
show(pathMetricsObj,'Metrics',{'StatesClearance'})
legend('Inflated Areas','Planned Path','Clearance of Path States')
xlabel('X (meters)')
ylabel('Y (meters)')
```




**Path Planning and Metrics Computation in 3-D Environment**

Plan a path through a city block using the RRT algorithm. Compute and visualize the smoothness, clearance, and validity of the planned path.

**Load and Assign Map to State Validator**

Load a 3-D occupancy map of a city block into the workspace. Specify the threshold to consider cells as obstacle-free.

```
mapData = load("dMapCityBlock.mat");
omap = mapData.omap;
omap.FreeThreshold = 0.5;
```

Inflate the occupancy map to add a buffer zone for safe operation around the obstacles.

```
inflate(omap,1)
```

Create an SE(3) state space object with bounds for state variables.

```
ss = stateSpaceSE3([0 220;0 220;0 100;inf inf;inf inf;inf inf;inf inf]);
```

Create a 3-D occupancy map state validator using the created state space. Assign the occupancy map to the state validator object. Specify the sampling distance interval.

```
sv = validatorOccupancyMap3D(ss, ...
     Map = omap, ...
     ValidationDistance = 0.1);
```

#### Plan Path

Create a RRT path planner with increased maximum connection distance and reduced maximum number of iterations. Specify a custom goal function that determines that a path reaches the goal if the Euclidean distance to the target is below a threshold of 1 meter.

```
planner = plannerRRT(ss,sv, ...
          MaxConnectionDistance = 50, ...
          MaxIterations = 1000, ...
          GoalReachedFcn = @(~,s,g)(norm(s(1:3)-g(1:3))<1), ...
          GoalBias = 0.1);
```

Specify start and goal poses.

```
start = [50 180 25 0.7 0.2 0 0.1];
goal = [150 33 35 0.3 0 0.1 0.6];
```

Configure the random number generator for repeatable result.

```
rng(1,"twister")
```

Plan the path.

```
[pthObj,solnInfo] = plan(planner,start,goal);
```

#### Compute and Visualize Path Metrics

Create a path metrics object.

```
pathMetricsObj = pathmetrics(pthObj,sv);
```

Check path validity. The result is `1 (true)` if the planned path is obstacle free. `0 (false)` indicates an invalid path.

```
isPathValid(pathMetricsObj)
```

```
ans = logical
   1
```

Calculate the minimum clearance of the path.

```
clearance(pathMetricsObj)
```

```
ans = 10
```

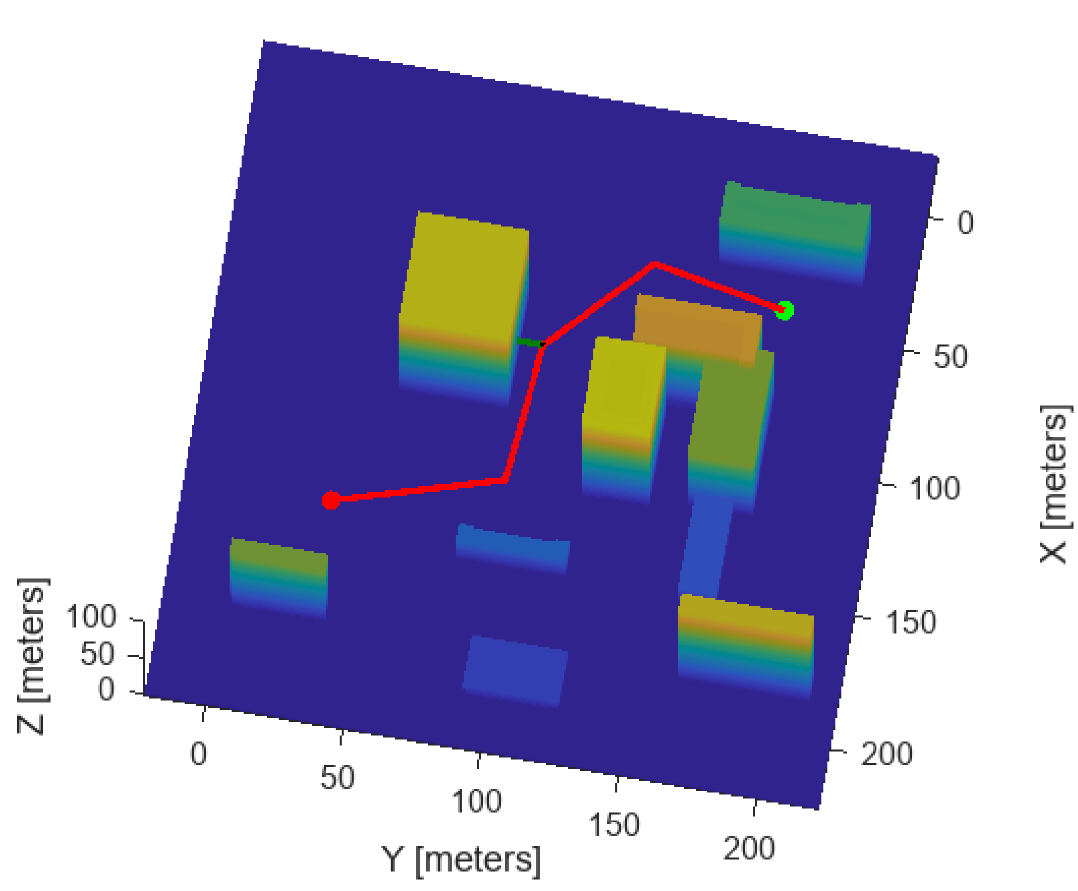
Evaluate the smoothness of the path. Values close to `0` indicate a smoother path. Straight-line paths return a value of `0`.

```
smoothness(pathMetricsObj)
```

```
ans = 0.0011
```

Visualize the minimum clearance of the path.

```
show(pathMetricsObj)
axis equal
view([100 75])
hold on
% Start state
scatter3(start(1,1),start(1,2),start(1,3),"g","filled")
% Goal state
scatter3(goal(1,1),goal(1,2),goal(1,3),"r","filled")
% Path
plot3(pthObj.States(:,1),pthObj.States(:,2),pthObj.States(:,3), ...
      "r-",LineWidth=2)
```




## Input Arguments

**`pathMetricsObj` — Information for path metrics**
`pathmetrics` object

Information for path metrics, specified as a `pathmetrics` object.

## Version History

**Introduced in R2019b**

## References

[1] Lindemann, Stephen R., and Steven M. LaValle. "Simple and efficient algorithms for computing smooth, collision-free feedback laws over given cell decompositions." *The International Journal of Robotics Research 28, no. 5*. 2009, pp. 600-621.

## See Also

**Objects**
`pathmetrics`

**Functions**
`clearance` | `isPathValid` | `show`

# plannerAStar

Graph-based A* path planner

## Description

The `plannerAStar` object creates an A* path planner from a graph object. The A* algorithm finds the shortest path in the graph by using a heuristic function to efficiently guide its exploration of the nodes.

## Creation

### Syntax

```
planner = plannerAStar(graph)
planner = plannerAStar( ___ ,Name=Value)
```

#### Description

`planner = plannerAStar(graph)` creates a `plannerAStar` object from a `navGraph` object, `graph`. The `graph` input sets the value of the Graph property.

`planner = plannerAStar( ___ ,Name=Value)` sets properties using one or more name-value arguments in addition to the input argument in the previous syntax. You can specify the HeuristicCostFcn and TieBreaker properties as name-value arguments.

### Properties

**`Graph` — Graph object of planning environment**
`navGraph` object

Graph object of the planning environment, specified as a `navGraph` object. If using a `digraph` object, you must first convert it to a `navGraph` object. The planner uses the link (or edge) weights from the `navGraph` object to compute the path cost.

**`HeuristicCostFcn` — Heuristic cost function between state and goal in graph**
`@nav.algs.distanceManhattan` (default) | `@nav.algs.distanceEuclidean` | `@nav.algs.distanceEuclideanSquared` | custom cost function handle

The heuristic cost between a state and the goal in a graph, specified as one of the predefined cost function handles, `@nav.algs.distanceManhattan`, `@nav.algs.distanceEuclidean`, or `@nav.algs.distanceEuclideanSquared`, or a custom cost function handle.

The cost function must accept two *N*-by-*S* matrices, `state1` and `state2`, where *N* is the number of states, and *S* is the length of the state vector. The function must return an *N*-element column vector of heuristic costs, `H`. If *N* is the same for both inputs, then `H` contains the pairwise costs between the states. Otherwise, one matrix must have a single row, and `H` contains the cost between that state and each state in the opposing matrix. Vectorize the custom cost function for best performance.

Example: HeuristicCostFcn=@nav.algs.distanceEuclidean

Example:
HeuristicCostFcn=@(state1,state2)nav.algs.distanceManhattan(state1,state2,weight)

Example: HeuristicCostFcn=@(state1,state2)sqrt(sum((state1-state2).^2,2))

Data Types: function_handle

**TieBreaker — Tiebreaker mode toggle**
false or 0 (default) | true or 1

Tiebreaker mode toggle, specified as either a logical 0 (false) or 1 (true). When you enable the TieBreaker property, the A* path planner chooses between multiple paths of the same length by adjusting the heuristic cost value.

Example: TieBreaker=true

Data Types: logical

## Object Functions

plan Find shortest path between two states in graph
copy Create deep copy of A* path planner object

## Examples

### Plan Shortest Path Between Two States in Graph Using A-Star Path Planner

Load the Queensland road network.

```
load("queenslandRoutes","places","routes")
```

Specify states, links, and weights for a navGraph object.

```
states = places.utm;              % UTM coordinates of cities
names = places.name;              % Names of cities
links = [routes.start routes.end]; % Adjacent cities
weights = routes.time;            % Travel time between adjacent cities
```

Create a navGraph object.

```
graphObj = navGraph(states,links,Weight=weights, ...
                    Name=names);
```

Create a graph-based A* path planner.

```
planner = plannerAStar(graphObj);
```

Create a deep copy of the plannerAStar object.

```
planner2 = copy(planner)
```

```
planner2 = 
  plannerAStar with properties:

    HeuristicCostFcn: @nav.algs.distanceManhattan
```

```
TieBreaker: 0
     Graph: [1x1 navGraph]
```

Specify a heuristic function returns an estimated time to reach the goal.

```
planner.HeuristicCostFcn = @(state1,state2) ...
    sum(abs(state1-state2),2)/100;
```

Define the start and goal cities.

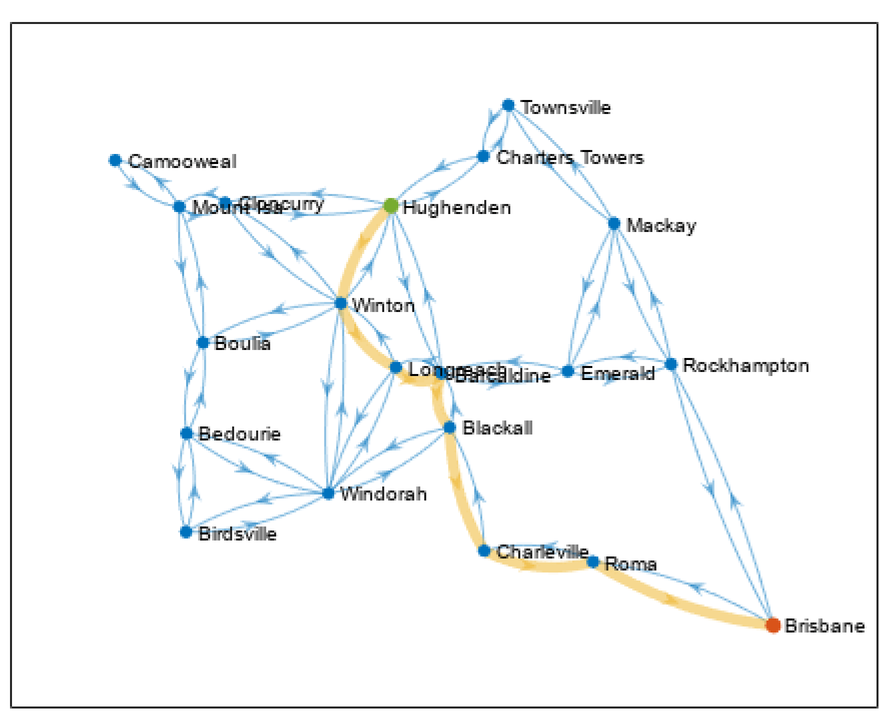
```
start = "Hughenden";
goal = "Brisbane";
```

Find the shortest path using the graph-based A* algorithm.

```
[pathOutput,solutionInfo] = plan(planner,start,goal);
```

Visualize the results.

```
h = show(graphObj);
set(h,XData=graphObj.States.StateVector(:,1), ...
      YData=graphObj.States.StateVector(:,2))
pathStateIDs = solutionInfo.PathStateIDs;
highlight(h,pathStateIDs,EdgeColor="#EDB120",LineWidth=4)
highlight(h,pathStateIDs(1),NodeColor="#77AC30",MarkerSize=5)
highlight(h,pathStateIDs(end),NodeColor="#D95319",MarkerSize=5)
```



# Version History

**Introduced in R2023a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

Usage notes and limitations:

- To use HeuristicCostFcn in code generation workflow, this property must be set to a function handle during object creation.
- `DynamicMemoryAllocation="off"` is not supported.

## See Also

### Objects

`navGraph` | `digraph`

### Functions

`plan` | `copy`

# plannerAStarGrid

A* path planner for grid map

## Description

The `plannerAStarGrid` object creates an A* path planner. The planner performs an A* search on an occupancy map and finds shortest obstacle-free path between the specified start and goal grid locations as determined by heuristic cost.

## Creation

### Syntax

```
planner = plannerAStarGrid
planner = plannerAStarGrid(map)
planner = plannerAStarGrid( ___ ,Name,Value)
```

#### Description

`planner = plannerAStarGrid` creates a `plannerAStarGrid` object with a `binaryOccupancyMap` object using a width and height of 10 meters and grid resolution of 1 cell per meter.

`planner = plannerAStarGrid(map)` creates a `plannerAStarGrid` object using the specified map object `map`. Specify `map` as either a `binaryOccupancyMap` or `occupancyMap` object. The `map` input sets the value of the Map property.

`planner = plannerAStarGrid( ___ ,Name,Value)` sets properties using one or more name-value pairs. Unspecified properties have default values. Enclose each property name in quotes.

For example, `plannerAStarGrid(map,'GCost','Manhattan')` creates an A* path planner object using the Manhattan cost function.

## Properties

**`Map` — Map representation**
`binaryOccupancyMap` object (default) | `occupancyMap` object

Map representation, specified as either a `binaryOccupancyMap` or `occupancyMap` object. This object represents the environment of the robot as an occupancy grid. The value of each grid cell indicates the occupancy of the associated location in the map.

Example: `planner.Map = binaryOccupancyMap(zeros(50,50));`

**`GCost` — General cost of moving between any two points in grid**
`'Euclidean'` (default) | `'Chebyshev'` | `'EuclideanSquared'` | `'Manhattan'`

The general cost of moving between any two points in a grid, specified as one of the following predefined cost functions `'Chebyshev'`, `'Euclidean'`, `'EuclideanSquared'`, or `'Manhattan'`.

The cost of moving between two points with Cartesian coordinates ($x_1$,$y_1$) and ($x_2$,$y_2$) are calculated as following:

- **Chebyshev**

  $$d = \max\left(|x_2 - x_1|, |y_2 - y_1|\right)$$

- **Euclidean**

  $$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$$

- **Euclidean Squared**

  $$d = (x_2 - x_1)^2 + (y_2 - y_1)^2$$

- **Manhattan**

  $$d = |x_2 - x_1| + |y_2 - y_1|$$

---

**Note** You can either use the predefined cost functions or a custom cost function. To use a custom cost function, see GCostFcn property.

---

Example: `planner = plannerAStarGrid(map,'GCost','Manhattan');`

Example: `planner.GCost = 'Chebyshev';`

Data Types: `string` | `char`

**`GCostFcn` — Custom GCost function**
function handle

Custom GCost function, specified as a function handle. The function handle must accept two pose inputs as [*row column*] vectors and return a scalar of type double.

---

**Note** You can either use the predefined cost functions or a custom cost function. To use the predefined cost functions, see GCost property.

---

Example: `planner = plannerAStarGrid(map,'GCostFcn',@(pose1,pose2)sum(abs(pose1-pose2),2));`

Example: `planner.GCostFcn = @(pose1,pose2)sum(abs(pose1-pose2),2);`

Data Types: `function_handle`

**`HCost` — Heuristic cost between point and goal in grid**
`'Euclidean'` (default) | `'Chebyshev'` | `'EuclideanSquared'` | `'Manhattan'`

The heuristic cost between a point and the goal in a grid, specified as one of the following predefined cost functions `'Chebyshev'`, `'Euclidean'`, `'EuclideanSquared'`, or `'Manhattan'`.

The cost of moving between two points with Cartesian coordinates ($x_1$,$y_1$) and ($x_2$,$y_2$) are calculated as following:

- **Chebyshev**

$$d = \max(|x_2 - x_1|, |y_2 - y_1|)$$

- **Euclidean**

$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$$

- **Euclidean Squared**

$$d = (x_2 - x_1)^2 + (y_2 - y_1)^2$$

- **Manhattan**

$$d = |x_2 - x_1| + |y_2 - y_1|$$

**Note** You can either use the predefined cost functions or a custom cost function. To use a custom cost function, see HCostFcn property.

Example: `planner = plannerAStarGrid(map,'HCost','Manhattan');`

Example: `planner.HCost = 'Chebyshev';`

Data Types: `string` | `char`

**`HCostFcn` — Custom HCost function**
function handle

Custom HCost function, specified as a function handle. The function handle must accept two pose inputs as [*row column*] vectors and return a scalar of type double.

**Note** You can either use the predefined cost functions or a custom cost function. To use the predefined cost functions, see HCost property.

Example: `planner = plannerAStarGrid(map,'HCostFcn',@(pose1,pose2)sum(abs(pose1-pose2),2));`

Example: `planner.HCostFcn = @(pose1,pose2)sum(abs(pose1-pose2),2);`

Data Types: `function_handle`

**`TieBreaker` — Toggle tiebreaker mode**
`'off'` (default) | `'on'`

Toggle tiebreaker mode, specified as either `'on'` or `'off'`.

When you enable the `TieBreaker` property, the A* path planner chooses between multiple paths of the same length by adjusting the heuristic cost value.

Example: `planner = plannerAStarGrid(map,'TieBreaker','on');`

Example: `planner.TieBreaker = 'off';`

Data Types: `string` | `char`

#### `DiagonalSearch` — Toggle diagonal search mode
`'on'` (default) | `'off'`

Toggle diagonal search mode, specified as either `'on'` or `'off'`.

When you set this property to `'on'`, the A* path planner searches in diagonal direction along with the other four directions of the grid. When you set this property to `'off'`, the A* path planner searches only in the four directions of the grid.

Data Types: `char` | `string`

## Object Functions

plan Find shortest obstacle-free path between two points
show Plot and visualize A* explored nodes and planned path

## Examples

### Plan Obstacle-Free Path in Grid Map Using A-Star Path Planner

Plan the shortest collision-free path through an obstacle grid map using the A* path planning algorithm.

Generate a `binaryOccupancyMap` object with randomly scattered obstacles using the `mapClutter` function.

```
rng('default');
map = mapClutter;
```

Use the map to create a `plannerAStarGrid` object.

```
planner = plannerAStarGrid(map);
```

Define the start and goal points.

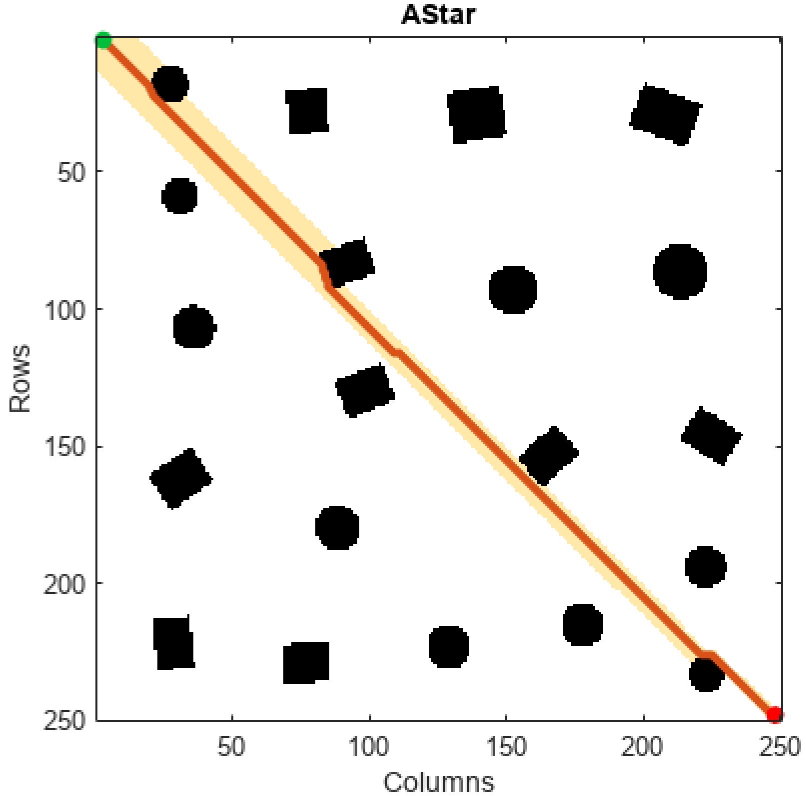
```
start = [2 3];
goal = [248 248];
```

Plan a path from the start point to the goal point.

```
plan(planner,start,goal);
```

Visualize the path and the explored nodes using the `show` object function.

```
show(planner)
```




## Version History

**Introduced in R2020b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`binaryOccupancyMap` | `occupancyMap` | `plannerRRT` | `plannerRRTStar` | `plannerHybridAStar`

# plan

Find shortest obstacle-free path between two points

## Syntax

```
path = plan(planner,start,goal)
path = plan(planner,start,goal,'world')
[path,debugInfo] = plan( ___ )
```

## Description

`path = plan(planner,start,goal)` finds the shortest obstacle-free path, `path`, between a specified start point, `start`, and goal point, `goal`, specified as `[row column]` in grid frame with origin at top-left corner, using the specified A* path planner `planner`.

`path = plan(planner,start,goal,'world')` finds the shortest obstacle-free path, `path`, between a specified start point, `start`, and goal point, `goal`, specified as `[x y]` in world coordinate frame with origin at bottom-left corner, using the specified A* path planner `planner`.

`[path,debugInfo] = plan( ___ )` also returns `debugInfo` that contains the path cost, number of nodes explored, and GCost for each explored node.

## Examples

### Plan Obstacle-Free Path in Grid Map Using A-Star Path Planner

Plan the shortest collision-free path through an obstacle grid map using the A* path planning algorithm.

Generate a `binaryOccupancyMap` object with randomly scattered obstacles using the `mapClutter` function.

```
rng('default');
map = mapClutter;
```

Use the map to create a `plannerAStarGrid` object.

```
planner = plannerAStarGrid(map);
```

Define the start and goal points.

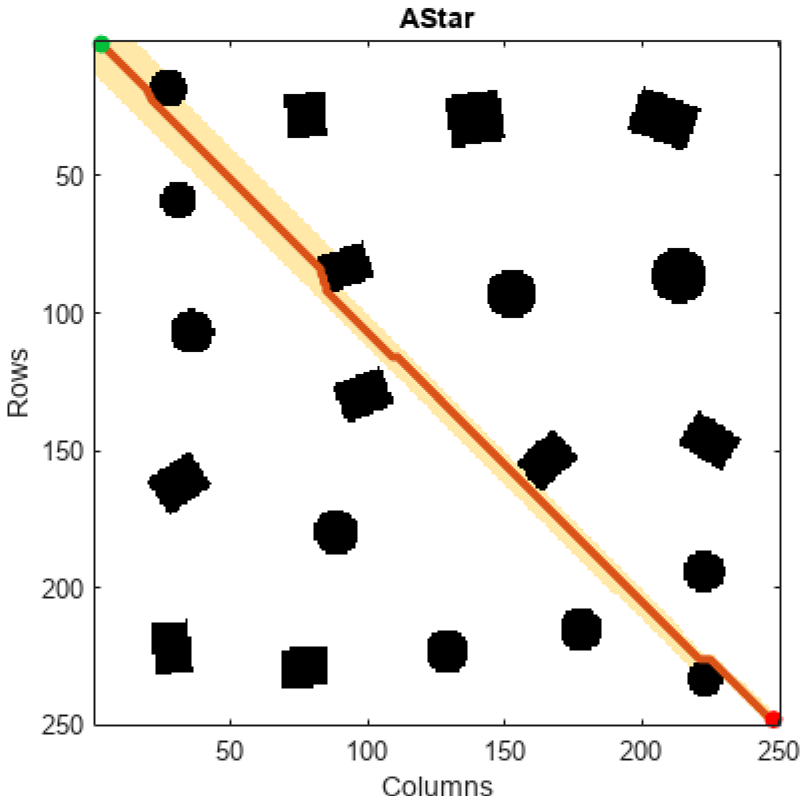
```
start = [2 3];
goal = [248 248];
```

Plan a path from the start point to the goal point.

```
plan(planner,start,goal);
```

Visualize the path and the explored nodes using the `show` object function.

```
show(planner)
```




## Input Arguments

**`planner` — A* path planner for grid map**
`plannerAStarGrid` object

A* path planner for a grid map, specified as a `plannerAStarGrid` object.

**`start` — Start position in grid or world**
two-element vector

Start position in the grid or world, specified as a two-element vector of the form [*row column*], or [*x y*]. The location is in grid positions or world coordinates based on syntax.

Example: `[2 3]`

Data Types: `double`

**`goal` — Goal position in grid or world**
two-element vector

Goal position in the grid or world, specified as a two-element vector of the form [*row column*], or [*x y*]. The location is in grid positions or world coordinates based on syntax.

Example: `[28 46]`

Data Types: `double`

## Output Arguments

**`path` — Shortest obstacle-free path**
*n*-by-2 matrix

Shortest obstacle-free path, returned as an *n*-by-2 matrix. *n* is the number of waypoints in the path. Each row represents the [*row column*], or [*x y*] location of a waypoint along the solved path from the start location to the goal. The location is in grid positions or world coordinates based on syntax.

Data Types: `double`

**`debugInfo` — Debugging information for path result**
structure

Debugging information for the path result, returned as a structure with these fields:

- `PathCost` — Cost of the path
- `NumNodesExplored` — Number of nodes explored
- `GCostMatrix` — GCost for each explored node

Data Types: `struct`

# Version History

**Introduced in R2020b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

`plannerAStarGrid` | `show`

# show

Plot and visualize A* explored nodes and planned path

## Syntax

```
show(planner)
axHandle = show(planner)
[ ___ ] = show( ___ ,Name,Value)
```

## Description

`show(planner)` plots and visualizes the A* explored nodes and the planned path in the associated map.

`axHandle = show(planner)` returns the axes handle of the figure used to plot the path.

`[ ___ ] = show( ___ ,Name,Value)` specifies options using one or more name-value pair arguments in addition to any of the arguments from previous syntaxes. Enclose argument name inside single quotes (' ').

For example, `'ExploredNodes','off'` plots and visualizes the planned path without displaying the explored nodes.

## Examples

### Plan Obstacle-Free Path in Grid Map Using A-Star Path Planner

Plan the shortest collision-free path through an obstacle grid map using the A* path planning algorithm.

Generate a `binaryOccupancyMap` object with randomly scattered obstacles using the `mapClutter` function.

```
rng('default');
map = mapClutter;
```

Use the map to create a `plannerAStarGrid` object.

```
planner = plannerAStarGrid(map);
```

Define the start and goal points.

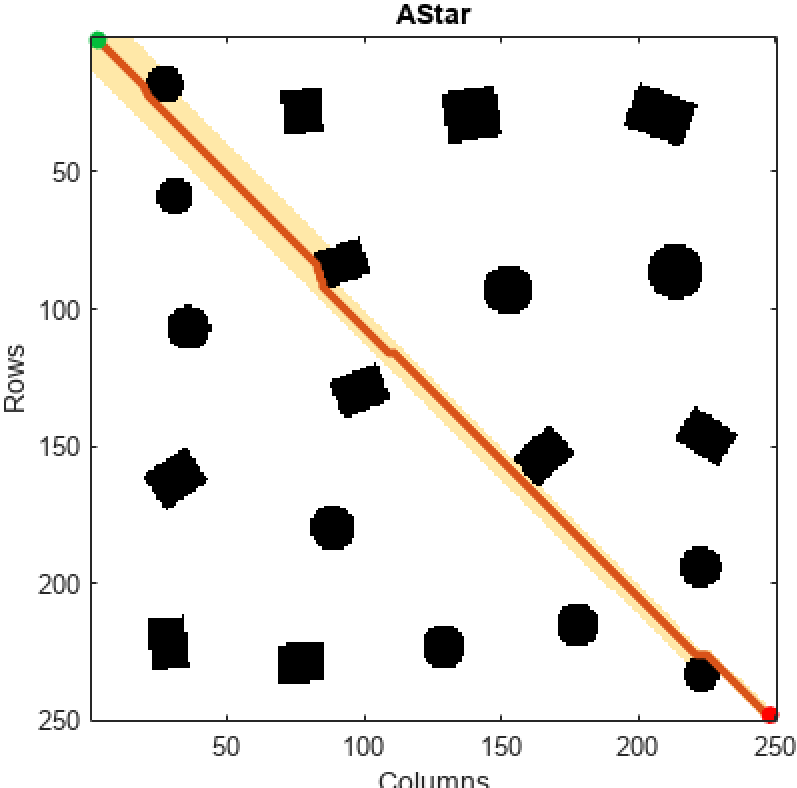
```
start = [2 3];
goal = [248 248];
```

Plan a path from the start point to the goal point.

```
plan(planner,start,goal);
```

Visualize the path and the explored nodes using the `show` object function.

```
show(planner)
```




## Input Arguments

**planner — A* path planner for grid map**
plannerAStarGrid object

A* path planner for a grid map, specified as a plannerAStarGrid object.

### Name-Value Pair Arguments

Specify optional pairs of arguments as Name1=Value1,...,NameN=ValueN, where Name is the argument name and Value is the corresponding value. Name-value arguments must appear after other arguments, but the order of the pairs does not matter.

*Before R2021a, use commas to separate each name and value, and enclose* Name *in quotes.*

Example: 'ExploredNodes','off' plots and visualizes the planned path without displaying the explored nodes.

**Parent — Axes used to plot path**
Axes object | UIAxes object

Axes used to plot path, specified as the comma-separated pair consisting of 'Parent' and either an Axes Properties or UIAxes Properties object. If you do not specify Parent, a new figure is created.

Example: `'Parent',axHandle`

**`ExploredNodes` — Display explored nodes**
`'on'` (default) | `'off'`

Display the explored nodes, specified as the comma-separated pair consisting of `'ExploredNodes'` and either `'on'` or `'off'`.

Example: `'ExploredNodes','off'`

Data Types: `string` | `char`

## Output Arguments

**`axHandle` — Axes used to plot path**
`Axes` object | `UIAxes` object

Axes used to plot the path, returned as an Axes Properties or UIAxes Properties object.

# Version History

**Introduced in R2020b**

## See Also

`plannerAStarGrid` | `plan`

# plannerBenchmark

Benchmark path planners using generated metrics

## Description

`plannerBenchmark` object benchmarks the 2-D path planners by running them on a specified environment with specified start and goal poses.

The `plannerBenchmark` object calculates the following metrics:

- `clearance` — Minimum distance to obstacles in the environment
- `executionTime` — Time taken by plan function to execute
- `initializationTime` — Time taken by initialization function to execute
- `isPathValid` — If true represent the path exists and is collision free
- `pathLength` — Length of the generated path
- `smoothness` — Smoothness of the path for all poses

The metrics like `executionTime` and `initializationTime` are calculated during the execution of planners. The metrics like `clearance`, `isPathValid`, `pathLength`, and `smoothness` are calculated from the resulting path outputs after executing planners. Calculated metrics are statistically summarized as a table and can be visualized as plots.

## Creation

### Syntax

```
plannerBM = plannerBenchmark(environment,start,goal)
```

#### Description

`plannerBM = plannerBenchmark(environment,start,goal)` creates a `plannerBenchmark` object with the specified `environment`, `start` and `goal` poses. The inputs `environment`, `start`, and `goal` sets the `Environment`, `Start`, and `Goal` properties, respectively.

### Properties

**`Environment` — Environment for benchmarking path planners**
`occupancyMap` object | `binaryOccupancyMap` object | `validatorOccupancyMap` object

Environment for benchmarking path planners, specified as `occupancyMap`, `binaryOccupancyMap`, or `validatorOccupancyMap` object.

**`Start` — Start pose of path for all planners**
vector of the form [*x y*] | vector of the form [*x y theta*]

Start pose of path for all planners, specified as a vector of the form [*x y*] or [*x y theta*].

Data Types: `single` | `double`

**`Goal` — Goal pose of path for all planners**
vector of the form `[x y]` | vector of the form `[x y theta]`

Goal pose of path for all planners, specified as a vector of the form `[x y]` or `[x y theta]`.

Data Types: `single` | `double`

**`PlannerOutput` — Output of planners after execution**
structure

This property is read-only.

Output of planners after execution, returned as a structure that contains the initialization function output and plan function output for all planners. The fields of the structure are named by planner name specified in `addPlanner` function.

Each structure contains an initialization output and a plan function output. The plan function output is further a structure containing plan function output for each run of the planner.

Data Types: `struct`

## Object Functions

| | |
|---|---|
| addPlanner | Add path planner for benchmarking |
| copy | Create deep copy of plannerBenchmark object |
| metric | Return path planner metrics |
| report | Create benchmark report |
| runPlanner | Run path planners |
| show | Visualize path planner metrics |

## Examples

### Benchmark 2-D Path Planners

Create an occupancy map from an example map.

```
load("exampleMaps.mat","simpleMap");
map = occupancyMap(simpleMap);
```

Create a state validator with `stateSpaceSE2` using the map.

```
sv = validatorOccupancyMap(stateSpaceSE2,Map=map);
```

Specify the start and goal states.

```
start = [5 8 pi/2];
goal = [7 18 pi/2];
```

Create a `plannerBenchmark` object.

```
pbo = plannerBenchmark(sv,start,goal);
```

Define the function handles for the initialization functions of the planners.

```
plannerHAFcn = @(sv)plannerHybridAStar(sv);
plannerRRTSFcn = @(sv)plannerRRTStar(sv.StateSpace,sv);
```

Define the function handle for the plan function, which is common for both planners.

```
plnFcn = @(initOut,s,g)plan(initOut,s,g);
```

Add the path planners for benchmarking.

```
addPlanner(pbo,plnFcn,plannerHAFcn);
addPlanner(pbo,plnFcn,plannerRRTSFcn,PlannerName="ppRRTStar");
```

Set the `rng` for repetitive results.

```
rng('default')
```

Run the path planners for the number of times specified in `runCount` to collect metrics.

```
runCount = 5;
runPlanner(pbo,runCount)
```

```
Initializing plannerHAFcn_plnFcn ...
Done.
Planning a path from the start pose (5 8 1.5708) to the goal pose (7 18 1.5708) using plannerHAF
Executing run 1.
Executing run 2.
Executing run 3.
Executing run 4.
Executing run 5.
Initializing ppRRTStar ...
Done.
Planning a path from the start pose (5 8 1.5708) to the goal pose (7 18 1.5708) using ppRRTStar.
Executing run 1.
Executing run 2.
Executing run 3.
Executing run 4.
Executing run 5.
```

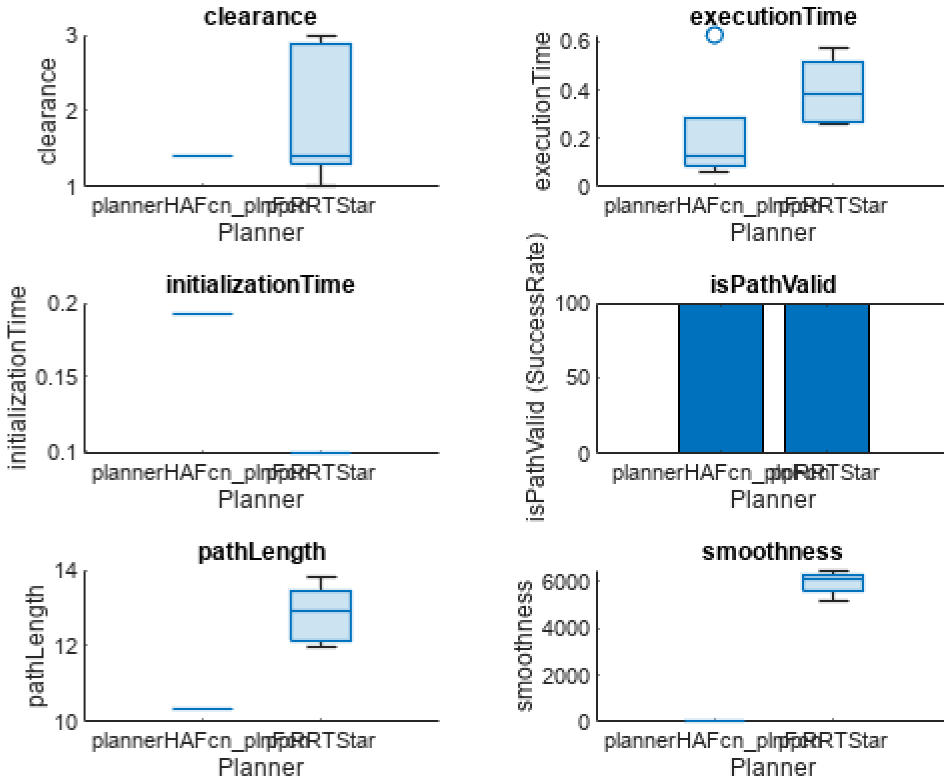
Access path length metric for all the runs on the environment.

```
[pLenSummary,pLenData] = metric(pbo,"pathLength")
```

```
pLenSummary=2×4 table
                            Mean     Median    StdDev     sampleSize
                           ______    ______    _______    __________

    plannerHAFcn_plnFcn    10.349    10.349          0        5
    ppRRTStar               12.84      12.9    0.67112        5


pLenData=2×5 table
                            Run1      Run2      Run3      Run4      Run5
                           ______    ______    ______    ______    ______

    plannerHAFcn_plnFcn    10.349    10.349    10.349    10.349    10.349
    ppRRTStar                13.8      12.9      12.2        12      13.3
```

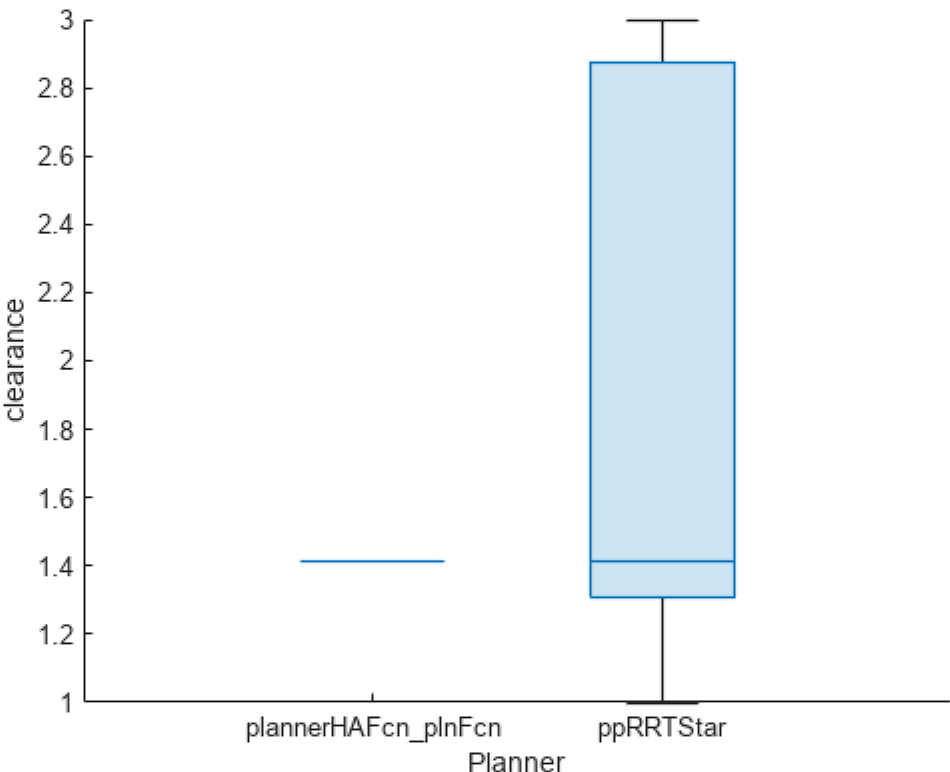
Visualize all the metrics.

```
show(pbo)
```




Closely inspect the clearance metric.

```
figure
show(pbo,"clearance")
```




## Version History

**Introduced in R2022a**

## See Also

**Objects**
`occupancyMap` | `binaryOccupancyMap` | `validatorOccupancyMap`

**Functions**
`addPlanner` | `copy` | `metric` | `report` | `runPlanner` | `show`

# plannerBiRRT

Create bidirectional RRT planner for geometric planning

## Description

The `plannerBiRRT` object is a single-query planner that uses the bidirectional rapidly exploring random tree (RRT) algorithm with an optional connect heuristic for increased speed.

The bidirectional RRT planner creates one tree with a root node at the specified start state and another tree with a root node at the specified goal state. To extend each tree, the planner generates a random state and, if valid, takes a step from the nearest node based on the MaxConnectionDistance property. The start and goal trees alternate this extension process until both trees are connected. If the EnableConnectHeuristic property is enabled, the extension process ignores the MaxConnectionDistance property. Invalid states or connections that collide with the environment are not added to the tree.

## Creation

### Syntax

```
planner = plannerBiRRT(stateSpace,stateVal)
planner = plannerBiRRT( ___ ,Name=Value)
```

#### Description

`planner = plannerBiRRT(stateSpace,stateVal)` creates a bidirectional RRT planner from a state space object, `stateSpace`, and a state validator object, `stateVal`. The state space of `stateVal` must be the same as `stateSpace`. The `stateSpace` and `stateVal` arguments also set the StateSpace and StateValidator properties, respectively, of the planner.

`planner = plannerBiRRT( ___ ,Name=Value)` sets properties using one or more name-value arguments in addition to the input arguments in the previous syntax. You can specify the MaxConnectionDistance, MaxIterations, MaxNumTreeNodes, and EnableConnectHeuristic properties as name-value arguments.

### Properties

**`StateSpace` — State space for planner**
state space object

State space for the planner, specified as a state space object. You can use state space objects such as `stateSpaceSE2`, `stateSpaceDubins`, `stateSpaceReedsShepp`, and `stateSpaceSE3`. You can also customize a state space object using the `nav.StateSpace` class.

**`StateValidator` — State validator for planner**
state validator object

State validator for the planner, specified as a state validator object. You can use state validator objects such as `validatorOccupancyMap`, `validatorVehicleCostmap`, and `validatorOccupancyMap3D`.

#### `MaxConnectionDistance` — Maximum length between planned configurations

`0.1` (default) | positive scalar

Maximum length between planned configurations, specified as a positive scalar.

If the EnableConnectHeuristic property is set to `true`, the object ignores this distance when connecting the two trees during the connect stage.

Example: `MaxConnectionDistance=0.3`

Data Types: `single` | `double`

#### `MaxIterations` — Maximum number of iterations

`1e4` (default) | positive integer

Maximum number of iterations, specified as a positive integer.

Example: `MaxIterations=2500`

Data Types: `single` | `double`

#### `MaxNumTreeNodes` — Maximum number of nodes in search tree

`1e4` (default) | positive integer

Maximum number of nodes in the search tree, specified as a positive integer.

Example: `MaxNumTreeNodes=2500`

Data Types: `single` | `double`

#### `EnableConnectHeuristic` — Directly join trees during connect phase

`false` or `0` (default) | `true` or `1`

Directly join trees during the connect phase of the planner, specified as a logical `0` (`false`) or `1` (`true`).

Setting this property to `true` causes the object to ignore the MaxConnectionDistance property when attempting to connect the two trees together.

Example: `EnableConnectHeuristic=true`

Data Types: `logical`

## Object Functions

plan — Plan path between two states
copy — Create deep copy of planner object

## Examples

### Plan Path Between Two States Using Bidirectional RRT

Use the `plannerBiRRT` object to plan a path between two states in an environment with obstacles. Visualize the planned path with interpolated states.

Create a state space.

```
ss = stateSpaceSE2;
```

Create an `occupancyMap`-based state validator using the created state space.

```
sv = validatorOccupancyMap(ss);
```

Create an occupancy map from an example map and set map resolution as 10 cells per meter.

```
load exampleMaps
map = occupancyMap(ternaryMap,10);
```

Assign the occupancy map to the state validator object. Specify the sampling distance interval.

```
sv.Map = map;
sv.ValidationDistance = 0.01;
```

Update the state space bounds to be the same as the map limits.

```
ss.StateBounds = [map.XWorldLimits; map.YWorldLimits; [-pi pi]];
```

Create the path planner and increase the maximum connection distance.

```
planner = plannerBiRRT(ss,sv);
planner.MaxConnectionDistance = 0.3;
% planner = plannerBiRRT(ss,sv,MaxConnectionDistance=0.3);
```

Specify the start and goal states.

```
start = [20 10 0];
goal = [40 40 0];
```

Plan a path. Due to the randomness of the RRT algorithm, set the `rng` seed for repeatability.

```
rng(100,'twister')
[pthObj,solnInfo] = plan(planner,start,goal);
```

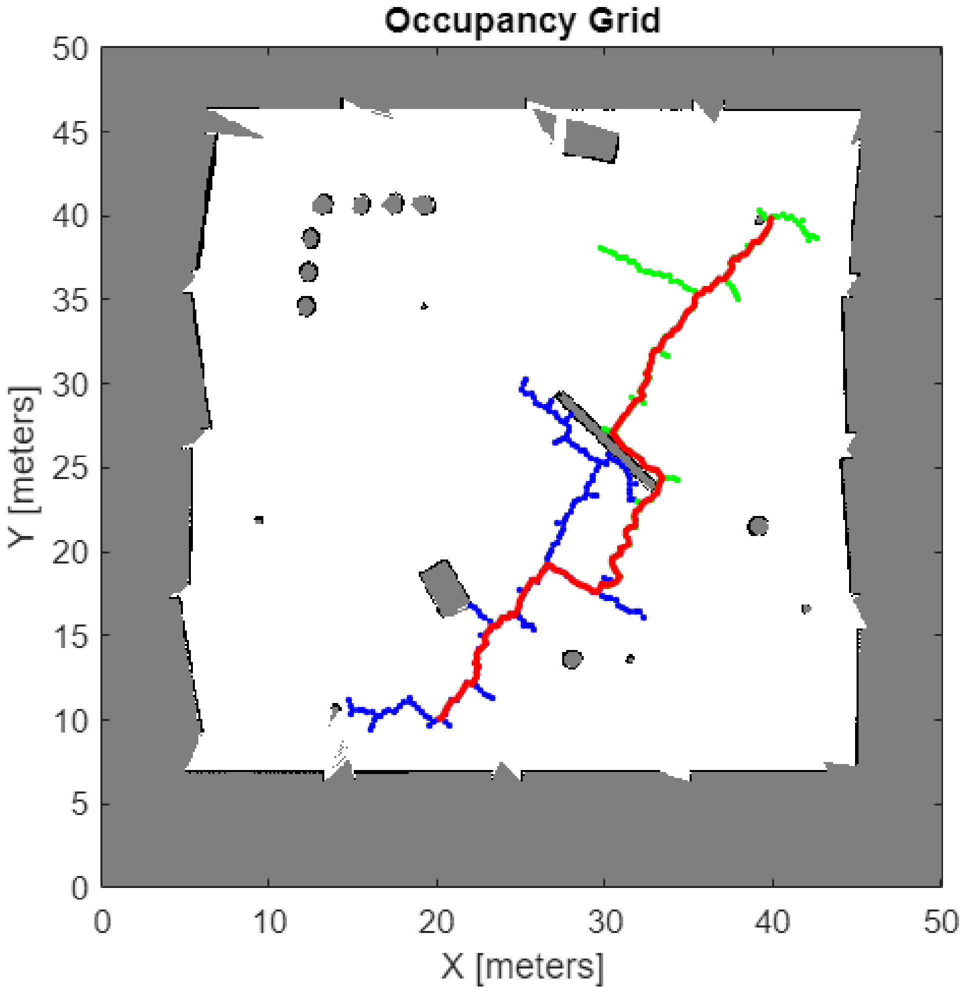
Display the number of iterations taken for the tree to converge.

```
fprintf("Number of iterations: %d\n",solnInfo.NumIterations)
```

```
Number of iterations: 346
```

Visualize the results.

```
show(map)
hold on
% Start tree expansion
plot(solnInfo.StartTreeData(:,1),solnInfo.StartTreeData(:,2), ...
    '.-','color','b')
% Goal tree expansion
plot(solnInfo.GoalTreeData(:,1),solnInfo.GoalTreeData(:,2), ...
    '.-','color','g')
% Draw path
plot(pthObj.States(:,1),pthObj.States(:,2),'r-','LineWidth',2)
hold off
```




Replan the path with the EnableConnectHeuristic property set to true.

```
planner.EnableConnectHeuristic = true;
[pthObj,solnInfo] = plan(planner,start,goal);
```

Display the number of iterations taken for the tree to converge. Observe that the planner requires significantly fewer iterations compared to when the EnableConnectHeuristic property is set to false.

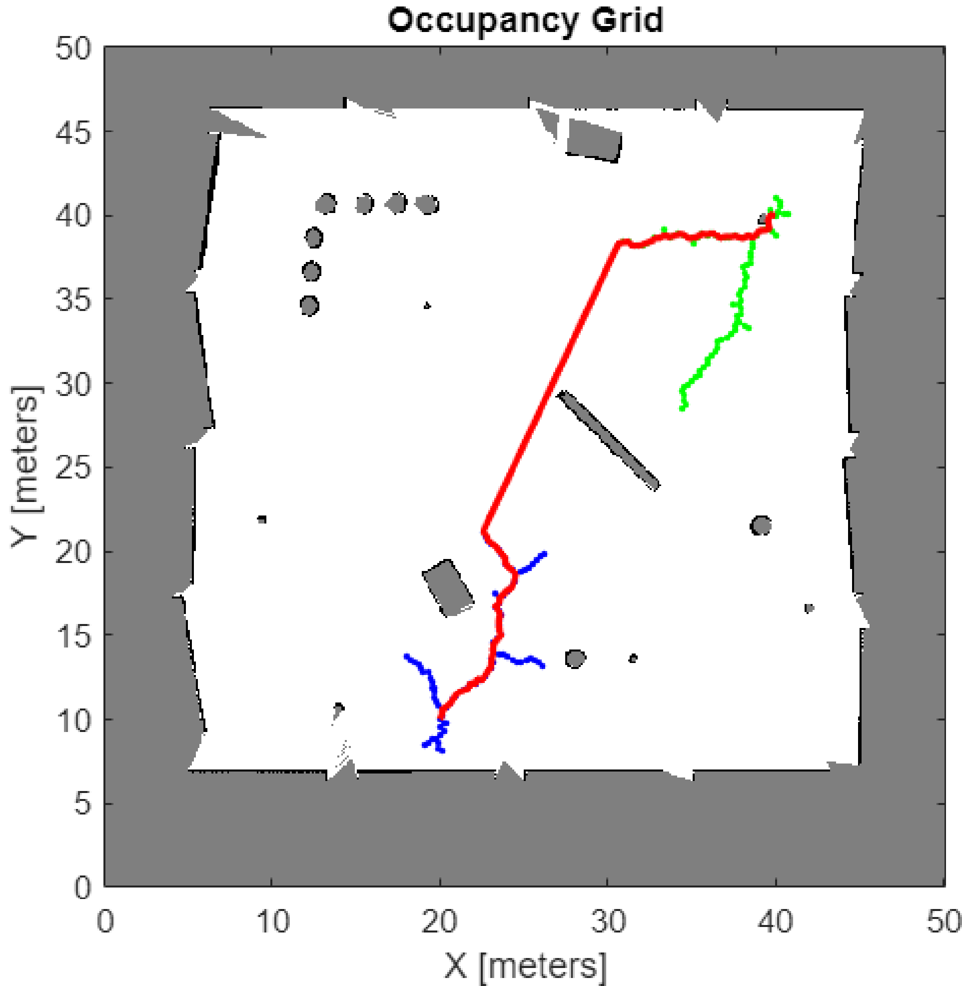
```
fprintf("Number of iterations: %d\n",solnInfo.NumIterations)
```

```
Number of iterations: 192
```

Visualize the results.

```
figure
show(map)
hold on
% Start tree expansion
plot(solnInfo.StartTreeData(:,1),solnInfo.StartTreeData(:,2), ...
    '.-','color','b')
```

```
% Goal tree expansion
plot(solnInfo.GoalTreeData(:,1),solnInfo.GoalTreeData(:,2), ...
    '.-','color','g')
% Draw path
plot(pthObj.States(:,1),pthObj.States(:,2),'r-','LineWidth',2)
```




**Plan Path Through 3-D Occupancy Map Using Bidirectional RRT Planner**

Load a 3-D occupancy map of a city block into the workspace. Specify the threshold to consider cells as obstacle-free.

```
mapData = load("dMapCityBlock.mat");
omap = mapData.omap;
omap.FreeThreshold = 0.5;
```

Inflate the occupancy map to add a buffer zone for safe operation around the obstacles.

```
inflate(omap,1)
```

Create an SE(3) state space object with bounds for state variables.

```
ss = stateSpaceSE3([0 220;0 220;0 100;inf inf;inf inf;inf inf;inf inf]);
```

Create a 3-D occupancy map state validator using the created state space. Assign the occupancy map to the state validator object. Specify the sampling distance interval.

```
sv = validatorOccupancyMap3D(ss, ...
     Map = omap, ...
     ValidationDistance = 0.1);
```

Create a bidirectional RRT path planner with increased maximum connection distance and reduced maximum number of iterations. Set `EnableConnectHeuristic` property to true.

```
planner = plannerBiRRT(ss,sv, ...
          MaxConnectionDistance = 50, ...
          MaxIterations = 1000, ...
          EnableConnectHeuristic = true);
```

Specify start and goal poses.

```
start = [40 180 25 0.7 0.2 0 0.1];
goal = [150 33 35 0.3 0 0.1 0.6];
```

Configure the random number generator for repeatable result.

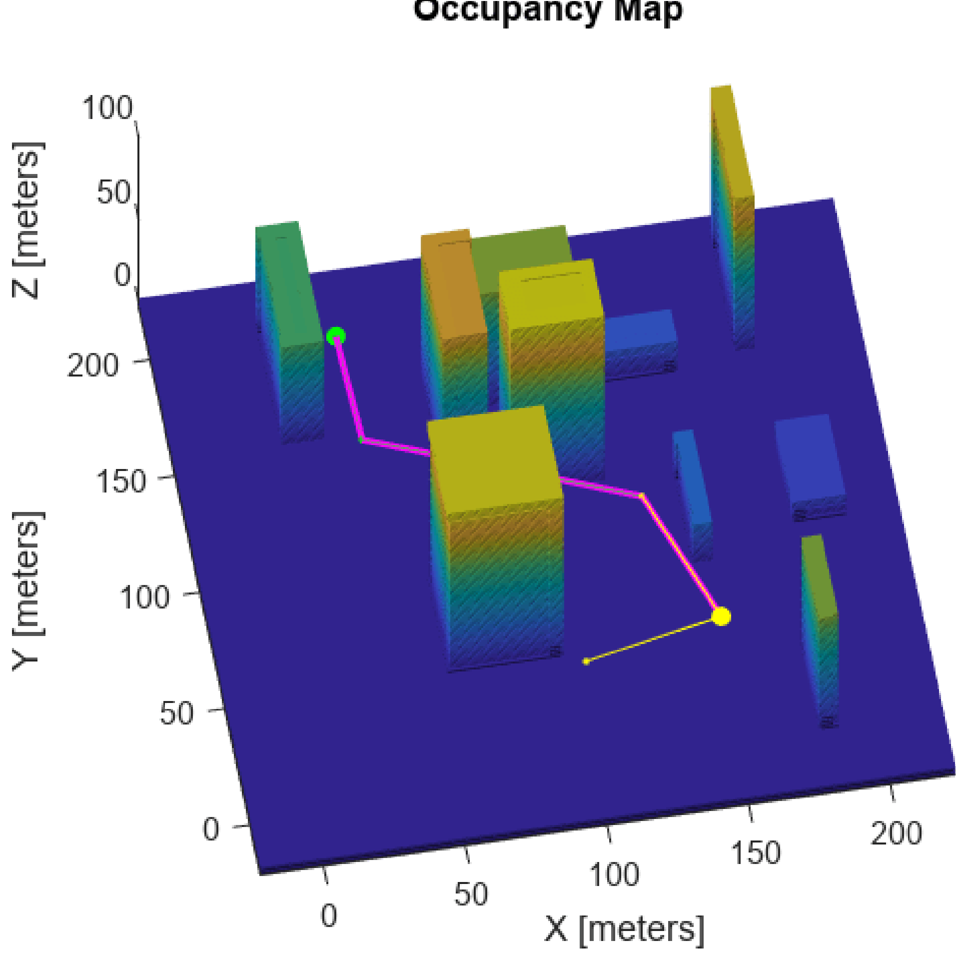
```
rng(1,"twister");
```

Plan the path.

```
[pthObj,solnInfo] = plan(planner,start,goal);
```

Visualize the planned path.

```
show(omap)
axis equal
view([-10 55])
hold on
% Start state
scatter3(start(1,1),start(1,2),start(1,3),"g","filled")
% Start tree expansion
plot3(solnInfo.StartTreeData(:,1),solnInfo.StartTreeData(:,2), ...
      solnInfo.StartTreeData(:,3),".-",Color="g")
% Goal state
scatter3(goal(1,1),goal(1,2),goal(1,3),"y","filled")
% Goal tree expansion
plot3(solnInfo.GoalTreeData(:,1),solnInfo.GoalTreeData(:,2), ...
      solnInfo.GoalTreeData(:,3),".-",Color="y")
% Path
plot3(pthObj.States(:,1),pthObj.States(:,2),pthObj.States(:,3), ...
      "m-",LineWidth=2)
```




## Version History

**Introduced in R2021a**

### References

[1] Kuffner, J. J., and S. M. LaValle. "RRT-Connect: An Efficient Approach to Single-Query Path Planning." In *Proceedings 2000 ICRA. Millennium Conference. IEEE International Conference on Robotics and Automation. Symposia Proceedings (Cat. No.00CH37065)*, 2:995–1001. San Francisco, CA, USA: IEEE, 2000. https://doi:10.1109/ROBOT.2000.844730.

### Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
`plannerRRT` | `plannerRRTStar` | `stateSpaceReedsShepp` | `stateSpaceDubins` | `stateSpaceSE2` | `stateSpaceSE3` | `validatorOccupancyMap` | `validatorVehicleCostmap` | `validatorOccupancyMap3D`

**Functions**
`plan` | `copy`

# copy

Create deep copy of planner object

## Syntax

```
plannerCopy = copy(planner)
```

## Description

`plannerCopy = copy(planner)` creates a deep copy of the planner object with the same properties.

## Examples

### Create Copy of plannerBiRRT Object

Create an occupancy map from an example map and set the map resolution as 10 cells/meter.

```
map = load("exampleMaps.mat").simpleMap;
map = occupancyMap(map,10);
```

Create a state space and update the state space bounds to be the same as the map limits.

```
ss = stateSpaceSE2;
ss.StateBounds = [map.XWorldLimits; map.YWorldLimits; [-pi pi]];
```

Create a state validator with `stateSpaceSE2` using the map and set the validation distance.

```
sv = validatorOccupancyMap(ss,Map=map);
sv.ValidationDistance = 0.01;
```

Create a `plannerBiRRT` object.

```
planner = plannerBiRRT(ss,sv)
```

```
planner = 
  plannerBiRRT with properties:

                StateSpace: [1x1 stateSpaceSE2]
            StateValidator: [1x1 validatorOccupancyMap]
           MaxNumTreeNodes: 10000
             MaxIterations: 10000
     MaxConnectionDistance: 0.1000
    EnableConnectHeuristic: 0
```

Create a copy of the `plannerBiRRT` object.

```
plannerNew = copy(planner)
```

```
plannerNew = 
  plannerBiRRT with properties:
```

```
              StateSpace: [1x1 stateSpaceSE2]
          StateValidator: [1x1 validatorOccupancyMap]
         MaxNumTreeNodes: 10000
           MaxIterations: 10000
   MaxConnectionDistance: 0.1000
  EnableConnectHeuristic: 0
```

## Input Arguments

**`planner` — Path planner**
`plannerBiRRT` object

Path planner, specified as a `plannerBiRRT` object.

## Output Arguments

**`plannerCopy` — Copy of path planner**
`plannerBiRRT` object

Copy of path planner, returned as a `plannerBiRRT` object.

# Version History

**Introduced in R2021a**

## See Also

**Objects**
`plannerBiRRT`

**Functions**
`plan`

# plan

Plan path between two states

## Syntax

```
path = plan(planner,startState,goalState)
[path,solnInfo] = plan(planner,startState,goalState)
```

## Description

`path = plan(planner,startState,goalState)` returns a bidirectional rapidly exploring random tree (RRT) path from the start state to the goal state as a `navPath` object.

`[path,solnInfo] = plan(planner,startState,goalState)` also returns the solution information from path planning.

## Examples

### Plan Path Between Two States Using Bidirectional RRT

Use the `plannerBiRRT` object to plan a path between two states in an environment with obstacles. Visualize the planned path with interpolated states.

Create a state space.

```
ss = stateSpaceSE2;
```

Create an `occupancyMap`-based state validator using the created state space.

```
sv = validatorOccupancyMap(ss);
```

Create an occupancy map from an example map and set map resolution as 10 cells per meter.

```
load exampleMaps
map = occupancyMap(ternaryMap,10);
```

Assign the occupancy map to the state validator object. Specify the sampling distance interval.

```
sv.Map = map;
sv.ValidationDistance = 0.01;
```

Update the state space bounds to be the same as the map limits.

```
ss.StateBounds = [map.XWorldLimits; map.YWorldLimits; [-pi pi]];
```

Create the path planner and increase the maximum connection distance.

```
planner = plannerBiRRT(ss,sv);
planner.MaxConnectionDistance = 0.3;
% planner = plannerBiRRT(ss,sv,MaxConnectionDistance=0.3);
```

Specify the start and goal states.

```
start = [20 10 0];
goal = [40 40 0];
```

Plan a path. Due to the randomness of the RRT algorithm, set the `rng` seed for repeatability.

```
rng(100,'twister')
[pthObj,solnInfo] = plan(planner,start,goal);
```

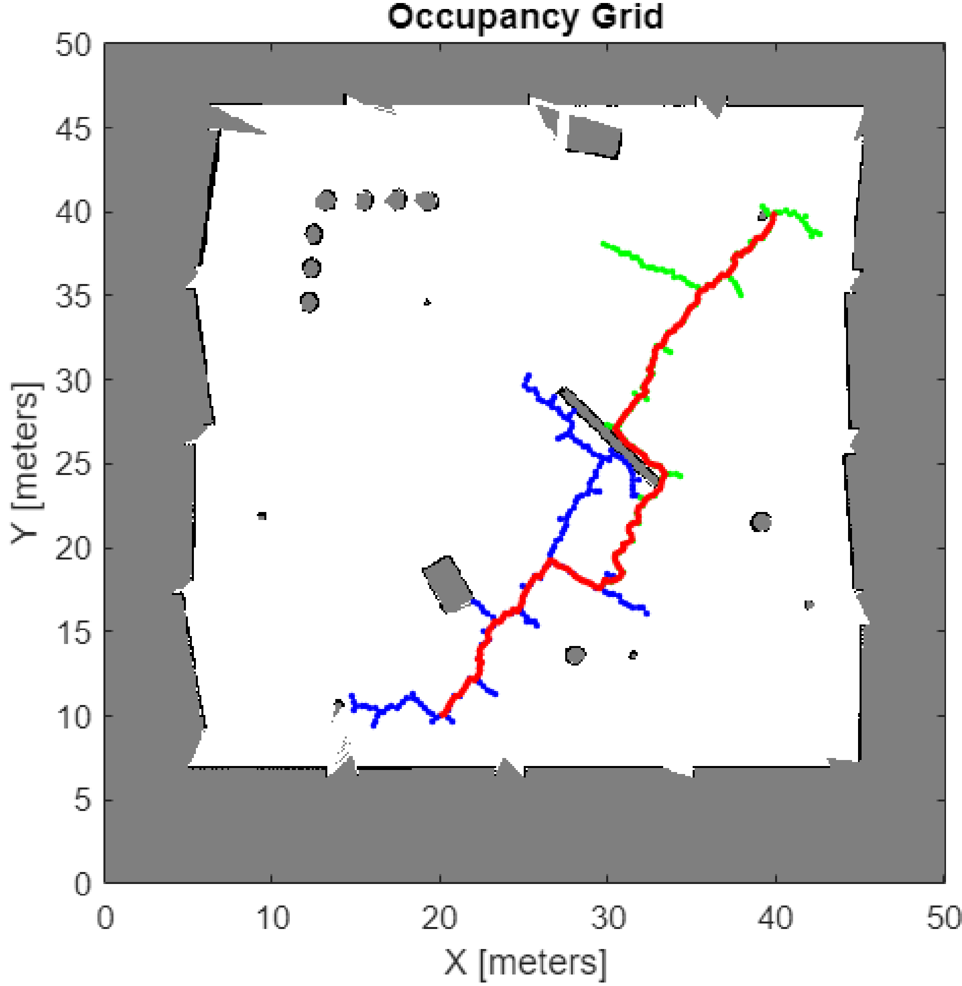
Display the number of iterations taken for the tree to converge.

```
fprintf("Number of iterations: %d\n",solnInfo.NumIterations)
```

```
Number of iterations: 346
```

Visualize the results.

```
show(map)
hold on
% Start tree expansion
plot(solnInfo.StartTreeData(:,1),solnInfo.StartTreeData(:,2), ...
    '.-','color','b')
% Goal tree expansion
plot(solnInfo.GoalTreeData(:,1),solnInfo.GoalTreeData(:,2), ...
    '.-','color','g')
% Draw path
plot(pthObj.States(:,1),pthObj.States(:,2),'r-','LineWidth',2)
hold off
```




Replan the path with the `EnableConnectHeuristic` property set to true.

```
planner.EnableConnectHeuristic = true;
[pthObj,solnInfo] = plan(planner,start,goal);
```

Display the number of iterations taken for the tree to converge. Observe that the planner requires significantly fewer iterations compared to when the `EnableConnectHeuristic` property is set to false.

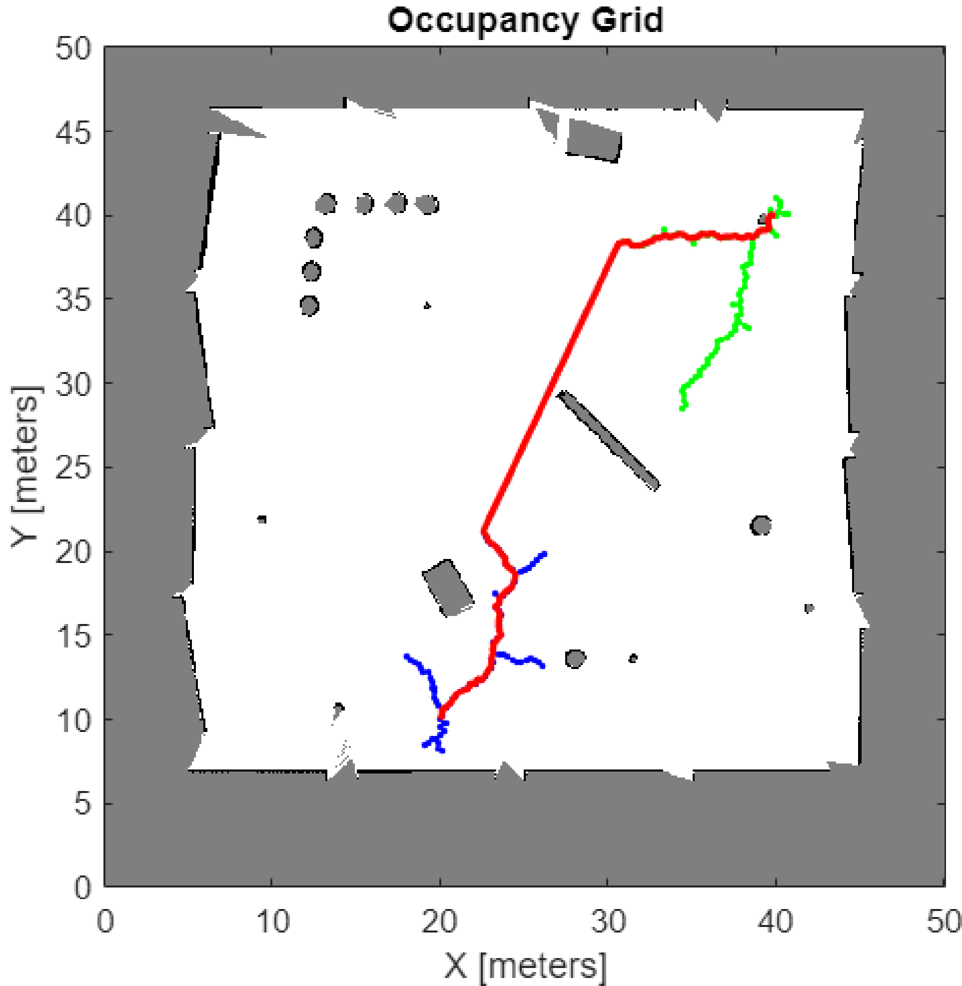
```
fprintf("Number of iterations: %d\n",solnInfo.NumIterations)
```

```
Number of iterations: 192
```

Visualize the results.

```
figure
show(map)
hold on
% Start tree expansion
plot(solnInfo.StartTreeData(:,1),solnInfo.StartTreeData(:,2), ...
    '.-','color','b')
```

```
% Goal tree expansion
plot(solnInfo.GoalTreeData(:,1),solnInfo.GoalTreeData(:,2), ...
    '.-','color','g')
% Draw path
plot(pthObj.States(:,1),pthObj.States(:,2),'r-','LineWidth',2)
```




### Plan Path Through 3-D Occupancy Map Using Bidirectional RRT Planner

Load a 3-D occupancy map of a city block into the workspace. Specify the threshold to consider cells as obstacle-free.

```
mapData = load("dMapCityBlock.mat");
omap = mapData.omap;
omap.FreeThreshold = 0.5;
```

Inflate the occupancy map to add a buffer zone for safe operation around the obstacles.

```
inflate(omap,1)
```

Create an SE(3) state space object with bounds for state variables.

```
ss = stateSpaceSE3([0 220;0 220;0 100;inf inf;inf inf;inf inf;inf inf]);
```

Create a 3-D occupancy map state validator using the created state space. Assign the occupancy map to the state validator object. Specify the sampling distance interval.

```
sv = validatorOccupancyMap3D(ss, ...
     Map = omap, ...
     ValidationDistance = 0.1);
```

Create a bidirectional RRT path planner with increased maximum connection distance and reduced maximum number of iterations. Set `EnableConnectHeuristic` property to true.

```
planner = plannerBiRRT(ss,sv, ...
          MaxConnectionDistance = 50, ...
          MaxIterations = 1000, ...
          EnableConnectHeuristic = true);
```

Specify start and goal poses.

```
start = [40 180 25 0.7 0.2 0 0.1];
goal = [150 33 35 0.3 0 0.1 0.6];
```

Configure the random number generator for repeatable result.

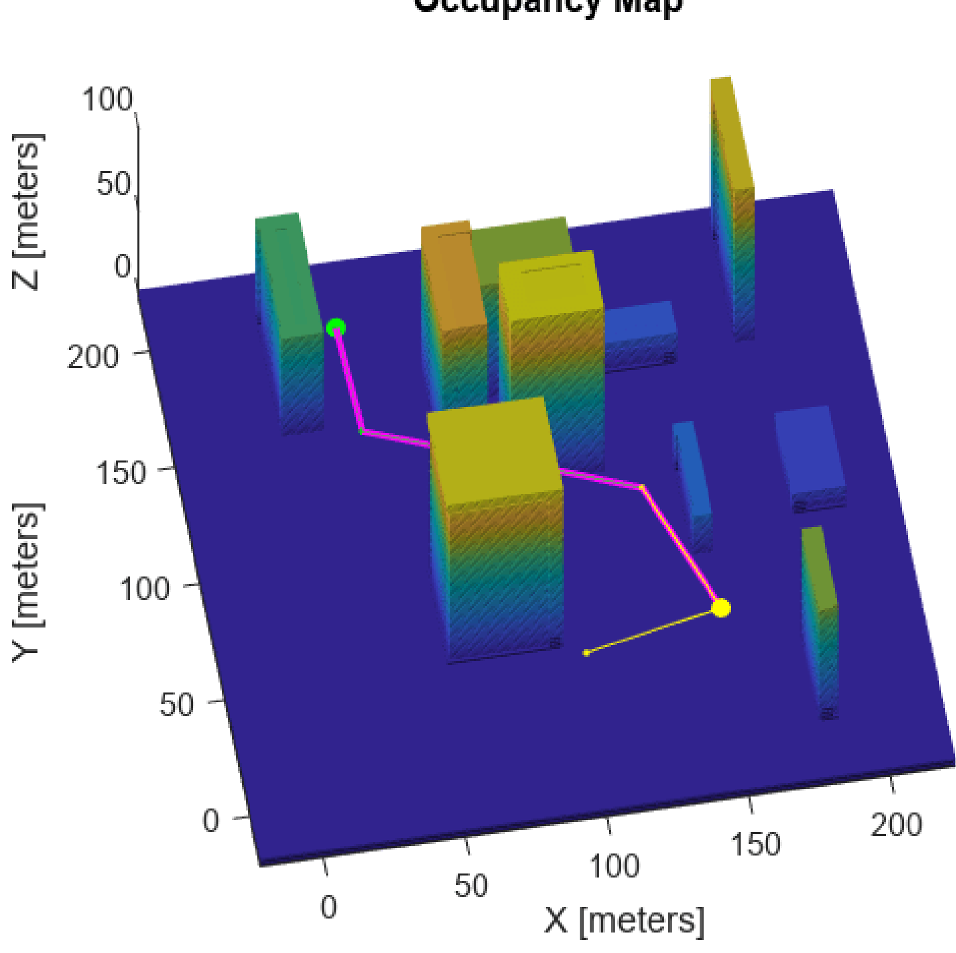
```
rng(1,"twister");
```

Plan the path.

```
[pthObj,solnInfo] = plan(planner,start,goal);
```

Visualize the planned path.

```
show(omap)
axis equal
view([-10 55])
hold on
% Start state
scatter3(start(1,1),start(1,2),start(1,3),"g","filled")
% Start tree expansion
plot3(solnInfo.StartTreeData(:,1),solnInfo.StartTreeData(:,2), ...
      solnInfo.StartTreeData(:,3),".-",Color="g")
% Goal state
scatter3(goal(1,1),goal(1,2),goal(1,3),"y","filled")
% Goal tree expansion
plot3(solnInfo.GoalTreeData(:,1),solnInfo.GoalTreeData(:,2), ...
      solnInfo.GoalTreeData(:,3),".-",Color="y")
% Path
plot3(pthObj.States(:,1),pthObj.States(:,2),pthObj.States(:,3), ...
      "m-",LineWidth=2)
```




## Input Arguments

**`planner` — Path planner**
`plannerBiRRT` object

Path planner, specified as a `plannerBiRRT` object.

**`startState` — Start state of path**
*N*-element real-valued vector

Start state of the path, specified as an *N*-element real-valued vector. *N* is the number of dimensions in the state space.

Example: `[1 1 pi/6]`

Example: `[40 180 25 0.7 0.2 0 0.1]`

Data Types: `single` | `double`

**goalState — Goal state of path**
*N*-element real-valued vector

Goal state of the path, specified as an *N*-element real-valued vector. *N* is the number of dimensions in the state space.

Example: `[2 2 pi/3]`

Example: `[150 33 35 0.3 0 0.1 0.6]`

Data Types: `single` | `double`

## Output Arguments

**path — Planned path information**
`navPath` object

Planned path information, returned as a `navPath` object.

**solnInfo — Solution Information**
structure

Solution Information, returned as a structure. The structure contains these fields:

| Field | Description |
| --- | --- |
| `IsPathFound` | Indicates whether a path is found. It returns `1` (`true`) if a path is found. Otherwise, it returns `0` (`false`). |
| `ExitFlag` | Indicates the termination cause of the planner, returned as:<br>• `1` — The planner reaches the goal.<br>• `2` — The planner reaches the maximum number of iterations.<br>• `3` — The planner reaches the maximum number of nodes. |
| `StartTreeNumNodes` | Number of nodes in the start search tree when the planner terminates, excluding the root node. |
| `GoalTreeNumNodes` | Number of nodes in the goal search tree when the planner terminates, excluding the root node. |
| `NumIterations` | Number of combined iterations by both the start tree and goal tree. |
| `StartTreeData` | Collection of explored states that reflect the status of the start search tree when the planner terminates. Note that `NaN` values are inserted as delimiters to separate each individual edge. |
| `GoalTreeData` | Collection of explored states that reflect the status of the goal search tree when the planner terminates. Note that `NaN` values are inserted as delimiters to separate each individual edge. |

Data Types: `structure`

## Version History

**Introduced in R2021a**

## See Also

**Objects**

`plannerBiRRT` | `navPath`

**Functions**

`copy`

# plannerControlRRT

Control-based RRT planner

## Description

The `plannerControlRRT` object is a rapidly exploring random tree (RRT) planner for solving kinematic and dynamic (kinodynamic) planning problems using controls. The RRT algorithm is a tree-based motion planning routine that incrementally grows a search tree. In kinematic planners, the tree grows by randomly sampling states in system configuration space, and then attempts to propagate the nearest node toward that state. The state propagator samples controls for reaching the state based on the kinematic model and control policies. As the tree adds nodes, the sampled states span the search space and eventually connect the start and goal states.

These are the control-based RRT algorithm steps:

- Planner, `plannerControlRRT`, requests a state from the state space.
- Planner finds the nearest state in the search tree based on cost.
- State propagator, `mobileRobotPropagator`, samples control commands and durations to propagate toward the target state.
- State propagator propagates toward the target state.
- If the propagator returns a valid trajectory to the state, then add the state to the tree.
- **Optional**: Attempt to direct trajectory toward final goal based on NumGoalExtension and GoalBias properties.
- Continue searching until the search tree reaches the goal or satisfies other exit criteria.

The benefit of a kinodynamic planner like `plannerControlRRT` is that it is guaranteed to return a sequence of states, controls, and references which comprise a kinematically or dynamically feasibly path. The drawback to a kinodynamic planner is that the kinematic propagations cannot guarantee that new states are exactly equal to the target states unless there exists and analytic representation for a sequence of controls that drive the system between two configurations with zero residual error. This means that kinodynamic planners are typically asymptotically complete and guarantee kinematic feasibility, but often can not guarantee asymptotic optimality.

## Creation

### Syntax

```
controlPlanner = plannerControlRRT(propagator)
controlPlanner = plannerControlRRT(propagator,Name=Value)
```

#### Description

`controlPlanner = plannerControlRRT(propagator)` creates a kinodynamic RRT planner from a state propagator object and sets the `StatePropagator` property.

`controlPlanner = plannerControlRRT(propagator,Name=Value)` specifies additional properties using name-value arguments. For example, `plannerControlRRT(propagator,ContinueAfterGoalReached=1)` continues to search for alternative paths after the tree first reaches the goal.

## Properties

**`StatePropagator` — State propagator**
`mobileRobotPropagator` object (default) | object of subclass of `nav.StatePropagator`

Mobile robot state propagator, specified as a `mobileRobotPropagator` object or an object of a subclass of `nav.StatePropagator`.

**`ContinueAfterGoalReached` — Optimization after reaching goal**
`false` or `0` (default) | `true` or `1`

Optimization after reaching the goal, specified as a logical `0` (`false`) or `1` (`true`). If specified as true, the planner continues to search for alternative paths after it first reaches the goal. The planner terminates regardless of the value of this property if it reaches the maximum number of iterations or maximum number of tree nodes.

Data Types: `logical`

**`MaxPlanningTime` — Maximum time allowed for planning**
`Inf` (default) | positive scalar in seconds

Maximum time allowed for planning, specified as a positive scalar in seconds.

Data Types: `single` | `double`

**`MaxNumTreeNodes` — Maximum number of nodes in search tree**
`1e4` (default) | positive integer

Maximum number of nodes in the search tree, excluding the root node, specified as a positive integer.

Data Types: `single` | `double`

**`MaxNumIteration` — Maximum number of iterations**
`1e4` (default) | positive integer

Maximum number of iterations, specified as a positive integer.

Data Types: `single` | `double`

**`NumGoalExtension` — Number of times to propagate towards goal**
`1` (default) | positive integer

The maximum number of times the planner can propagate towards the goal, specified as a positive integer. After successfully adding a new node to the tree, the planner attempts to propagate the new node toward the goal using the `propagateWhileValid` object function of the state propagator. The planner continues propagating until the function returns an empty state vector indicating that no valid control is found, the planner reaches the goal, or the function has been called `NumGoalExtension` times.

To turn this behavior off, set the property to `0`. Turning this behavior off will result in propagating randomly instead of toward the goal.

Data Types: `single` | `double`

**`GoalBias` — Probability of choosing goal state during state sampling**
`0.1` (default) | real scalar in range [0, 1]

Probability of choosing the goal state during state sampling, specified as a real scalar in the range [0, 1]. This property determines the likelihood of the planner choosing the actual goal state when randomly selecting states from the state space. You can start by setting the probability to a small value, such as `0.05`.

Data Types: `single` | `double`

**`GoalReachedFcn` — Callback function to determine whether goal is reached**
`@plannerControlRRT.GoalReachedDefault` | function handle

Callback function to determine whether the goal is reached, specified as a function handle. You can create your own goal-reached function. The function must follow this syntax:

```
isReached = myGoalReachedFcn(planner,currentState,goalState)
```

where:

- `planner` — is the created planner object, specified as a `plannerControlRRT` object.
- `currentState` — is the current state, specified as a *s*-element real vector. *s* is the number of state variables in the state space.
- `goalState` — is the goal state, specified as a *s*-element real vector. *s* is the number of state variables in the state space.
- `isReached` — is a boolean that indicates whether the current state has reached the goal state, returned as `true` or `false`.

Data Types: `function handle`

## Object Functions

plan — Plan kinematically feasible path between two states
copy — Creates deep copy of planner object

## Examples

### Plan Kinodynamic Path with Controls for Mobile Robot

Plan control paths for a bicycle kinematic model with the `mobileRobotPropagator` object. Specify a map for the environment, set state bounds, and define a start and goal location. Plan a path using the control-based RRT algorithm, which uses a state propagator for planning motion and the required control commands.

#### Set State and State Propagator Parameters

Load a ternary map matrix and create an `occupancyMap` object. Create the state propagator using the map. By default, the state propagator uses a bicycle kinematic model.

```
load('exampleMaps','ternaryMap')
map = occupancyMap(ternaryMap,10);
```

```
propagator = mobileRobotPropagator(Environment=map); % Bicycle model
```

Set the state bounds on the state space based on the map world limits.

```
propagator.StateSpace.StateBounds(1:2,:) = ...
                    [map.XWorldLimits; map.YWorldLimits];
```

#### Plan Path

Create the path planner from the state propagator.

```
planner = plannerControlRRT(propagator);
```

Specify the start and goal states.

```
start = [10 15 0];
goal  = [40 30 0];
```

Plan a path between the states. For repeatable results, reset the random number generator before planning. The `plan` function outputs a `navPathControl` object, which contains the states, control commands, and durations.

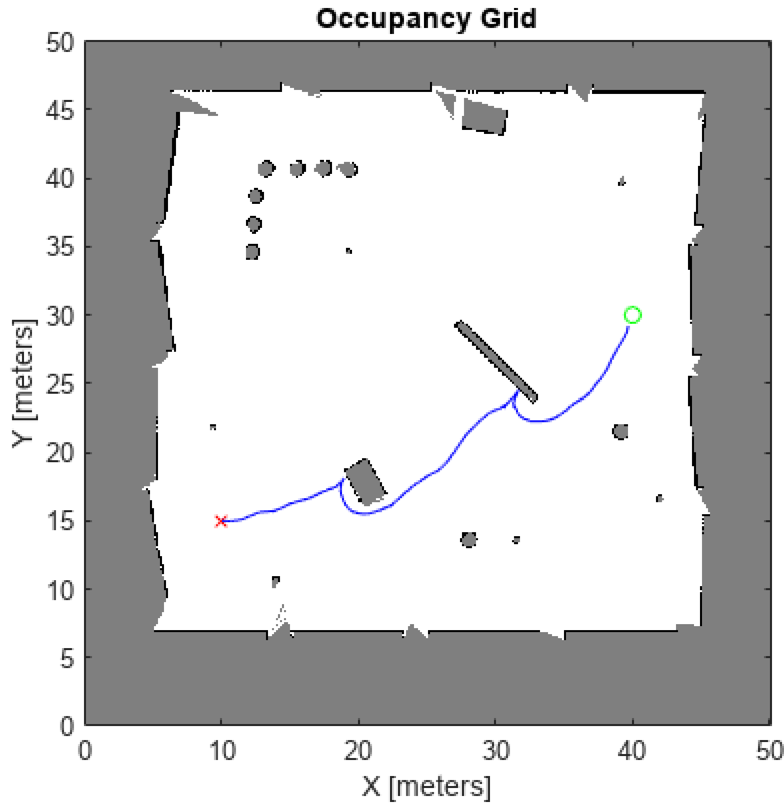
```
rng("default")
path = plan(planner,start,goal)
```

```
path = 
  navPathControl with properties:

    StatePropagator: [1x1 mobileRobotPropagator]
             States: [192x3 double]
           Controls: [191x2 double]
          Durations: [191x1 double]
       TargetStates: [191x3 double]
          NumStates: 192
        NumSegments: 191
```

#### Visualize Results

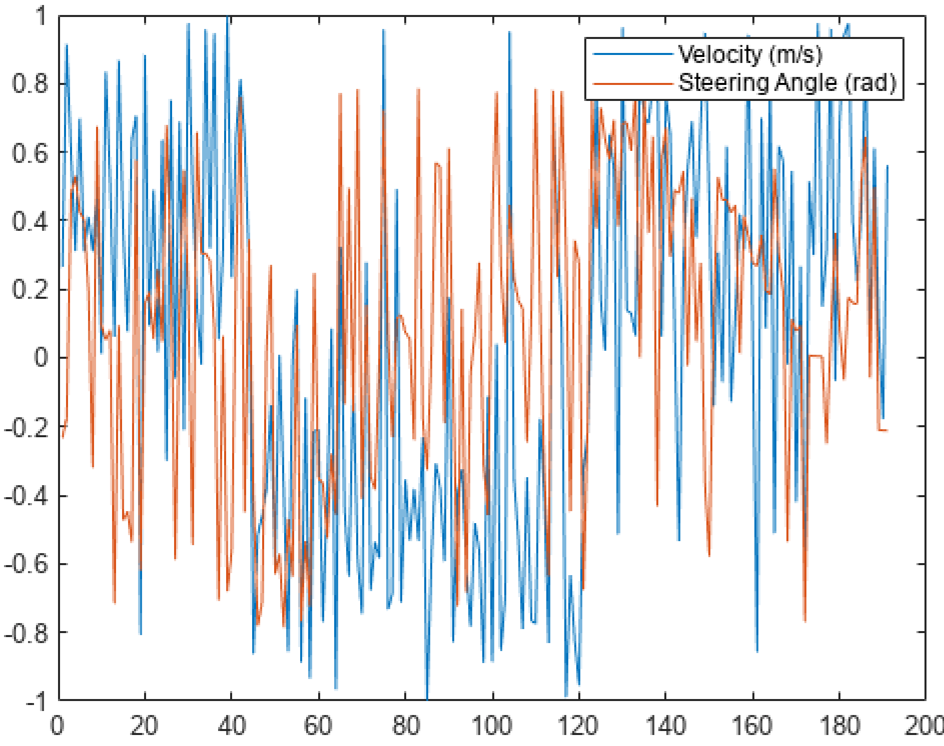
Visualize the map and plot the path states.

```
show(map)
hold on
plot(start(1),start(2),"rx")
plot(goal(1),goal(2),"go")
plot(path.States(:,1),path.States(:,2),"b")
hold off
```




Display the `[v psi]` control inputs of forward velocity and steering angle.

```
plot(path.Controls)
ylim([-1 1])
legend(["Velocity (m/s)","Steering Angle (rad)"])
```




# Version History

**Introduced in R2021b**

## References

[1] S.M. Lavalle, J.J. Kuffner, "Randomized kinodynamic planning", *International Journal of Robotics Research*, vol. 20, no. 5, pp. 378-400, May 2001

[2] Kavraki, L. and S. LaValle. "Chapter 5 Motion Planning", 1st ed., B. Siciliano et O. Khatib, Ed. New York: *Springer-Verlag Berlin Heidelberg*, 2008, pp. 109-131.

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
`plannerAStarGrid` | `plannerBiRRT` | `plannerHybridAStar` | `plannerRRT` | `plannerRRTStar`

**Functions**
`plan` | `copy`

### Topics

“Reverse-Capable Motion Planning for Tractor-Trailer Model Using plannerControlRRT”

# plan

Plan kinematically feasible path between two states

## Syntax

```
path = plan(planner,startState,goalState)
[___,solutionInfo] = plan(planner,startState,goalState)
[___] = plan(planner,startState,goalSampleFcn)
```

## Description

`path = plan(planner,startState,goalState)` tries to find a valid path between `startState` and `goalState`.

The planning is carried out based on the state propagator, which leverages a kinematic model and controllers of the system to search the configuration space. The planner returns a `navPathControl` object, `path`, which contains the propagator used during planning and a sequence of states, controls, target states, and control durations.

`[___,solutionInfo] = plan(planner,startState,goalState)` also returns the solution information `solutionInfo` of the path planning.

`[___] = plan(planner,startState,goalSampleFcn)` takes in a function handle that produces a goal configuration when called. The function handle should take no inputs and generate a goal state whose size matches `startState`.

## Examples

### Plan Kinodynamic Path with Controls for Mobile Robot

Plan control paths for a bicycle kinematic model with the `mobileRobotPropagator` object. Specify a map for the environment, set state bounds, and define a start and goal location. Plan a path using the control-based RRT algorithm, which uses a state propagator for planning motion and the required control commands.

#### Set State and State Propagator Parameters

Load a ternary map matrix and create an `occupancyMap` object. Create the state propagator using the map. By default, the state propagator uses a bicycle kinematic model.

```
load('exampleMaps','ternaryMap')
map = occupancyMap(ternaryMap,10);

propagator = mobileRobotPropagator(Environment=map); % Bicycle model
```

Set the state bounds on the state space based on the map world limits.

```
propagator.StateSpace.StateBounds(1:2,:) = ...
                    [map.XWorldLimits; map.YWorldLimits];
```

#### Plan Path

Create the path planner from the state propagator.

```
planner = plannerControlRRT(propagator);
```

Specify the start and goal states.

```
start = [10 15 0];
goal  = [40 30 0];
```

Plan a path between the states. For repeatable results, reset the random number generator before planning. The `plan` function outputs a `navPathControl` object, which contains the states, control commands, and durations.

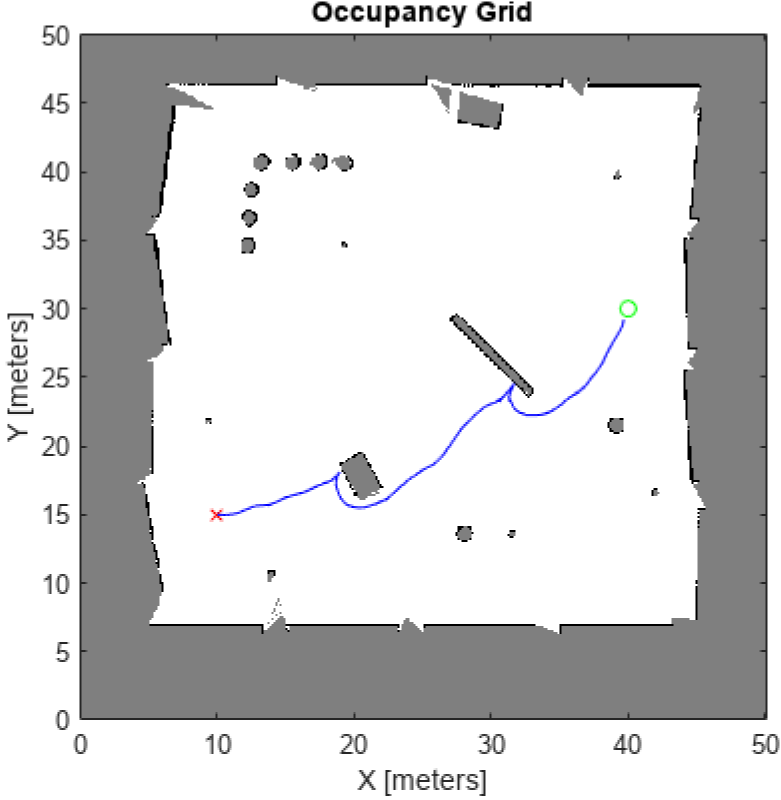
```
rng("default")
path = plan(planner,start,goal)
```

```
path = 
  navPathControl with properties:

    StatePropagator: [1x1 mobileRobotPropagator]
             States: [192x3 double]
           Controls: [191x2 double]
          Durations: [191x1 double]
       TargetStates: [191x3 double]
          NumStates: 192
        NumSegments: 191
```

#### Visualize Results

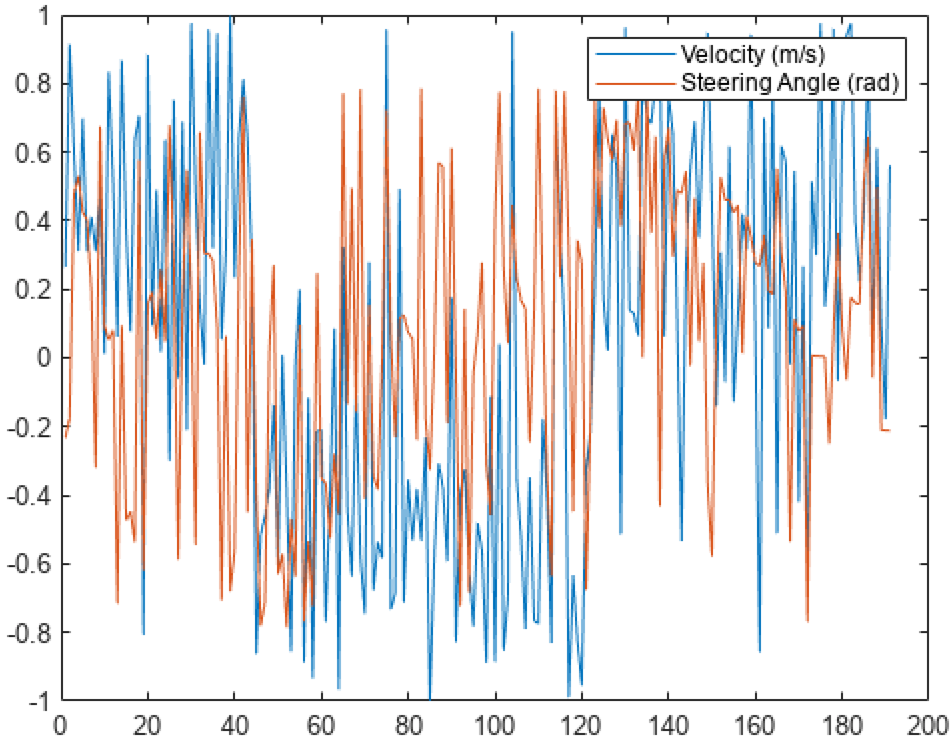
Visualize the map and plot the path states.

```
show(map)
hold on
plot(start(1),start(2),"rx")
plot(goal(1),goal(2),"go")
plot(path.States(:,1),path.States(:,2),"b")
hold off
```




Display the `[v psi]` control inputs of forward velocity and steering angle.

```
plot(path.Controls)
ylim([-1 1])
legend(["Velocity (m/s)","Steering Angle (rad)"])
```




## Input Arguments

**`planner` — Path planner**
`plannerControlRRT` object

Path planner, specified as a `plannerControlRRT` object.

**`startState` — Start state of path**
*s*-element vector

Initial state of the path, specified as an *s*-element vector. *s* is the number of state variables in the state space. For example, a robot in the SE(2) space has a state vector of `[x y theta]`.

Example: `[1 1 pi/6]`

Data Types: `single` | `double`

**`goalState` — Goal state of path**
*s*-element vector

Goal state of the path, specified as an *s*-element vector. *s* is the number of state variables in the state space. For example, a robot in the SE(2) space has a state vector of `[x y theta]`.

Example: `[2 2 pi/3]`

Data Types: `single` | `double`

**goalSampleFcn — Goal state sample function**
function handle

Goal state sample function, specified as a function handle. The function handle should take no inputs and generate a goal state whose size matches `startState`.

Example:

Data Types: `function_handle`

## Output Arguments

**path — Planned path information**
`navPathControl` object

Planned path information, returned as a `navPathControl` object.

**solutionInfo — Solution Information**
structure

Solution Information, returned as a structure. The structure contains these fields:

| Field | Description |
| --- | --- |
| `IsPathFound` | Indicates whether a path is found. It returns as `1` if a path is found. Otherwise, it returns as `0`. |
| `ExitFlag` | Indicates the terminate status of the planner, returned as one of these options:<br>• `1` — Goal successfully reached<br>• `2` — Exceeded maximum number of iterations<br>• `3` — Exceeded maximum number of nodes<br>• `4` — Exceeded maximum planning time |
| `NumTreeNode` | Number of nodes in the search tree when the planner terminates excluding the root node. |
| `NumIterations` | Number of target states propagated. |
| `PlanningTime` | Elapsed time while planning, returned as a scalar in seconds. |
| `TreeInfo` | Collection of explored states that reflects the status of the search tree when the planner terminates. Note that the planner inserts `NaN` values as delimiters to separate each individual edge. |

Data Types: `structure`

# Version History

**Introduced in R2021b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Objects

`plannerControlRRT`

### Functions

`copy`

# copy

Creates deep copy of planner object

## Syntax

```
plannerCopy = copy(planner)
```

## Description

`plannerCopy = copy(planner)` creates a deep copy of the planner object with the same properties.

## Examples

### Create Copy of plannerControlRRT Object

Create an occupancy map from an example map and set the map resolution as 10 cells/meter.

```
load("exampleMaps","ternaryMap")
map = occupancyMap(ternaryMap,10);
```

Create the state propagator using the map. By default, the state propagator uses a bicycle kinematic model.

```
propagator = mobileRobotPropagator(Environment=map);
```

Set the state bounds on the state space based on the map world limits.

```
propagator.StateSpace.StateBounds(1:2,:) = ...
                    [map.XWorldLimits; map.YWorldLimits];
```

Create a `plannerControlRRT` object.

```
planner = plannerControlRRT(propagator)
```

```
planner = 
  plannerControlRRT with properties:

             StatePropagator: [1x1 mobileRobotPropagator]
    ContinueAfterGoalReached: 0
             MaxPlanningTime: Inf
              MaxNumTreeNode: 10000
             MaxNumIteration: 10000
            NumGoalExtension: 1
                    GoalBias: 0.1000
              GoalReachedFcn: @plannerControlRRT.GoalReachedDefault
```

Create a copy of the `plannerControlRRT` object.

```
plannerNew = copy(planner)
```

```
plannerNew = 
  plannerControlRRT with properties:

              StatePropagator: [1x1 mobileRobotPropagator]
    ContinueAfterGoalReached: 0
              MaxPlanningTime: Inf
               MaxNumTreeNode: 10000
              MaxNumIteration: 10000
             NumGoalExtension: 1
                     GoalBias: 0.1000
               GoalReachedFcn: @plannerControlRRT.GoalReachedDefault
```

## Input Arguments

**planner — Path planner**
plannerControlRRT object

Path planner, specified as a plannerControlRRT object.

## Output Arguments

**plannerCopy — Copy of path planner**
plannerControlRRT object

Copy of path planner, returned as a plannerControlRRT object.

# Version History

**Introduced in R2021b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
plannerControlRRT

**Functions**
plan

# plannerHybridAStar

Hybrid A* path planner

## Description

The Hybrid A* path planner object generates a smooth path in a given 2-D space for vehicles with nonholonomic constraints.

`plannerHybridAStar` object uses the Reeds-Shepp connection to find an obstacle-free path. You can modify the behavior of the connection by tuning properties like `MinTurningRadius`, `ForwardCost`, and `ReverseCost`. You can use the `AnalyticExpansionInterval` property to set the cycle to check for the Reeds-Shepp connection.

---

**Note** The Hybrid A* planner checks for collisions in the map by interpolating the motion primitives and analytic expansion based on the `ValidationDistance` property of the `stateValidator` object. If the `ValidationDistance` property is set to `Inf`, the object interpolates based on the cell size of the map specified in the state validator. Inflate the occupancy map before assigning it to the planner to account for the vehicle size.

---

## Creation

### Syntax

```
planner = plannerHybridAStar(validator)
planner = plannerHybridAStar(validator,Name,Value)
```

#### Description

`planner = plannerHybridAStar(validator)` creates a path planner object using the Hybrid A* algorithm. Specify the `validator` input as a `validatorOccupancyMap` or `validatorVehicleCostmap` object. The `validator` input sets the value of the "StateValidator" on page 2-0 property.

`planner = plannerHybridAStar(validator,Name,Value)` sets "Properties" on page 2-1205 of the path planner by using one or more name-value pair arguments. Enclose each property name inside single quotes (' ').

### Properties

**`StateValidator` — State validator for planning**
`validatorOccupancyMap` object | `validatorVehicleCostmap` object

State validator for planning, specified either as a `validatorOccupancyMap` or `validatorVehicleCostmap` object based on SE(2) state space.

**`MotionPrimitiveLength` — Length of motion primitives to be generated**
`ceil(sqrt(2)*map_CellSize)` (default) | positive scalar

Length of motion primitives to be generated, specified as the comma-separated pair consisting of `'MotionPrimitiveLength'` and a positive scalar in meters. Increase the length for large maps or sparse environments. Decrease the length for dense environments.

---

**Note** `'MotionPrimitiveLength'` cannot exceed one-fourth the length of the circumference of a circle based on the `'MinTurningRadius'`.

---

Data Types: `double`

**`MinTurningRadius` — Minimum turning radius of vehicle**
`(2*motion_primitive_length)/pi` (default) | positive scalar

Minimum turning radius of vehicle, specified as the comma-separated pair consisting of `'MinTurningRadius'` and a positive scalar in meters.

---

**Note** The value of `'MinTurningRadius'` is set such that the `'MotionPrimitiveLength'` cannot exceed one-fourth the length of the circumference of a circle based on it.

---

Data Types: `double`

**`NumMotionPrimitives` — Number of motion primitives to be generated**
`5` (default) | positive odd integer scalar greater than or equal to 3

Number of motion primitives to be generated, specified as the comma-separated pair consisting of `'NumMotionPrimitives'` and a positive odd integer scalar greater than or equal to 3.

**`ForwardCost` — Cost multiplier to travel in forward direction**
`1` (default) | positive scalar

Cost multiplier to travel in forward direction, specified as the comma-separated pair consisting of `'ForwardCost'` and a positive scalar. Increase the cost value to penalize forward motion.

Data Types: `double`

**`ReverseCost` — Cost multiplier to travel in reverse direction**
`3` (default) | positive scalar

Cost multiplier to travel in reverse direction, specified as the comma-separated pair consisting of `'ReverseCost'` and a positive scalar. Increase the cost value to penalize reverse motion.

Data Types: `double`

**`DirectionSwitchingCost` — Additive cost for switching direction of motion**
`0` (default) | positive scalar

Additive cost for switching direction of motion, specified as the comma-separated pair consisting of `'DirectionSwitchingCost'` and a positive scalar. Increase the cost value to penalize direction switching.

Data Types: `double`

**`AnalyticExpansionInterval` — Interval for attempting analytic expansion from lowest cost node available**
5 (default) | positive integer scalar

Interval for attempting analytic expansion from the lowest cost node available at that instance, specified as the comma-separated pair consisting of `'AnalyticExpansionInterval'` and a positive integer scalar.

The Hybrid A* path planner expands the motion primitives from the nodes with the lowest cost available at that instance:

- The number of nodes to be expanded depends upon the number of primitives to be generated in both the direction and their validity, the cycle repeats until `'AnalyticExpansionInterval'` is reached.
- The planner then attempts an analytic expansion to reach the goal pose from the tree using a Reeds-Shepp model. If the attempt fails, the planner repeats the cycle.

Improve the algorithm performance by reducing the interval to increase the number of checks for a Reeds-Shepp connection to the final goal.

**`InterpolationDistance` — Distance between interpolated poses in output path**
1 (default) | positive scalar

Distance between interpolated poses in output path, specified as the comma-separated pair consisting of `'InterpolationDistance'` and a positive scalar in meters.

Data Types: `double`

## Object Functions

plan Find obstacle-free path between two poses
show Visualize the planned path

## Examples

### Obstacle-Free Path Planning Using Hybrid A Star

Plan a collision-free path for a vehicle through a parking lot by using the Hybrid A* algorithm.

#### Create and Assign Map to State Validator

Load the cost values of cells in the vehicle costmap of a parking lot.

```
load parkingLotCostVal.mat % costVal
```

Create a `binaryOccupancyMap` with cost values.

```
resolution = 3;
map = binaryOccupancyMap(costVal,resolution);
```

Create a state space.

```
ss = stateSpaceSE2;
```

Update state space bounds to be the same as map limits.

```
ss.StateBounds = [map.XWorldLimits;map.YWorldLimits;[-pi pi]];
```

Create a state validator object for collision checking.

```
sv = validatorOccupancyMap(ss);
```

Assign the map to the state validator object.

```
sv.Map = map;
```

**Plan and Visualize Path**

Initialize the `plannerHybridAStar` object with the state validator object. Specify the `MinTurningRadius` and `MotionPrimitiveLength` properties of the planner.

```
planner = plannerHybridAStar(sv, ...
                             MinTurningRadius=4, ...
                             MotionPrimitiveLength=6);
```

Define start and goal poses for the vehicle as [*x, y, theta*] vectors. *x* and *y* specify the position in meters, and *theta* specifies the orientation angle in radians.

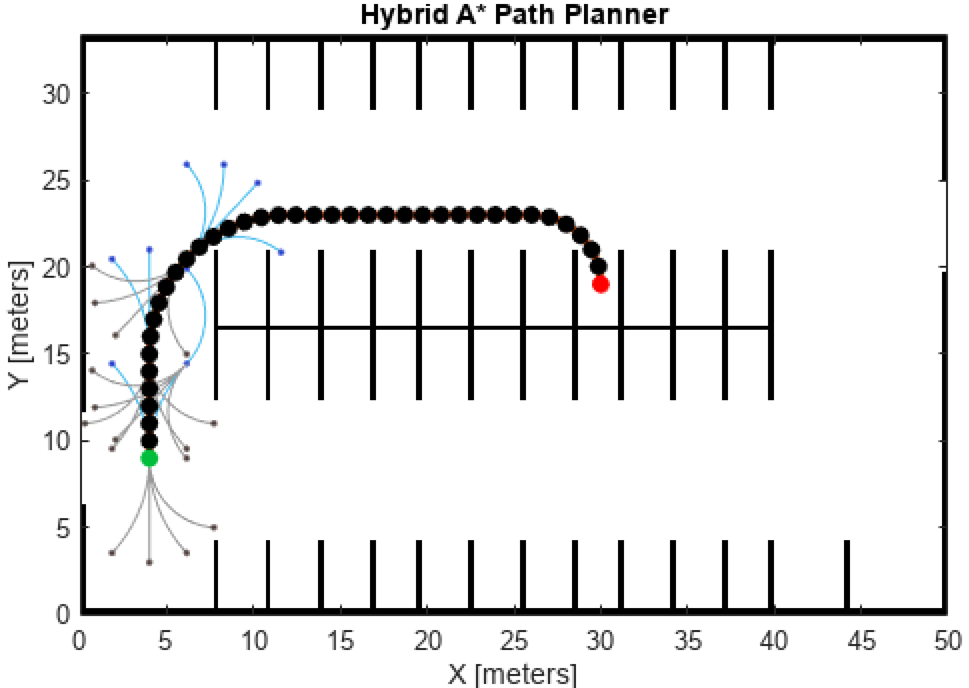
```
startPose = [4 9 pi/2]; % [meters, meters, radians]
goalPose = [30 19 -pi/2];
```

Plan a path from the start pose to the goal pose.

```
refpath = plan(planner,startPose,goalPose,SearchMode='exhaustive');
```

Visualize the path using show function.

```
show(planner)
```




## Version History

**Introduced in R2019b**

## References

[1] Dolgov, Dmitri, Sebastian Thrun, Michael Montemerlo, and James Diebel. *Practical Search Techniques in Path Planning for Autonomous Driving*. American Association for Artificial Intelligence, 2008.

[2] Petereit, Janko, Thomas Emter, Christian W. Frey, Thomas Kopfstedt, and Andreas Beutel. "Application of Hybrid A* to an Autonomous Mobile Robot for Path Planning in Unstructured Outdoor Environments." *ROBOTIK 2012: 7th German Conference on Robotics*. 2012, pp. 1-6.

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`validatorOccupancyMap` | `validatorVehicleCostmap` | `navPath`

**Topics**

“Generate Code for Path Planning Using Hybrid A Star”
“Enable Vehicle Collision Checking for Path Planning Using Hybrid A*”

# plan

Find obstacle-free path between two poses

## Syntax

```
path = plan(planner,start,goal)
[path,directions] = plan(planner,start,goal)
[path,directions,solutionInfo] = plan(planner,start,goal)
[ ___ ] = plan( ___ ,"SearchMode",mode)
```

## Description

`path = plan(planner,start,goal)` computes an obstacle-free path between start and goal poses, specified as `[x y theta]` vectors, using the input `plannerHybridAStar` object.

`[path,directions] = plan(planner,start,goal)` also returns the direction of motion for each pose along the path, `directions`, as a column vector. A value of `1` indicates forward direction and a value of `-1` indicates reverse direction. The function returns an empty column vector when the planner is unable to find a path.

`[path,directions,solutionInfo] = plan(planner,start,goal)` also returns `solutionInfo` that contains the solution information of the path planning as a structure.

`[ ___ ] = plan( ___ ,"SearchMode",mode)` specifies the search algorithm mode `mode` in addition to any combination of arguments from previous syntaxes.

## Examples

### Obstacle-Free Path Planning Using Hybrid A Star

Plan a collision-free path for a vehicle through a parking lot by using the Hybrid A* algorithm.

#### Create and Assign Map to State Validator

Load the cost values of cells in the vehicle costmap of a parking lot.

```
load parkingLotCostVal.mat % costVal
```

Create a `binaryOccupancyMap` with cost values.

```
resolution = 3;
map = binaryOccupancyMap(costVal,resolution);
```

Create a state space.

```
ss = stateSpaceSE2;
```

Update state space bounds to be the same as map limits.

```
ss.StateBounds = [map.XWorldLimits;map.YWorldLimits;[-pi pi]];
```

Create a state validator object for collision checking.

```
sv = validatorOccupancyMap(ss);
```

Assign the map to the state validator object.

```
sv.Map = map;
```

**Plan and Visualize Path**

Initialize the `plannerHybridAStar` object with the state validator object. Specify the `MinTurningRadius` and `MotionPrimitiveLength` properties of the planner.

```
planner = plannerHybridAStar(sv, ...
                             MinTurningRadius=4, ...
                             MotionPrimitiveLength=6);
```

Define start and goal poses for the vehicle as [*x*, *y*, *theta*] vectors. *x* and *y* specify the position in meters, and *theta* specifies the orientation angle in radians.

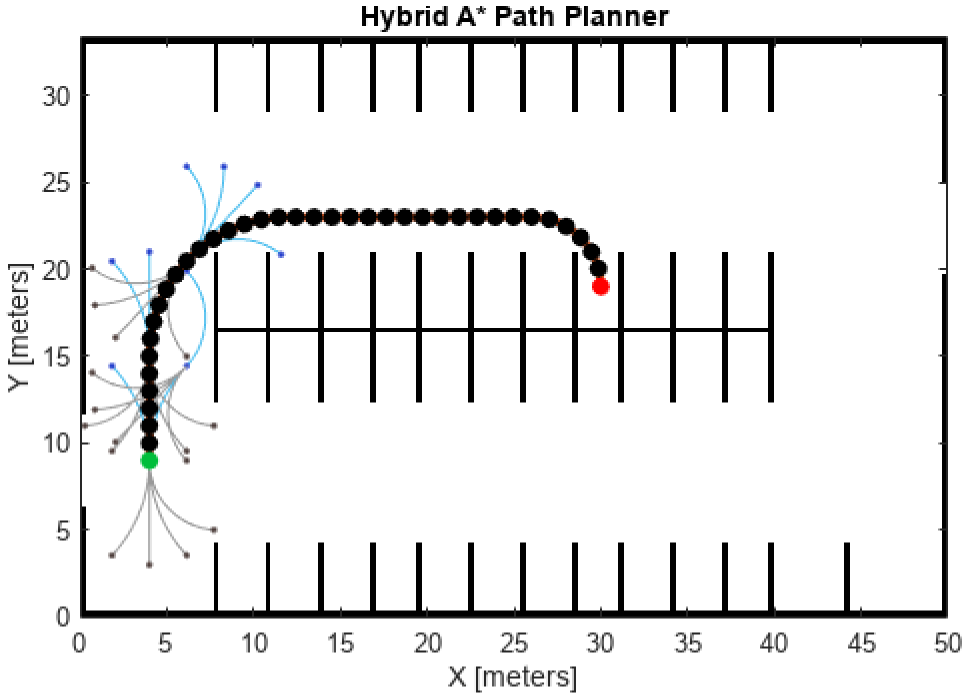
```
startPose = [4 9 pi/2]; % [meters, meters, radians]
goalPose = [30 19 -pi/2];
```

Plan a path from the start pose to the goal pose.

```
refpath = plan(planner,startPose,goalPose,SearchMode='exhaustive');
```

Visualize the path using show function.

```
show(planner)
```




## Input Arguments

**planner — Hybrid A* path planner**
plannerHybridAStar object

Hybrid A* path planner, specified as a plannerHybridAStar object.

**start — Start location of path**
three-element vector

Start location of path, specified as a 1-by-3 vector in the form [*x y theta*]. *x* and *y* specify the position in meters, and *theta* specifies the orientation angle in radians.

Example: [5 5 pi/2]

Data Types: double

**goal — Final location of path**
three-element vector

Final location of path, specified as a 1-by-3 vector in the form [*x y theta*]. *x* and *y* specify the position in meters, and *theta* specifies the orientation angle in radians.

Example: [45 45 pi/4]

Data Types: double

**mode — Search algorithm mode**
"greedy" (default) | "exhaustive"

Search algorithm mode, specified as one of these options:

- "greedy" — Prioritize finding a solution in the shortest time on average.
- "exhaustive" — Increase the number of nodes in the open set to optimize the solution.

Example: plan(phastar,start,goal,"SearchMode","greedy")

Data Types: string | char

## Output Arguments

**path — Obstacle-free path**
navPath object

Obstacle-free path, returned as a navPath object.

**directions — Directions of motion**
column vector of 1s (forward) and –1s (reverse)

Direction of motion for each pose along the path, returned as a column vector of 1s (forward) and –1s (reverse).

Data Types: double

**solutionInfo — Solution Information**
structure

Solution Information, returned as a structure. The fields of the structure are:

**Fields of solutionInfo**

| Fields | Description |
| --- | --- |
| IsPathFound | Indicates whether a path is found. It returns as 1 if a path is found. Otherwise, it returns 0. |
| NumNodes | Number of nodes in the search tree when the planner terminates (excluding the root node). |
| NumIterations | Number of planning iterations executed. |

Data Types: struct

# Version History

**Introduced in R2019b**

**R2022b: Set search algorithm mode with name-value argument**

Use the SearchMode name-value argument to set the search algorithm mode.

## Extended Capabilities

### C/C++ Code Generation
Generate C and C++ code using MATLAB® Coder™.

## See Also
`validatorOccupancyMap` | `validatorVehicleCostmap` | `navPath`

### Topics
"Enable Vehicle Collision Checking for Path Planning Using Hybrid A*"

# show

Visualize the planned path

## Syntax

```
show(planner)
show(planner,Name,Value)
axHandle = show(planner)
```

## Description

`show(planner)` plots the Hybrid A* expansion tree and the planned path in the map.

`show(planner,Name,Value)` specifies additional options using one or more name-value pair arguments.

`axHandle = show(planner)` outputs the axes handle of the figure used to plot the path.

## Examples

### Obstacle-Free Path Planning Using Hybrid A Star

Plan a collision-free path for a vehicle through a parking lot by using the Hybrid A* algorithm.

#### Create and Assign Map to State Validator

Load the cost values of cells in the vehicle costmap of a parking lot.

```
load parkingLotCostVal.mat % costVal
```

Create a `binaryOccupancyMap` with cost values.

```
resolution = 3;
map = binaryOccupancyMap(costVal,resolution);
```

Create a state space.

```
ss = stateSpaceSE2;
```

Update state space bounds to be the same as map limits.

```
ss.StateBounds = [map.XWorldLimits;map.YWorldLimits;[-pi pi]];
```

Create a state validator object for collision checking.

```
sv = validatorOccupancyMap(ss);
```

Assign the map to the state validator object.

```
sv.Map = map;
```

### Plan and Visualize Path

Initialize the `plannerHybridAStar` object with the state validator object. Specify the `MinTurningRadius` and `MotionPrimitiveLength` properties of the planner.

```
planner = plannerHybridAStar(sv, ...
                             MinTurningRadius=4, ...
                             MotionPrimitiveLength=6);
```

Define start and goal poses for the vehicle as [*x*, *y*, *theta*] vectors. *x* and *y* specify the position in meters, and *theta* specifies the orientation angle in radians.

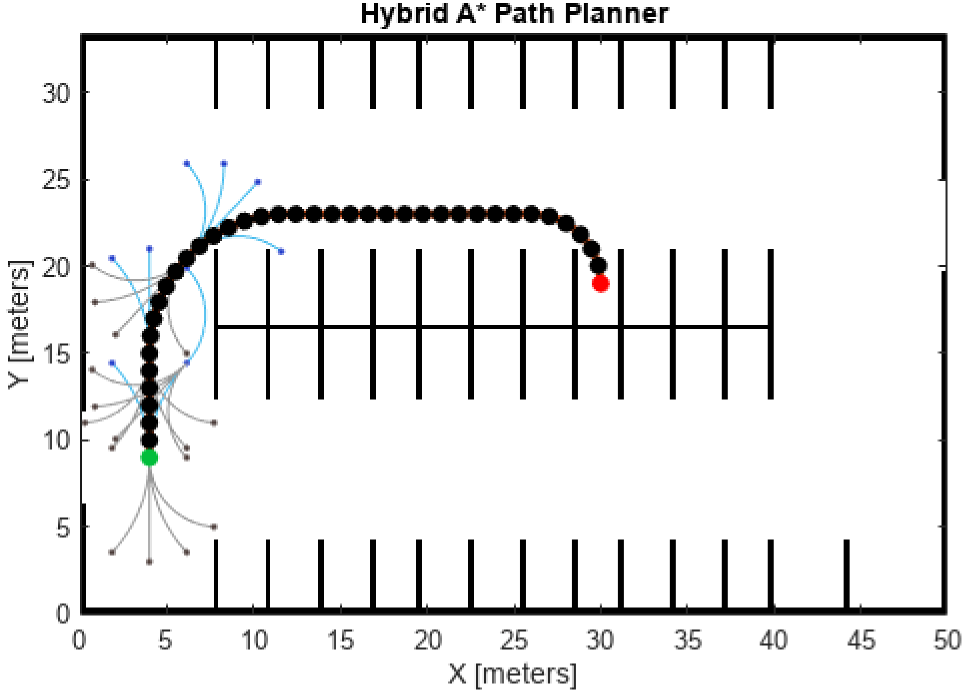
```
startPose = [4 9 pi/2]; % [meters, meters, radians]
goalPose = [30 19 -pi/2];
```

Plan a path from the start pose to the goal pose.

```
refpath = plan(planner,startPose,goalPose,SearchMode='exhaustive');
```

Visualize the path using show function.

```
show(planner)
```




## Input Arguments

**planner — Hybrid A* path planner**
`plannerHybridAStar` object

Hybrid A* path planner, specified as a `plannerHybridAStar` object.

### Name-Value Pair Arguments

Specify optional pairs of arguments as `Name1=Value1,...,NameN=ValueN`, where `Name` is the argument name and `Value` is the corresponding value. Name-value arguments must appear after other arguments, but the order of the pairs does not matter.

*Before R2021a, use commas to separate each name and value, and enclose* `Name` *in quotes.*

Example: `'Positions','none'`

**`Parent` — Axes used to plot path**
`Axes` object | `UIAxes` object

Axes used to plot path, specified as the comma-separated pair consisting of `'Parent'` and either an `axes` or `uiaxes` object. If you do not specify `'Parent'`, a new figure is created.

**`Tree` — Display expansion tree**
`'on'` (default) | `'off'`

Display expansion tree option, specified as the comma-separated pair consisting of `'Tree'` and either `'on'` or `'off'`.

Example: `show(planner,'Tree','off')`

Data Types: `string`

**`Path` — Display planned path**
`'on'` (default) | `'off'`

Display planned path option, specified as the comma-separated pair consisting of `'Path'` and either `'on'` or `'off'`.

Example: `show(planner,'Path','off')`

Data Types: `string`

**`Positions` — Display start and goal points**
`'both'` (default) | `'start'` | `'goal'` | `'none'`

Display the start and goal points, specified as the comma-separated pair consisting of `'Positions'` and one of the following:

- `'start'` — Display the start point.
- `'goal'` — Display the goal point.
- `'both'` — Display the start and goal points.
- `'none'` — Do not display any points.

Example: `show(planner,'Positions','start')`

Data Types: `string`

**`HeadingLength` — Length of heading**
`0.4*InterpolationDistance` (default) | positive numeric scalar

Length of heading, specified as positive numeric scalar. No poses will be visualized when this value is set to 0.

Data Types: `single` | `double`

## Output Arguments

**`axHandle` — Axes used to plot path**
`Axes` object | `UIAxes` object

Axes used to plot path, returned as either an `axes` or `uiaxes` object.

# Version History

**Introduced in R2019b**

## See Also

`validatorOccupancyMap` | `validatorVehicleCostmap` | `navPath`

# plannerPRM

Create probabilistic roadmap path planner

## Description

The probabilistic roadmap path planner constructs a roadmap without start and goal states. Use the `plan` function to find an obstacle-free path between the specified start and goal states. If the `plan` function does not find a connected path between the start and the goal states, it returns an empty path.

## Creation

### Syntax

```
planner = plannerPRM(stateSpace,stateVal)
planner = plannerPRM( ___ ,Name=Value)
```

#### Description

`planner = plannerPRM(stateSpace,stateVal)` creates a PRM planner from a state space object, `stateSpace`, and a state validator object, `stateVal`. The state space of `stateVal` must be the same as `stateSpace`. `stateSpace` and `stateVal` also sets the `StateSpace` and `StateValidator` properties, respectively, of the planner.

`planner = plannerPRM( ___ ,Name=Value)` sets properties using one or more name-value pair arguments in addition to the input arguments in the previous syntax. You can specify the `MaxNumNodes` or `MaxConnectionDistance` properties as name-value pairs.

## Properties

**`StateSpace` — State space for planner**
state space object

State space for the planner, specified as a state space object. You can use state space objects such as `stateSpaceSE2`, `stateSpaceDubins`, and `stateSpaceReedsShepp`. You can also customize a state space object using the `nav.StateSpace` object.

**`StateValidator` — State validator for planner**
state validator object

State validator for the planner, specified as a state validator object. You can use state validator objects such as `validatorOccupancyMap` and `validatorVehicleCostmap`. You can also customize a state validator object using the `nav.StateValidator` object.

**`MaxNumNodes` — Maximum number of nodes in graph**
`50` (default) | positive scalar

Maximum number of nodes in the graph, specified as a positive scalar. By increasing this value, the chance of finding a path increases while also increasing the computation time for the path planner.

**`MaxConnectionDistance` — Maximum connection distance between two states**
`inf` (default) | positive scalar

Maximum distance between two connected nodes, specified as a positive scalar in meters. Nodes with distance greater than this value will not be connected in the graph.

## Object Functions

| | |
|---|---|
| copy | Create deep copy of plannerPRM object |
| graphData | Retrieve graph as digraph object |
| plan | Plan path between start and goal states on roadmap |

## Examples

### Plan Obstacle-Free Path Using Probabilistic Roadmap Path Planner

Create an occupancy map from an example map and set the map resolution as 10 cells/meter.

```
map = load("exampleMaps.mat").simpleMap;
map = occupancyMap(map,10);
```

Create a state space and update the state space bounds to be the same as the map limits.

```
ss = stateSpaceSE2;
ss.StateBounds = [map.XWorldLimits; map.YWorldLimits; [-pi pi]];
```

Create a state validator with `stateSpaceSE2` using the map and set the validation distance.

```
sv = validatorOccupancyMap(ss,Map=map);
sv.ValidationDistance = 0.01;
```

Create a `plannerPRM` object.

```
planner = plannerPRM(ss,sv);
```

Retrieve graph as a digraph object.

```
graph = graphData(planner);
```

Extract nodes and edges from graph.

```
edges = table2array(graph.Edges);
nodes = table2array(graph.Nodes);
```

Specify the start and goal states.

```
start = [0.5 0.5 0];
goal = [2.5 0.2 0];
```

Plot map and graph.

```
show(sv.Map)
hold on
```

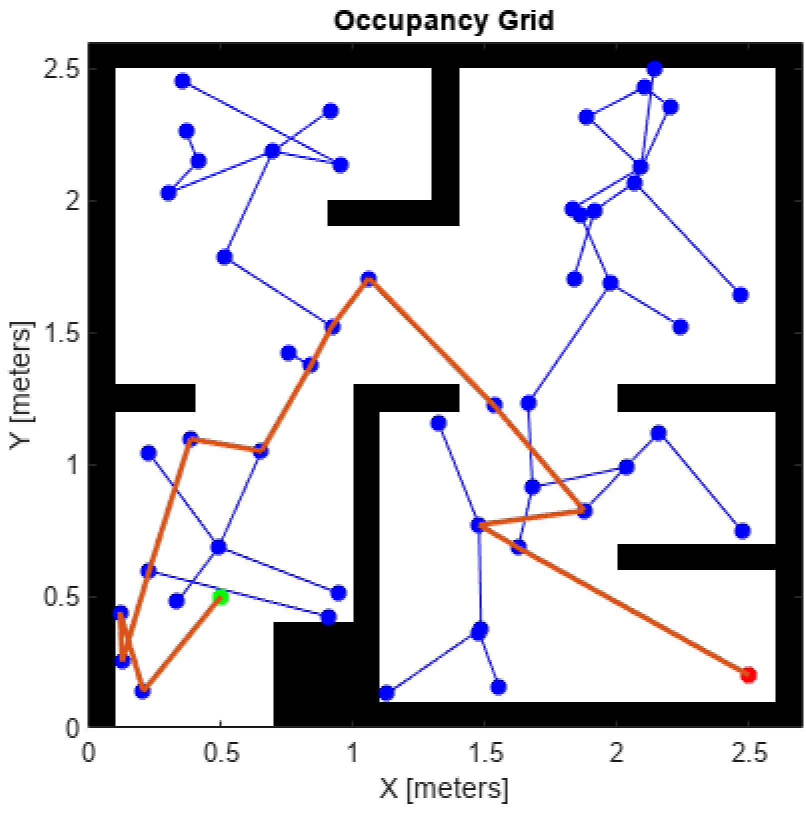
```
plot(nodes(:,1),nodes(:,2),"*","Color","b","LineWidth",2)
for i = 1:size(edges,1)
    % Samples states at distance 0.02 meters.
    states = interpolate(ss,nodes(edges(i,1),:), ...
                         nodes(edges(i,2),:),0:0.02:1);
    plot(states(:,1),states(:,2),"Color","b")
end
plot(start(1),start(2),"*","Color","g","LineWidth",3)
plot(goal(1),goal(2),"*","Color","r","LineWidth",3)
```

Plan a path with default settings. Set the `rng` seed for repeatability.

```
rng(100,"twister");
[pthObj, solnInfo] = plan(planner,start,goal);
```

Visualize the results.

```
if solnInfo.IsPathFound
    interpolate(pthObj,1000);
    plot(pthObj.States(:,1),pthObj.States(:,2), ...
         "Color",[0.85 0.325 0.098],"LineWidth",2)
else
    disp("Path not found")
end
hold off
```



**Plan Path Through 3-D Occupancy Map Using Probabilistic Roadmap Planner**

Load a 3-D occupancy map of a city block into the workspace. Specify the threshold to consider cells as obstacle-free.

```
mapData = load("dMapCityBlock.mat");
omap = mapData.omap;
omap.FreeThreshold = 0.5;
```

Inflate the occupancy map to add a buffer zone for safe operation around the obstacles.

```
inflate(omap,1)
```

Create an SE(3) state space object with bounds for state variables.

```
ss = stateSpaceSE3([0 220;0 220;0 100;inf inf;inf inf;inf inf;inf inf]);
```

Create a 3-D occupancy map state validator using the created state space. Assign the occupancy map to the state validator object. Specify the sampling distance interval.

```
sv = validatorOccupancyMap3D(ss, ...
     Map = omap, ...
     ValidationDistance = 0.1);
```

Create a probabilistic roadmap path planner with increased maximum connection distance.

```
planner = plannerPRM(ss,sv);
```

Specify start and goal poses.

```
start = [40 180 25 0.7 0.2 0 0.1];
goal = [150 33 35 0.3 0 0.1 0.6];
```

Configure the random number generator for repeatable result.

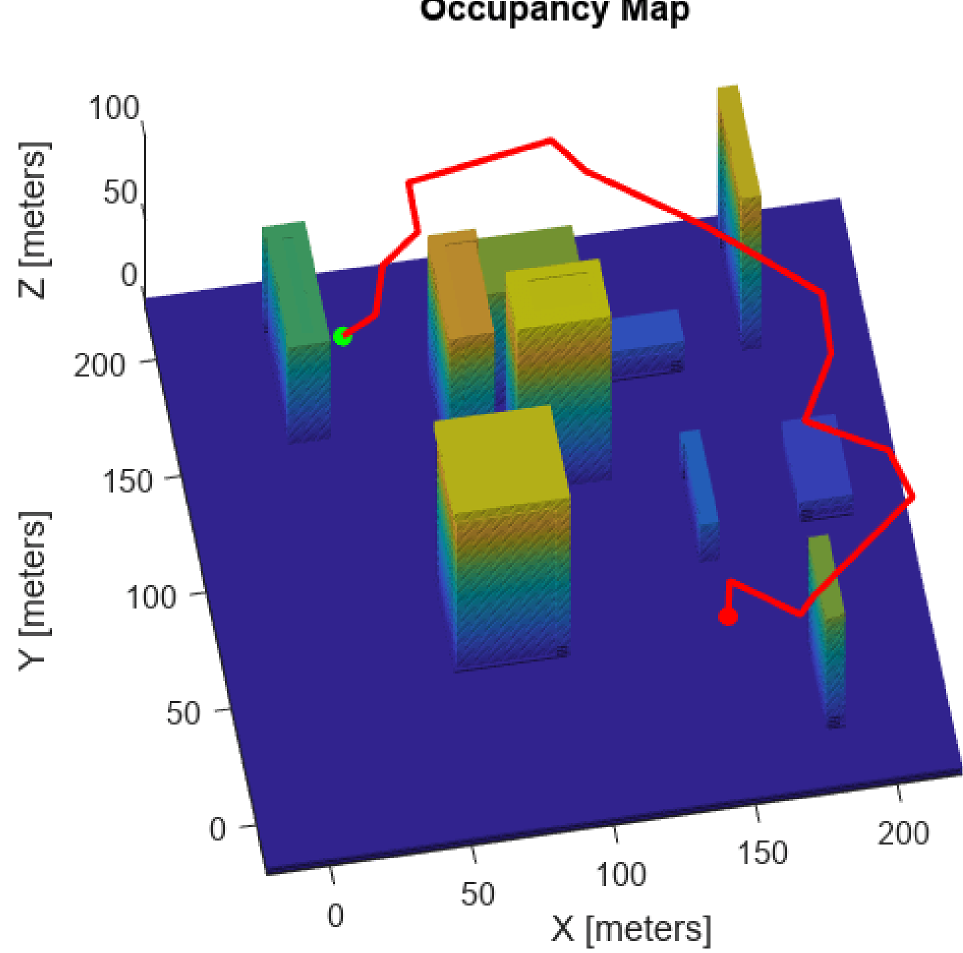
```
rng(1,"twister");
```

Plan the path.

```
[pthObj,solnInfo] = plan(planner,start,goal);
```

Visualize the planned path.

```
show(omap)
axis equal
view([-10 55])
hold on
% Start state
scatter3(start(1,1),start(1,2),start(1,3),"g","filled")
% Goal state
scatter3(goal(1,1),goal(1,2),goal(1,3),"r","filled")
% Path
plot3(pthObj.States(:,1),pthObj.States(:,2),pthObj.States(:,3), ...
      "r-",LineWidth=2)
```




## Version History

**Introduced in R2022a**

### References

[1] L.E. Kavraki, P. Svestka, J.C. Latombe, M.H. Overmars, "Probabilistic roadmaps for path planning in high-dimensional configuration spaces," *IEEE Transactions on Robotics and Automation*, Vol. 12, No. 4, pp. 566-580, Aug 1996.

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Functions**
`copy` | `graphData` | `plan`

# plannerRRT

Create an RRT planner for geometric planning

## Description

The `plannerRRT` object creates a rapidly-exploring random tree (RRT) planner for solving geometric planning problems. RRT is a tree-based motion planner that builds a search tree incrementally from samples randomly drawn from a given state space. The tree eventually spans the search space and connects the start state to the goal state. The general tree growing process is as follows:

1. The planner samples a random state $x_{rand}$ in the state space.
2. The planner finds a state $x_{near}$ that is already in the search tree and is closest (based on the distance definition in the state space) to $x_{rand}$.
3. The planner expands from $x_{near}$ towards $x_{rand}$, until a state $x_{new}$ is reached.
4. Then new state $x_{new}$ is added to the search tree.

For geometric RRT, the expansion and connection between two states can be found analytically without violating the constraints specified in the state space of the planner object.

## Creation

### Syntax

```
planner = plannerRRT(stateSpace,stateVal)
planner = plannerRRT( ___ ,Name=Value)
```

#### Description

`planner = plannerRRT(stateSpace,stateVal)` creates an RRT planner from a state space object, `stateSpace`, and a state validator object, `stateVal`. The state space of `stateVal` must be the same as `stateSpace`. `stateSpace` and `stateVal` also sets the StateSpace and StateValidator properties of the `planner`.

`planner = plannerRRT( ___ ,Name=Value)` sets properties using one or more name-value arguments in addition to the input arguments in the previous syntax. You can specify the MaxNumTreeNodes, MaxIterations, MaxConnectionDistance, GoalReachedFcn, and GoalBias properties as name-value arguments.

## Properties

**`StateSpace` — State space for the planner**
state space object

State space for the planner, specified as a state space object. You can use state space objects such as `stateSpaceSE2`, `stateSpaceDubins`, `stateSpaceReedsShepp`, and `stateSpaceSE3`. You can also customize a state space object using the `nav.StateSpace` object.

**`StateValidator` — State validator for the planner**
state validator object

State validator for the planner, specified as a state validator object. You can use state validator objects such as `validatorOccupancyMap`, `validatorVehicleCostmap`, and `validatorOccupancyMap3D`.

**`MaxNumTreeNodes` — Maximum number of nodes in the search tree**
`1e4` (default) | positive integer

Maximum number of nodes in the search tree (excluding the root node), specified as a positive integer.

Example: `MaxNumTreeNodes=2500`

Data Types: `single` | `double`

**`MaxIterations` — Maximum number of iterations**
`1e4` (default) | positive integer

Maximum number of iterations, specified as a positive integer.

Example: `MaxIterations=2500`

Data Types: `single` | `double`

**`MaxConnectionDistance` — Maximum length of motion**
`0.1` (default) | positive scalar

Maximum length of a motion allowed in the tree, specified as a scalar.

Example: `MaxConnectionDistance=0.3`

Data Types: `single` | `double`

**`GoalReachedFcn` — Callback function to evaluate whether goal is reached**
`@nav.algs.checkIfGoalIsReached` | function handle

Callback function to evaluate whether the goal is reached, specified as a function handle. You can create your own goal reached function. The function must follow this syntax:

```
function isReached = myGoalReachedFcn(planner,currentState,goalState)
```

where:

- `planner` — The created planner object, specified as `plannerRRT` object.
- `currentState` — The current state, specified as a three element real vector.
- `goalState` — The goal state, specified as a three element real vector.
- `isReached` — A boolean variable to indicate whether the current state has reached the goal state, returned as `true` or `false`.

To use custom `GoalReachedFcn` in code generation workflow, this property must be set to a custom function handle before calling the plan function and it cannot be changed after initialization.

Data Types: `function handle`

**`GoalBias` — Probability of choosing goal state during state sampling**
`0.05` (default) | real scalar in range [0,1]

Probability of choosing the goal state during state sampling, specified as a real scalar in range [0,1]. The property defines the probability of choosing the actual goal state during the process of randomly selecting states from the state space. You can start by setting the probability to a small value such as `0.05`.

Example: `GoalBias=0.1`

Data Types: `single` | `double`

## Object Functions

| | |
|---|---|
| plan | Plan path between two states |
| copy | Create copy of planner object |

## Examples

### Plan Path Between Two States

Create a state space.

```
ss = stateSpaceSE2;
```

Create an `occupancyMap`-based state validator using the created state space.

```
sv = validatorOccupancyMap(ss);
```

Create an occupancy map from an example map and set map resolution as 10 cells/meter.

```
load exampleMaps
map = occupancyMap(simpleMap,10);
sv.Map = map;
```

Set validation distance for the validator.

```
sv.ValidationDistance = 0.01;
```

Update state space bounds to be the same as map limits.

```
ss.StateBounds = [map.XWorldLimits;map.YWorldLimits;[-pi pi]];
```

Create the path planner and increase the maximum connection distance.

```
planner = plannerRRT(ss,sv,MaxConnectionDistance=0.3);
```

Set the start and goal states.

```
start = [0.5 0.5 0];
goal = [2.5 0.2 0];
```

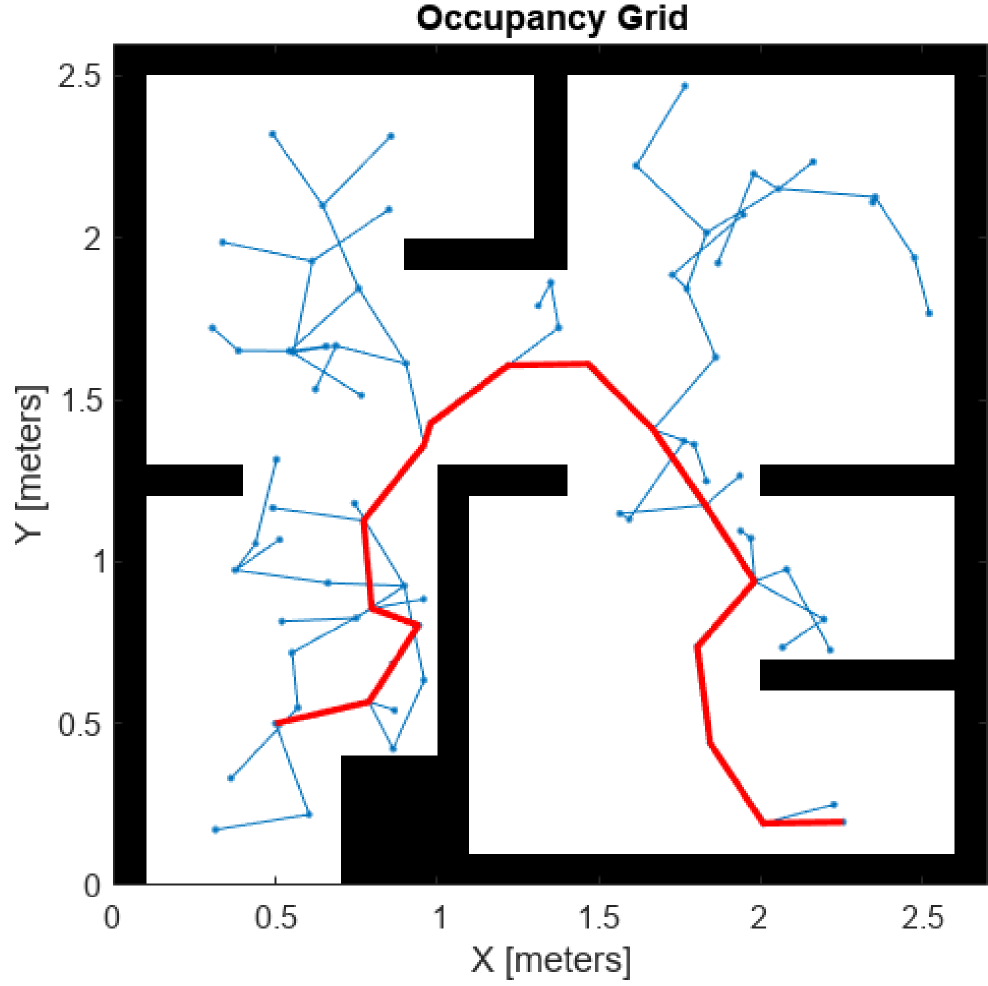
Plan a path with default settings.

```
rng(100,'twister'); % for repeatable result
[pthObj,solnInfo] = plan(planner,start,goal);
```

Visualize the results.

```
show(map)
hold on
```

```
% Tree expansion
plot(solnInfo.TreeData(:,1),solnInfo.TreeData(:,2),'.-')
% Draw path
plot(pthObj.States(:,1),pthObj.States(:,2),'r-','LineWidth',2)
```




### Plan Path Through 3-D Occupancy Map Using RRT Planner

Load a 3-D occupancy map of a city block into the workspace. Specify the threshold to consider cells as obstacle-free.

```
mapData = load("dMapCityBlock.mat");
omap = mapData.omap;
omap.FreeThreshold = 0.5;
```

Inflate the occupancy map to add a buffer zone for safe operation around the obstacles.

```
inflate(omap,1)
```

Create an SE(3) state space object with bounds for state variables.

```
ss = stateSpaceSE3([0 220;0 220;0 100;inf inf;inf inf;inf inf;inf inf]);
```

Create a 3-D occupancy map state validator using the created state space. Assign the occupancy map to the state validator object. Specify the sampling distance interval.

```
sv = validatorOccupancyMap3D(ss, ...
     Map = omap, ...
     ValidationDistance = 0.1);
```

Create a RRT path planner with increased maximum connection distance and reduced maximum number of iterations. Specify a custom goal function that determines that a path reaches the goal if the Euclidean distance to the target is below a threshold of 1 meter.

```
planner = plannerRRT(ss,sv, ...
          MaxConnectionDistance = 50, ...
          MaxIterations = 1000, ...
          GoalReachedFcn = @(~,s,g)(norm(s(1:3)-g(1:3))<1), ...
          GoalBias = 0.1);
```

Specify start and goal poses.

```
start = [40 180 25 0.7 0.2 0 0.1];
goal = [150 33 35 0.3 0 0.1 0.6];
```

Configure the random number generator for repeatable result.

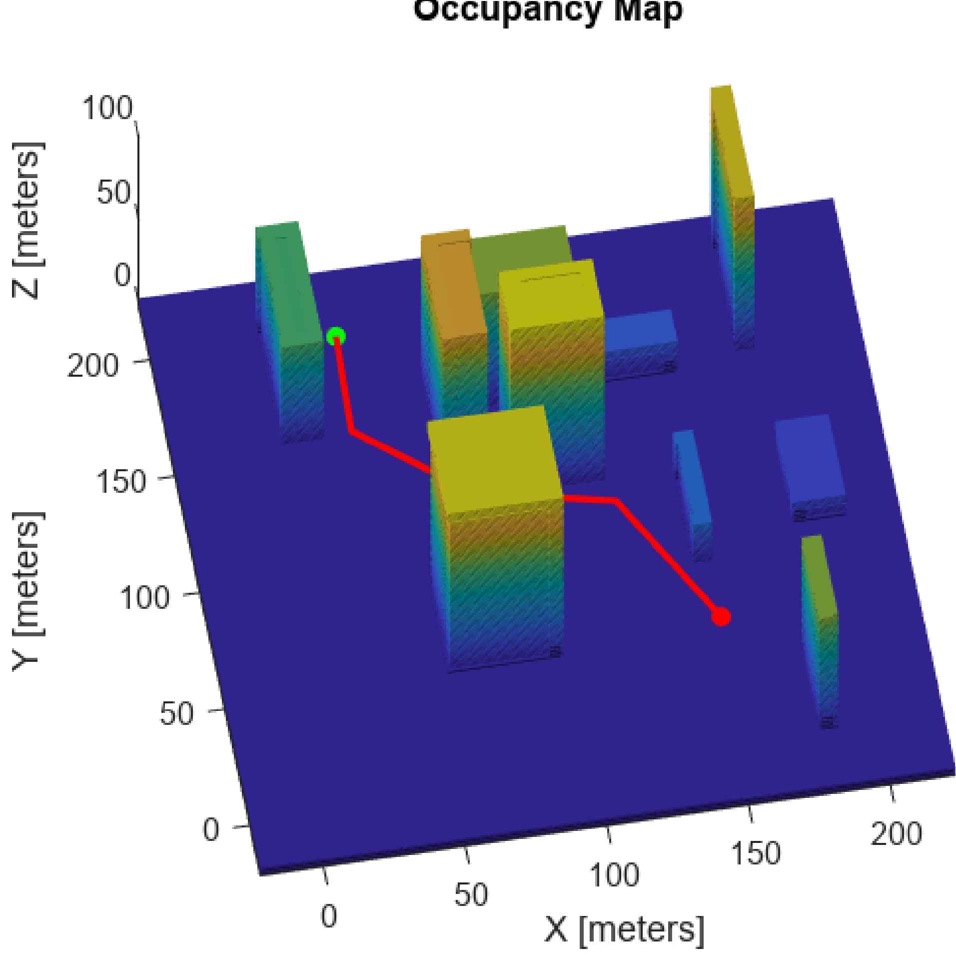
```
rng(1,"twister");
```

Plan the path.

```
[pthObj,solnInfo] = plan(planner,start,goal);
```

Visualize the planned path.

```
show(omap)
axis equal
view([-10 55])
hold on
% Start state
scatter3(start(1,1),start(1,2),start(1,3),"g","filled")
% Goal state
scatter3(goal(1,1),goal(1,2),goal(1,3),"r","filled")
% Path
plot3(pthObj.States(:,1),pthObj.States(:,2),pthObj.States(:,3), ...
      "r-",LineWidth=2)
```




## Version History

**Introduced in R2019b**

## References

[1] S.M. Lavalle and J.J. Kuffner. "Randomized Kinodynamic Planning." *The International Journal of Robotics Research*. Vol. 20, Number 5, 2001, pp. 378 – 400.

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

Usage notes and limitations:

- To use custom GoalReachedFcn in code generation workflow, this property must be set to a custom function handle before calling the plan function and it cannot be changed after initialization.

## See Also

**Objects**
`plannerRRTStar` | `plannerBiRRT` | `stateSpaceReedsShepp` | `stateSpaceDubins` | `stateSpaceSE2` | `stateSpaceSE3` | `validatorOccupancyMap` | `validatorVehicleCostmap` | `validatorOccupancyMap3D`

**Functions**
`plan` | `copy`

# plannerRRTStar

Create an optimal RRT path planner (RRT*)

## Description

The `plannerRRTStar` object creates an asymptotically-optimal RRT planner, RRT*. The RRT* algorithm converges to an optimal solution in terms of the state space distance. Also, its runtime is a constant factor of the runtime of the RRT algorithm. RRT* is used to solve geometric planning problems. A geometric planning problem requires that any two random states drawn from the state space can be connected.

## Creation

### Syntax

```
planner = plannerRRTStar(stateSpace,stateVal)
planner = plannerRRTStar( ___ ,Name=Value)
```

#### Description

`planner = plannerRRTStar(stateSpace,stateVal)` creates an RRT* planner from a state space object, `stateSpace`, and a state validator object, `stateVal`. The state space of `stateVal` must be the same as `stateSpace`. `stateSpace` and `stateVal` also sets the StateSpace and StateValidator properties of the `planner` object.

`planner = plannerRRTStar( ___ ,Name=Value)` sets properties using one or more name-value arguments in addition to the input arguments in the previous syntax. You can specify the BallRadiusConstant, ContinueAfterGoalReached, MaxNumTreeNodes, MaxIterations, MaxConnectionDistance, GoalReachedFcn, and GoalBias properties as name-value arguments.

### Properties

**`StateSpace` — State space for the planner**
state space object

State space for the planner, specified as a state space object. You can use state space objects such as `stateSpaceSE2`, `stateSpaceDubins`, `stateSpaceReedsShepp`, and `stateSpaceSE3`. You can also customize a state space object using the `nav.StateSpace` object.

**`StateValidator` — State validator for the planner**
state validator object

State validator for the planner, specified as a state validator object. You can use state validator objects such as `validatorOccupancyMap`, `validatorVehicleCostmap`, and `validatorOccupancyMap3D`.

**`BallRadiusConstant` — Constant used to estimate the near neighbors search radius**
`100` (default) | positive scalar

Constant used to estimate the near neighbors search radius, specified as a positive scalar. The radius is estimated as following:

$$r = \min\left(\gamma\left(\frac{\log(n)}{n}\right)^{\frac{1}{d}}, \eta\right)$$

where:

- $\gamma$ — The value of the `BallRadiusConstant` property
- $n$ — Current number of nodes in the tree
- $d$ — Dimension of the state space
- $\eta$ — The value of the `MaxConnectionDistance` property

$\gamma$ is defined as following:

$$\gamma = 2^d\left(1 + \frac{1}{d}\right)\left(\frac{V_{Free}}{V_{Ball}}\right)$$

where:

- $V_{Free}$ — Approximate free volume in search-space
- $V_{Ball}$ — Volume of unit ball in $d$ dimensions

The formulae above define a `BallRadiusConstant` of "appropriate" size for a given space, meaning that as the number of nodes filling the space grows and the radius shrinks, the expected number of neighbors grows logarithmically. Higher values will result in a higher average number of neighbors within the $d$-ball per iteration, leading to more rewire candidates. However, values below this suggested minimum could lead to a single nearby neighbor, which fails to produce asymptotically optimal results.

Example: `BallRadiusConstant=80`

Data Types: `single` | `double`

### `ContinueAfterGoalReached` — Continue to optimize after goal is reached

`false` (default) | `true`

Decide if the planner continues to optimize after the goal is reached, specified as `false` or `true`. The planner also terminates regardless of the value of this property if the maximum number of iterations or maximum number of tree nodes is reached.

Example: `ContinueAfterGoalReached=true`

Data Types: `logical`

### `MaxNumTreeNodes` — Maximum number of nodes in the search tree

`1e4` (default) | positive integer

Maximum number of nodes in the search tree (excluding the root node), specified as a positive integer.

Example: `MaxNumTreeNodes=2500`

Data Types: `single` | `double`

**`MaxIterations` — Maximum number of iterations**
`1e4` (default) | positive integer

Maximum number of iterations, specified as a positive integer.

Example: `MaxIterations=2500`

Data Types: `single` | `double`

**`MaxConnectionDistance` — Maximum length of motion**
`0.1` (default) | positive scalar

Maximum length of a motion allowed in the tree, specified as a scalar.

Example: `MaxConnectionDistance=0.3`

Data Types: `single` | `double`

**`GoalReachedFcn` — Callback function to determine whether goal is reached**
`@nav.algs.checkIfGoalIsReached` | function handle

Callback function to determine whether the goal is reached, specified as a function handle. You can create your own goal reached function. The function must follow this syntax:

```
function isReached = myGoalReachedFcn(planner,currentState,goalState)
```

where:

- `planner` — The created planner object, specified as `plannerRRTStar` object.
- `currentState` — The current state, specified as a three element real vector.
- `goalState` — The goal state, specified as a three element real vector.
- `isReached` — A boolean variable to indicate whether the current state has reached the goal state, returned as `true` or `false`.

To use custom `GoalReachedFcn` in code generation workflow, this property must be set to a custom function handle before calling the plan function and it cannot be changed after initialization.

Data Types: `function handle`

**`GoalBias` — Probability of choosing goal state during state sampling**
`0.05` (default) | real scalar in range [0,1]

Probability of choosing the goal state during state sampling, specified as a real scalar in range [0,1]. The property defines the probability of choosing the actual goal state during the process of randomly selecting states from the state space. You can start by setting the probability to a small value such as `0.05`.

Example: `GoalBias=0.1`

Data Types: `single` | `double`

## Object Functions

| | |
|---|---|
| plan | Plan path between two states |
| copy | Create copy of planner object |

## Examples

### Plan Optimal Path Between Two States

Create a state space.

```
ss = stateSpaceSE2;
```

Create an `occupancyMap`-based state validator using the created state space.

```
sv = validatorOccupancyMap(ss);
```

Create an occupancy map from an example map and set map resolution as 10 cells/meter.

```
load exampleMaps.mat
map = occupancyMap(simpleMap,10);
sv.Map = map;
```

Set validation distance for the validator.

```
sv.ValidationDistance = 0.01;
```

Update state space bounds to be the same as map limits.

```
ss.StateBounds = [map.XWorldLimits; map.YWorldLimits; [-pi pi]];
```

Create RRT* path planner and allow further optimization after goal is reached. Reduce the maximum iterations and increase the maximum connection distance.

```
planner = plannerRRTStar(ss,sv, ...
          ContinueAfterGoalReached=true, ...
          MaxIterations=2500, ...
          MaxConnectionDistance=0.3);
```

Set the start and goal states.

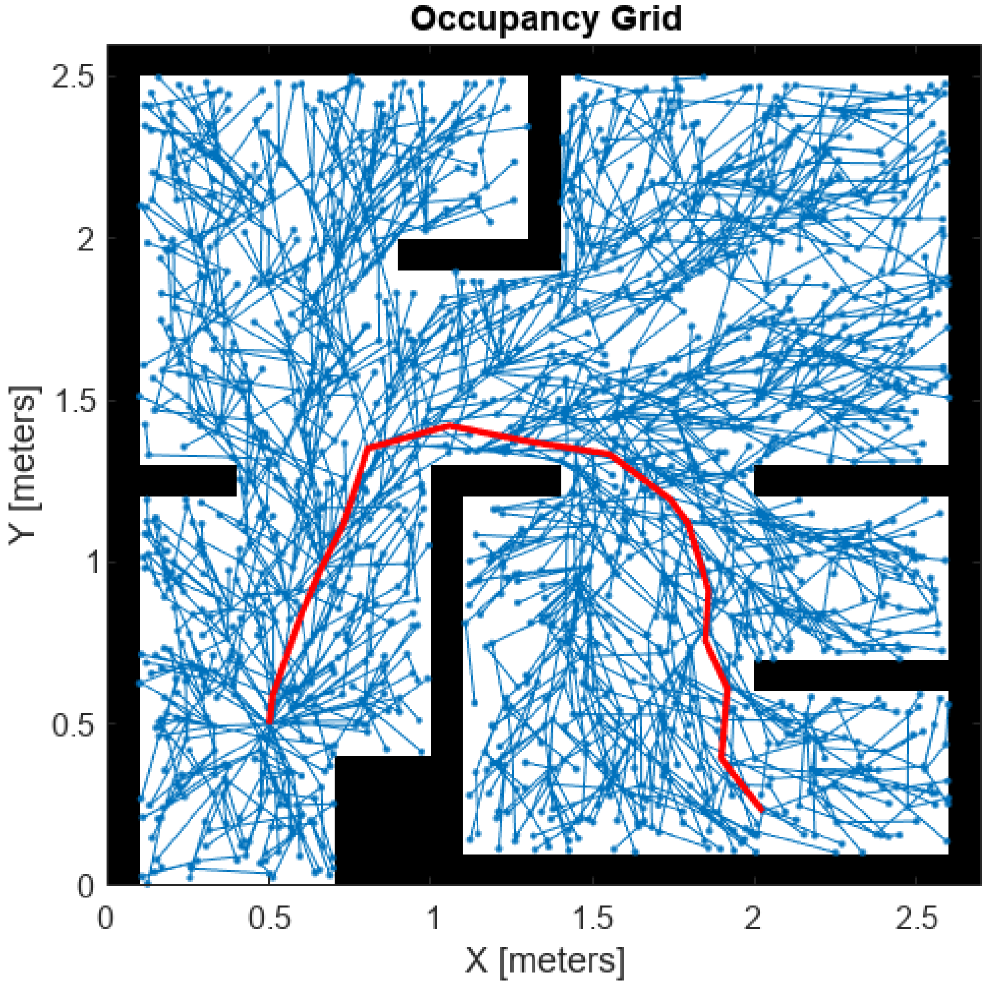
```
start = [0.5 0.5 0];
goal = [2.5 0.2 0];
```

Plan a path with default settings.

```
rng(100,'twister') % repeatable result
[pthObj,solnInfo] = plan(planner,start,goal);
```

Visualize the results.

```
map.show
hold on
% Tree expansion
plot(solnInfo.TreeData(:,1),solnInfo.TreeData(:,2),'.-')
% Draw path
plot(pthObj.States(:,1),pthObj.States(:,2),'r-','LineWidth',2)
```




### Plan Path Through 3-D Occupancy Map Using RRT Star Planner

Load a 3-D occupancy map of a city block into the workspace. Specify the threshold to consider cells as obstacle-free.

```
mapData = load("dMapCityBlock.mat");
omap = mapData.omap;
omap.FreeThreshold = 0.5;
```

Inflate the occupancy map to add a buffer zone for safe operation around the obstacles.

```
inflate(omap,1)
```

Create an SE(3) state space object with bounds for state variables.

```
ss = stateSpaceSE3([0 220;0 220;0 100;inf inf;inf inf;inf inf;inf inf]);
```

Create a 3-D occupancy map state validator using the created state space. Assign the occupancy map to the state validator object. Specify the sampling distance interval.

```
sv = validatorOccupancyMap3D(ss, ...
     Map = omap, ...
     ValidationDistance = 0.1);
```

Create a RRT star path planner with increased maximum connection distance and reduced maximum number of iterations. Specify a custom goal function that determines that a path reaches the goal if the Euclidean distance to the target is below a threshold of 1 meter.

```
planner = plannerRRTStar(ss,sv, ...
          MaxConnectionDistance = 50, ...
          MaxIterations = 1000, ...
          GoalReachedFcn = @(~,s,g)(norm(s(1:3)-g(1:3))<1), ...
          GoalBias = 0.1);
```

Specify start and goal poses.

```
start = [40 180 25 0.7 0.2 0 0.1];
goal = [150 33 35 0.3 0 0.1 0.6];
```

Configure the random number generator for repeatable result.

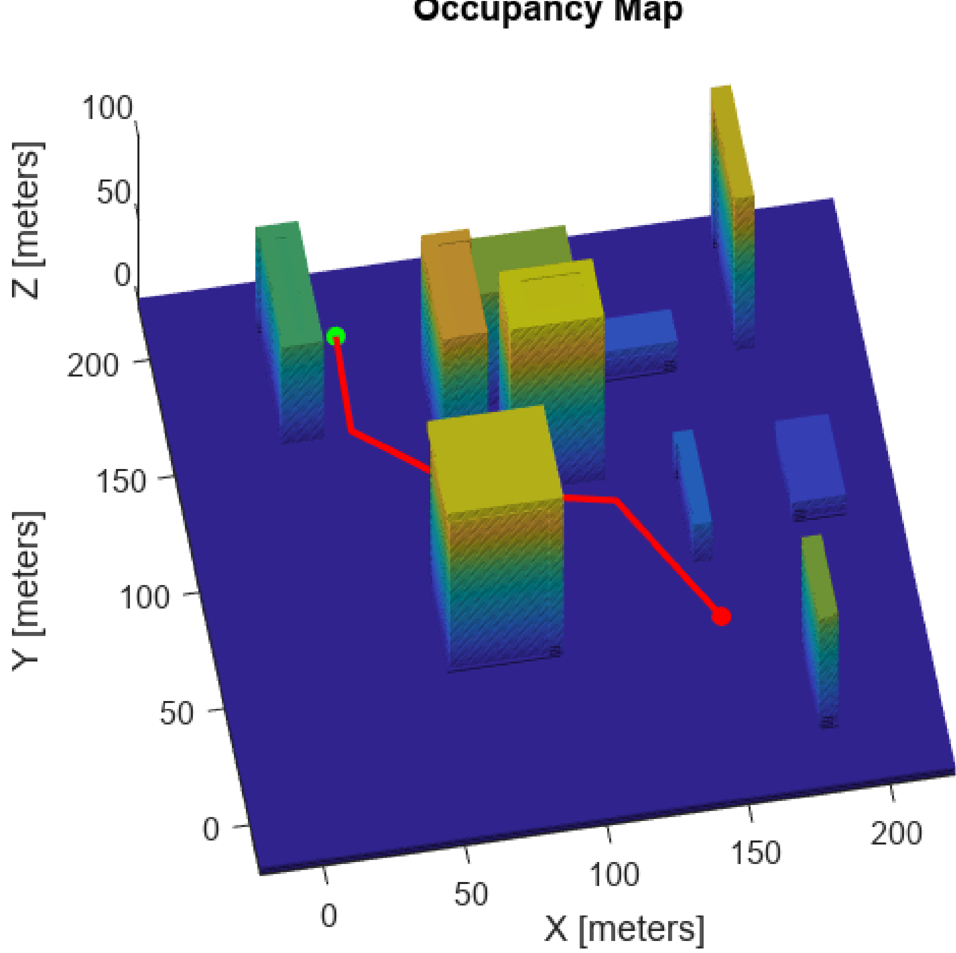
```
rng(1,"twister");
```

Plan the path.

```
[pthObj,solnInfo] = plan(planner,start,goal);
```

Visualize the planned path.

```
show(omap)
axis equal
view([-10 55])
hold on
% Start state
scatter3(start(1,1),start(1,2),start(1,3),"g","filled")
% Goal state
scatter3(goal(1,1),goal(1,2),goal(1,3),"r","filled")
% Path
plot3(pthObj.States(:,1),pthObj.States(:,2),pthObj.States(:,3), ...
      "r-",LineWidth=2)
```




## Version History

**Introduced in R2019b**

## References

[1] Karaman, S. and E. Frazzoli. "Sampling-Based Algorithms for Optimal Motion Planning." *The International Journal of Robotics Research*. Vol. 30, Number 7, 2011, pp 846 – 894.

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

Usage notes and limitations:

- To use custom GoalReachedFcn in code generation workflow, this property must be set to a custom function handle before calling the plan function and it cannot be changed after initialization.

## See Also

**Objects**
plannerRRT | plannerBiRRT | stateSpaceReedsShepp | stateSpaceDubins | stateSpaceSE2 | stateSpaceSE3 | validatorOccupancyMap | validatorVehicleCostmap | validatorOccupancyMap3D

**Functions**
plan | copy

# plan

Plan path between two states

## Syntax

```
path = plan(planner,startState,goalState)
[path,solutionInfo] = plan(planner,startState,goalState)
```

## Description

`path = plan(planner,startState,goalState)` returns a `path` from the start state to the goal state.

`[path,solutionInfo] = plan(planner,startState,goalState)` also returns `solutionInfo` that contains the solution information of the path planning.

## Examples

### Plan Path Between Two States

Create a state space.

```
ss = stateSpaceSE2;
```

Create an `occupancyMap`-based state validator using the created state space.

```
sv = validatorOccupancyMap(ss);
```

Create an occupancy map from an example map and set map resolution as 10 cells/meter.

```
load exampleMaps
map = occupancyMap(simpleMap,10);
sv.Map = map;
```

Set validation distance for the validator.

```
sv.ValidationDistance = 0.01;
```

Update state space bounds to be the same as map limits.

```
ss.StateBounds = [map.XWorldLimits;map.YWorldLimits;[-pi pi]];
```

Create the path planner and increase the maximum connection distance.

```
planner = plannerRRT(ss,sv,MaxConnectionDistance=0.3);
```

Set the start and goal states.

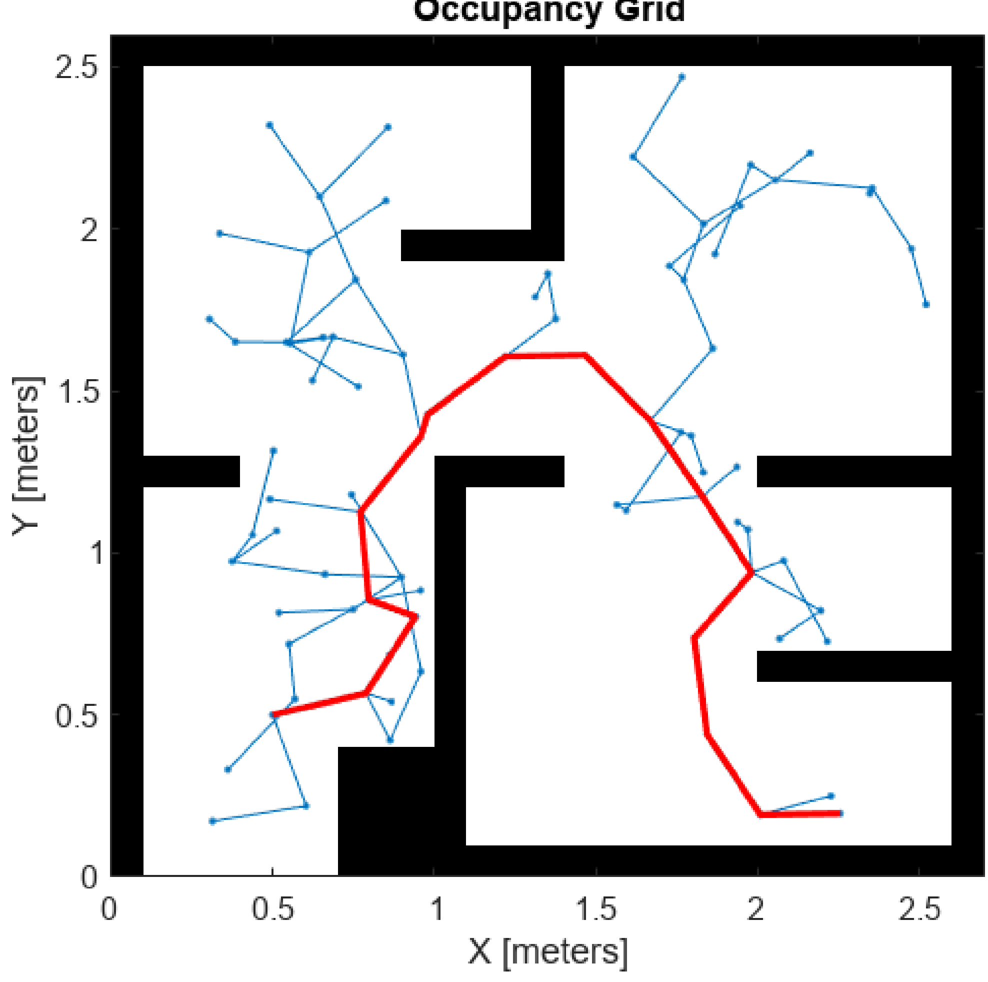
```
start = [0.5 0.5 0];
goal = [2.5 0.2 0];
```

Plan a path with default settings.

```
rng(100,'twister'); % for repeatable result
[pthObj,solnInfo] = plan(planner,start,goal);
```

Visualize the results.

```
show(map)
hold on
% Tree expansion
plot(solnInfo.TreeData(:,1),solnInfo.TreeData(:,2),'.-')
% Draw path
plot(pthObj.States(:,1),pthObj.States(:,2),'r-','LineWidth',2)
```




### Plan Path Through 3-D Occupancy Map Using RRT Planner

Load a 3-D occupancy map of a city block into the workspace. Specify the threshold to consider cells as obstacle-free.

```
mapData = load("dMapCityBlock.mat");
omap = mapData.omap;
omap.FreeThreshold = 0.5;
```

Inflate the occupancy map to add a buffer zone for safe operation around the obstacles.

```
inflate(omap,1)
```

Create an SE(3) state space object with bounds for state variables.

```
ss = stateSpaceSE3([0 220;0 220;0 100;inf inf;inf inf;inf inf;inf inf]);
```

Create a 3-D occupancy map state validator using the created state space. Assign the occupancy map to the state validator object. Specify the sampling distance interval.

```
sv = validatorOccupancyMap3D(ss, ...
     Map = omap, ...
     ValidationDistance = 0.1);
```

Create a RRT path planner with increased maximum connection distance and reduced maximum number of iterations. Specify a custom goal function that determines that a path reaches the goal if the Euclidean distance to the target is below a threshold of 1 meter.

```
planner = plannerRRT(ss,sv, ...
          MaxConnectionDistance = 50, ...
          MaxIterations = 1000, ...
          GoalReachedFcn = @(~,s,g)(norm(s(1:3)-g(1:3))<1), ...
          GoalBias = 0.1);
```

Specify start and goal poses.

```
start = [40 180 25 0.7 0.2 0 0.1];
goal = [150 33 35 0.3 0 0.1 0.6];
```

Configure the random number generator for repeatable result.

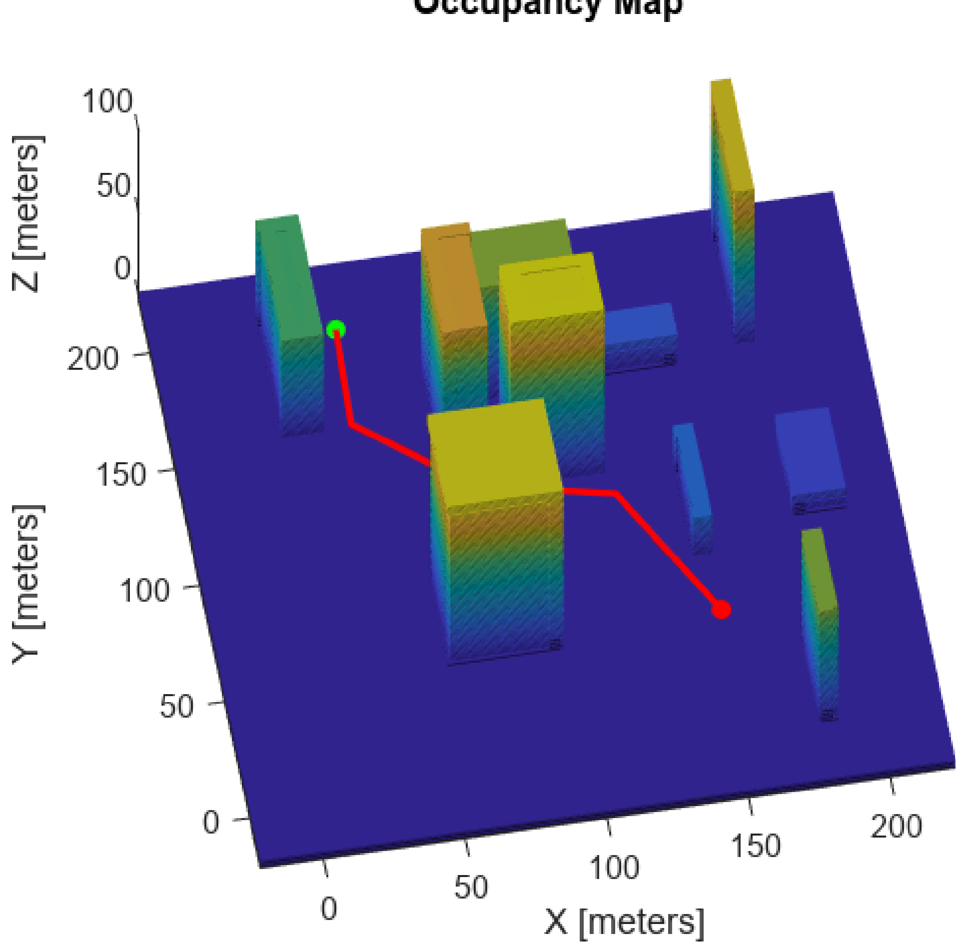
```
rng(1,"twister");
```

Plan the path.

```
[pthObj,solnInfo] = plan(planner,start,goal);
```

Visualize the planned path.

```
show(omap)
axis equal
view([-10 55])
hold on
% Start state
scatter3(start(1,1),start(1,2),start(1,3),"g","filled")
% Goal state
scatter3(goal(1,1),goal(1,2),goal(1,3),"r","filled")
% Path
plot3(pthObj.States(:,1),pthObj.States(:,2),pthObj.States(:,3), ...
      "r-",LineWidth=2)
```




## Input Arguments

**planner — Path planner**
plannerRRT object | plannerRRTStar object

Path planner, specified as a plannerRRT object or a plannerRRTStar object.

**startState — Start state of the path**
*N*-element real-valued vector

Start state of the path, specified as an *N*-element real-valued vector. *N* is the dimension of the state space.

Example: [1 1 pi/6]

Example: [40 180 25 0.7 0.2 0 0.1]

Data Types: single | double

**`goalState` — Goal state of the path**
*N*-element real-valued vector

Goal state of the path, specified as an *N*-element real-valued vector. *N* is the dimension of the state space.

Example: `[2 2 pi/3]`

Example: `[150 33 35 0.3 0 0.1 0.6]`

Data Types: `single` | `double`

## Output Arguments

**`path` — Object that holds planned path information**
`navPath` object

An object that holds the planned path information, returned as a `navPath` object.

**`solutionInfo` — Solution Information**
structure

Solution Information, returned as a structure. The fields of the structure are:

#### Fields of `solutionInfo`

| Fields | Description |
| --- | --- |
| `IsPathFound` | Indicates whether a path is found. It returns as `1` if a path is found. Otherwise, it returns `0`. |
| `ExitFlag` | Indicates the terminate status of the planner, returned as<br>• 1 — if the goal is reached<br>• 2 — if the maximum number of iterations is reached<br>• 3 — if the maximum number of nodes is reached |
| `NumNodes` | Number of nodes in the search tree when the planner terminates (excluding the root node). |
| `NumIterations` | Number of "extend" routines executed. |
| `TreeData` | A collection of explored states that reflects the status of the search tree when planner terminates. Note that `NaN` values are inserted as delimiters to separate each individual edge. |
| `PathCosts` | Contains the cost of the path at each iteration. Value for iterations when path has not reached the goal is denoted by a `NaN`. Size of the array is `NumIterations`-by-1. Last element contains the cost of the final path.<br><br>**Note** This field is applicable only for `plannerRRTStar` object. |

Data Types: `structure`

# Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Objects

`navPath` | `plannerRRT` | `plannerRRTStar`

### Functions

`copy`

# copy

Create copy of planner object

## Syntax

```
planner2 = copy(planner1)
```

## Description

`planner2 = copy(planner1)` creates a planner object, `planner2`, form a planner object, `planner1`.

## Examples

### Create Copy of plannerRRT Object

Create an occupancy map from an example map and set the map resolution as 10 cells/meter.

```
map = load("exampleMaps.mat").simpleMap;
map = occupancyMap(map,10);
```

Create a state space and update the state space bounds to be the same as the map limits.

```
ss = stateSpaceSE2;
ss.StateBounds = [map.XWorldLimits; map.YWorldLimits; [-pi pi]];
```

Create a state validator with `stateSpaceSE2` using the map and set the validation distance.

```
sv = validatorOccupancyMap(ss,Map=map);
sv.ValidationDistance = 0.01;
```

Create a `plannerRRT` object.

```
planner = plannerRRT(ss,sv)
```

```
planner = 
  plannerRRT with properties:

                StateSpace: [1x1 stateSpaceSE2]
            StateValidator: [1x1 validatorOccupancyMap]
           MaxNumTreeNodes: 10000
             MaxIterations: 10000
     MaxConnectionDistance: 0.1000
            GoalReachedFcn: @nav.algs.checkIfGoalIsReached
                  GoalBias: 0.0500
```

Create a copy of the `plannerRRT` object.

```
plannerNew = copy(planner)
```

```
plannerNew = 
  plannerRRT with properties:
```

```
              StateSpace: [1x1 stateSpaceSE2]
          StateValidator: [1x1 validatorOccupancyMap]
         MaxNumTreeNodes: 10000
           MaxIterations: 10000
   MaxConnectionDistance: 0.1000
          GoalReachedFcn: @nav.algs.checkIfGoalIsReached
                GoalBias: 0.0500
```

## Input Arguments

**planner1 — Path planner**
plannerRRT object | plannerRRTStar object

Path planner, specified as a plannerRRT object or a plannerRRTStar object.

## Output Arguments

**planner2 — Path planner**
plannerRRT object | plannerRRTStar object

Path planner, returned as a plannerRRT object or a plannerRRTStar object.

# Version History

**Introduced in R2018b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
plannerRRT | plannerRRTStar

**Functions**
plan

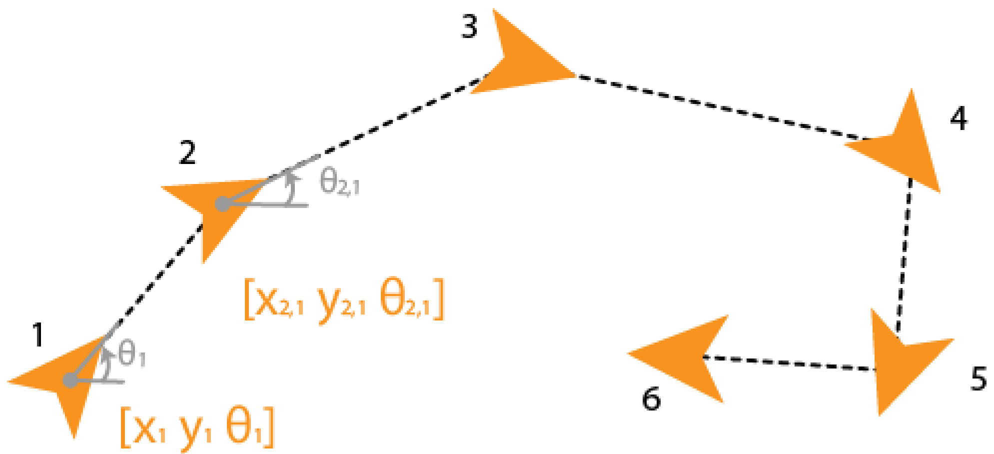
# poseGraph

Create 2-D pose graph

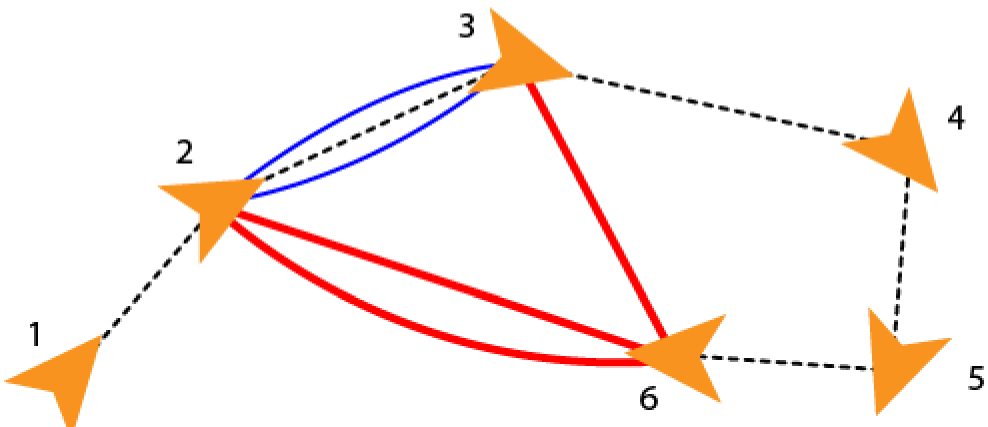
## Description

A `poseGraph` object stores information for a 2-D pose graph representation. A pose graph contains nodes connected by edges. Each node estimate is connected to the graph by edge constraints that define the relative pose between nodes and the uncertainty on that measurement.

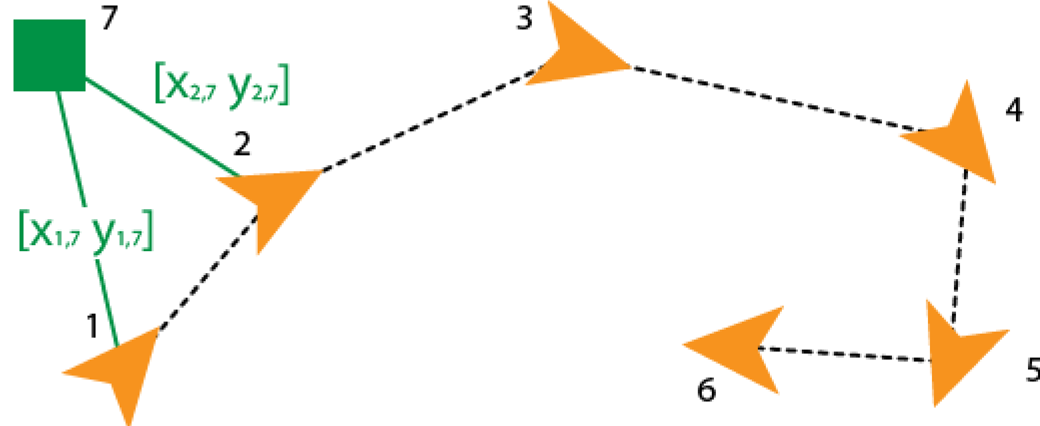
To construct a pose graph iteratively, use the `addRelativePose` function to add relative pose estimates and connect them to an existing node with specified edge constraints. Pose nodes must be specified relative to a pose node. Specify the uncertainty of the measurement using an information matrix.




Adding an edge between two nonsequential nodes creates a *loop closure* in the graph. Multiple edges or *multiedges* between node pairs are also supported, which includes loop closures. To add additional edge constraints or loop closures, specify the node IDs using the `addRelativePose` function. When optimizing the pose graph, the `optimizePoseGraph` function finds a solution to satisfy all these edge constraints.




To add landmark point nodes, use the `addPointLandmark` function. This function specifies nodes as *xy*-points without orientation estimates. Landmarks must be specified relative to a pose node.




The `lidarSLAM` object performs lidar-based simultaneous localization and mapping, which is based around the optimization of a 2-D pose graph.

For 3-D pose graphs, see the `poseGraph3D` object or the “Landmark SLAM Using AprilTag Markers” example.

# Creation

## Syntax

```
poseGraph = poseGraph
poseGraph = poseGraph('MaxNumEdges',maxEdges,'MaxNumNodes',maxNodes)
```

### Description

`poseGraph = poseGraph` creates a 2-D pose graph object. Add poses using `addRelativePose` to construct a pose graph iteratively.

`poseGraph = poseGraph('MaxNumEdges',maxEdges,'MaxNumNodes',maxNodes)` specifies an upper bound on the number of edges and nodes allowed in the pose graph when generating code. This syntax is only required when generating code.

## Properties

**`NumNodes` — Number of nodes in pose graph**
`1` (default) | positive integer

This property is read-only.

Number of nodes in pose graph, specified as a positive integer. Each node represents a pose measurement or a point landmark measurement. To specify relative poses between nodes, use `addRelativePose`. To specify a landmark pose, use `addLandmarkPose`. To get a list of all nodes, use `edgeNodePairs`.

**`NumEdges` — Number of edges in pose graph**
`0` (default) | nonnegative integer

This property is read-only.

Number of edges in pose graph, specified as a nonnegative integer. Each edge connects two nodes in the pose graph. Loop closure edges and landmark edges are included.

**`NumLoopClosureEdges` — Number of loop closures**
`0` (default) | nonnegative integer

This property is read-only.

Number of loop closures in pose graph, specified as a nonnegative integer. To get the edge IDs of the loop closures, use the `LoopClosureEdgeIDs` property.

**`LoopClosureEdgeIDs` — Loop closure edge IDs**
vector

This property is read-only.

Loop closure edges IDs, specified as a vector of edge IDs.

**`LandmarkNodeIDs` — Landmark node IDs**
vector

This property is read-only.

Landmark node IDs, specified as a vector of IDs for each node.

## Object Functions

| | |
|---|---|
| addPointLandmark | Add landmark point node to pose graph |
| addRelativePose | Add relative pose to pose graph |
| copy | Create copy of pose graph |
| edgeNodePairs | Edge node pairs in pose graph |
| edgeConstraints | Edge constraints in pose graph |
| edgeResidualErrors | Compute pose graph edge residual errors |
| findEdgeID | Find edge ID of edge |
| nodeEstimates | Poses of nodes in pose graph |
| removeEdges | Remove loop closure edges from graph |
| show | Plot pose graph |

## Examples

### Optimize a 2-D Pose Graph

Optimize a pose graph based on the nodes and edge constraints. The pose graph used in this example is from the Intel Research Lab Dataset and was generated from collecting wheel odometry and a laser range finder sensor information in an indoor lab.

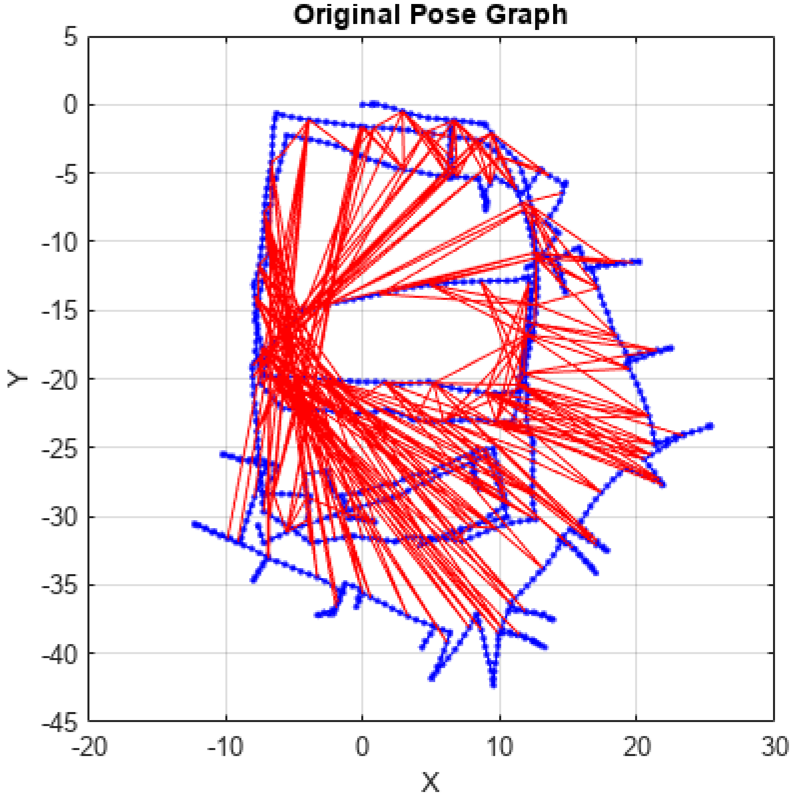
Load the Intel data set that contains a 2-D pose graph. Inspect the `poseGraph` object to view the number of nodes and loop closures.

```
load intel-2d-posegraph.mat pg
disp(pg)
```

```
  poseGraph with properties:

               NumNodes: 1228
               NumEdges: 1483
    NumLoopClosureEdges: 256
     LoopClosureEdgeIDs: [1228 1229 1230 1231 1232 1233 1234 1235 1236 1237 1238 1239 1240 1241
        LandmarkNodeIDs: [1x0 double]
```

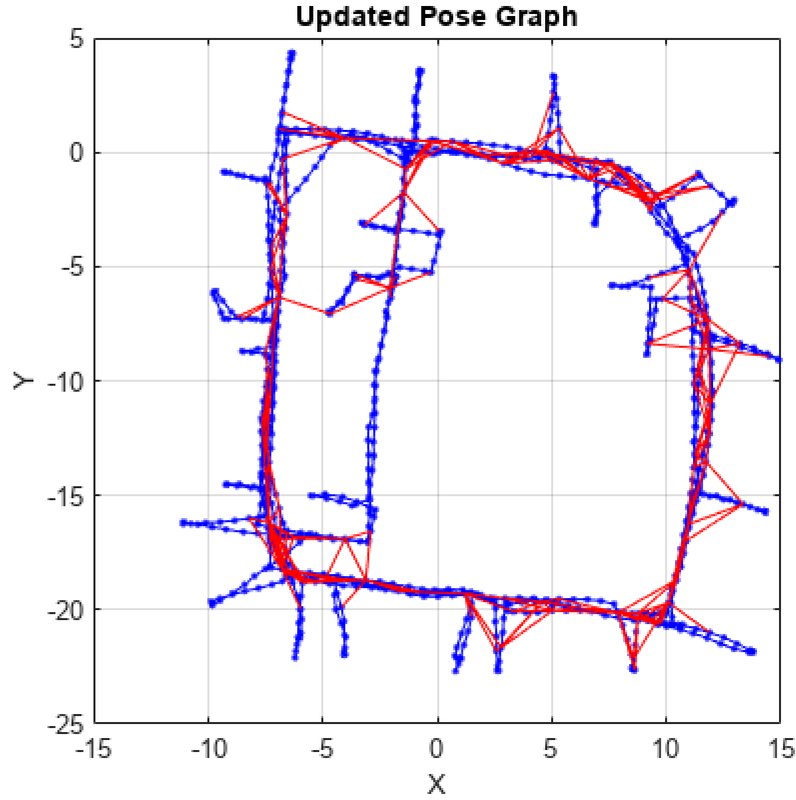
Plot the pose graph with IDs off. Red lines indicate loop closures identified in the dataset.

```
show(pg,'IDs','off');
title('Original Pose Graph')
```




Optimize the pose graph. Nodes are adjusted based on the edge constraints and loop closures. Plot the optimized pose graph to see the adjustment of the nodes with loop closures.

```
updatedPG = optimizePoseGraph(pg);
figure
show(updatedPG,'IDs','off');
title('Updated Pose Graph')
```




# Version History

**Introduced in R2019b**

## References

[1] Grisetti, G., R. Kummerle, C. Stachniss, and W. Burgard. "A Tutorial on Graph-Based SLAM." *IEEE Intelligent Transportation Systems Magazine*. Vol. 2, No. 4, 2010, pp. 31–43. doi:10.1109/mits.2010.939925.

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

Use this syntax when constructing `poseGraph` objects for code generation: `poseGraph = poseGraph('MaxNumEdges',maxEdges,'MaxNumNodes',maxNodes)` specifies an upper bound on the number of edges and nodes allowed in the pose graph when generating code. This limit is only required when generating code.

## See Also

### Functions
`optimizePoseGraph` | `addRelativePose` | `addPointLandmark` | `show`

### Objects
`lidarSLAM` | `poseGraph3D`

### Topics
"Implement Simultaneous Localization And Mapping (SLAM) with Lidar Scans"
"Implement Online Simultaneous Localization And Mapping (SLAM) with Lidar Scans"
"Landmark SLAM Using AprilTag Markers"

# addPointLandmark

Add landmark point node to pose graph

## Syntax

```
addPointLandmark(poseGraph,measurement)
addPointLandmark(poseGraph,measurement,infoMat)
addPointLandmark(poseGraph,measurement,infoMat,poseNodeID)
addPointLandmark(poseGraph,measurement,infoMat,poseNodeID,pointNodeID)
[nodePair,edgeID] = addPointLandmark( ___ )
```

## Description

`addPointLandmark(poseGraph,measurement)` adds a landmark point node, based on the input position `measurement` that connects to the last pose node in the pose graph. To add pose measurement nodes, see the `addRelativePose` function.

`addPointLandmark(poseGraph,measurement,infoMat)` also specifies the information matrix as part of the edge constraint, which represents the uncertainty of the landmark measurement.

`addPointLandmark(poseGraph,measurement,infoMat,poseNodeID)` adds a new landmark point node and connects it to the pose node specified by `poseNodeID`.

`addPointLandmark(poseGraph,measurement,infoMat,poseNodeID,pointNodeID)` creates an edge by specifying a point measurement between existing nodes, specified by `poseNodeID` and `pointNodeID`. If the node pair already exists, the function appends the new measurement.

`[nodePair,edgeID] = addPointLandmark( ___ )` returns the newly added edge and edge ID using any combination of inputs from the previous syntaxes.

## Examples

### Add Landmark Point Node to Pose Graph

Create a 2-D pose graph object.

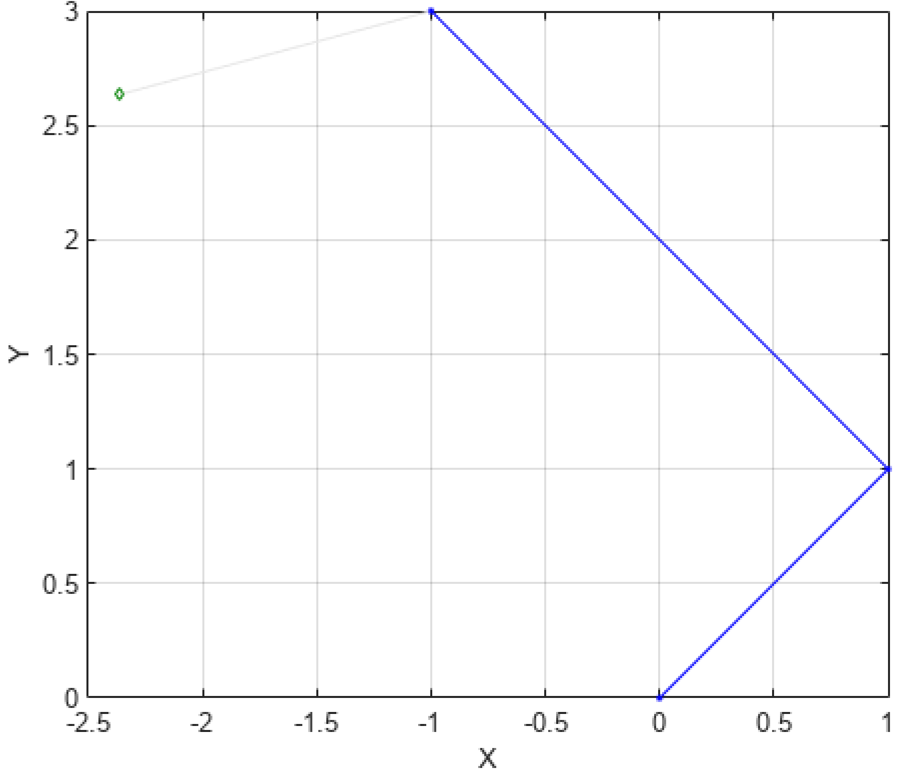
```
pg = poseGraph;
```

Add relative poses to the pose graph.

```
addRelativePose(pg,[1 1 pi/2]);
addRelativePose(pg,[2 2 pi/3]);
```

Add a landmark point node to the last pose node in the pose graph.

```
addPointLandmark(pg,[1 1]);
show(pg);
```




List all poses in the pose graph.

```
nodeEstimates(pg)
```

```
ans = 4×3

         0         0         0
    1.0000    1.0000    1.5708
   -1.0000    3.0000    2.6180
   -2.3660    2.6340       NaN
```

## Input Arguments

**poseGraph — Pose graph**
poseGraph object | poseGraph3D object

Pose graph, specified as a `poseGraph` or `poseGraph3D` object.

**measurement — Relative position of landmark point**
two-element vector of form `[x y]` | three-element vector of form `[x y z]`

Relative position of the landmark point, specified as one of the following:

For `poseGraph` (2-D), the pose is a two-element vector of form of the form `[x y]`, which defines an *xy*-position for the landmark.

For `poseGraph3D`, the pose is a three-element vector of the form `[x y z]`, which defines an *xyz*-position for the landmark.

**`infoMat` — Information matrix for landmark**
three-element vector | six-element vector

Information matrix for the landmark, specified as a three-element or six-element vector.

Each vector is the compact form of the upper triangle of the square information matrix. An information matrix represents the uncertainty of the measurement. The matrix is calculated as the inverse of the covariance. If the measurement is an `[x y]` vector, the covariance matrix is a 2-by-2 matrix of pairwise covariance calculations. Typically, the uncertainty is determined by the sensor model.

For `poseGraph` (2-D), each information matrix is a three-element vector. The default is `[1 1 0]`.

For `poseGraph3D`, each information matrix is a six-element vector. The default is `[1 0 0 1 0 1]`.

**`poseNodeID` — Pose node to attach from**
positive integer

Pose node to attach from, specified as a positive integer. This integer corresponds to the node ID of a pose node in `poseGraph`. When specified without the `pointNodeID` input, `addPointLandmark` creates a new landmark point node and adds an edge between the new node and the `poseNodeID` node.

**`pointNodeID` — Landmark point node to attach to**
positive integer

Landmark point node to attach to, specified as a positive integer. This integer corresponds to the ID of a landmark node in the pose graph. See the LandmarkNodeIDs property of the pose graph.

## Output Arguments

**`nodePair` — Edge node pair in pose graph**
two-element vector

Edge node pair in the pose graph, returned as a two-element vector that lists the IDs of the two nodes that the edge connects. Multiple edges may exist between the same pair of nodes.

**`edgeID` — ID of added edge**
positive integer

ID of added edge, returned as a positive integer.

# Version History

**Introduced in R2021a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

Use this syntax when constructing `poseGraph` or `poseGraph3D` objects for code generation:

`poseGraph = poseGraph('MaxNumEdges',maxEdges,'MaxNumNodes',maxNodes)` specifies an upper bound on the number of edges and nodes allowed in the pose graph when generating code. This limit is only required when generating code.

`poseGraph = poseGraph3D('MaxNumEdges',maxEdges,'MaxNumNodes',maxNodes)`

## See Also

**Functions**
`optimizePoseGraph` | `findEdgeID` | `edgeNodePairs` | `edgeConstraints` | `nodeEstimates` | `removeEdges`

**Objects**
`poseGraph` | `poseGraph3D` | `lidarSLAM`

**Topics**
"Implement Simultaneous Localization And Mapping (SLAM) with Lidar Scans"
"Implement Online Simultaneous Localization And Mapping (SLAM) with Lidar Scans"
"Landmark SLAM Using AprilTag Markers"

# addRelativePose

Add relative pose to pose graph

## Syntax

```
addRelativePose(poseGraph,measurement)
addRelativePose(poseGraph,measurement,infoMat)
addRelativePose(poseGraph,measurement,infoMat,fromNodeID)
addRelativePose(poseGraph,measurement,infoMat,fromNodeID,toNodeID)
[nodePair,edgeID] = addRelativePose( ___ )
```

## Description

`addRelativePose(poseGraph,measurement)` creates a node based on the input `measurement` that connects to the last pose node in the pose graph. To add landmark nodes, see the `addPointLandmark` function.

`addRelativePose(poseGraph,measurement,infoMat)` also specifies the information matrix as part of the edge constraint, which represents the uncertainty of the pose measurement.

`addRelativePose(poseGraph,measurement,infoMat,fromNodeID)` creates a new pose node and connects it to the specific node specified by `fromNodeID`.

`addRelativePose(poseGraph,measurement,infoMat,fromNodeID,toNodeID)` creates an edge by specifying a relative pose measurement between existing nodes specified by `fromNodeID` and `toNodeID`. This edge is called a loop closure. If a loop closure already exists, the function appends the new measurement. Calling the `optimizePoseGraph` function combines multiple appended measurements into a single edge. This syntax does not support adding edges to a landmark node.

`[nodePair,edgeID] = addRelativePose( ___ )` returns the newly added edge and edge ID using any of the previous syntaxes.

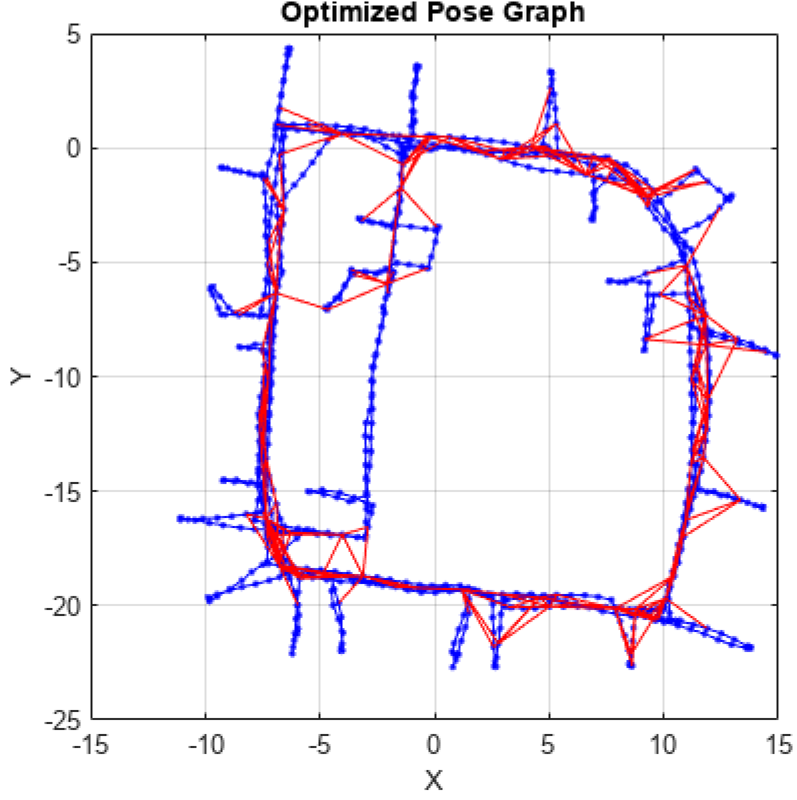
## Examples

### Identify and Remove Spurious Loop Closures from Pose Graph

This example shows how to identify and remove spurious loop closures from pose graph. To do this, you can modify the relative pose of a loop closure edge and try optimizing the pose graph with and without removing the auto spurious loop closure and compare the results.

Load the Intel Research Lab Dataset that contains a 2-D pose graph. Optimize the pose graph. Plot the pose graph with IDs off. Red lines indicate loop closures identified in the dataset.

```
load intel-2d-posegraph.mat pg
optimizedPG = optimizePoseGraph(pg);
show(optimizedPG,IDs="off");
title("Optimized Pose Graph")
```

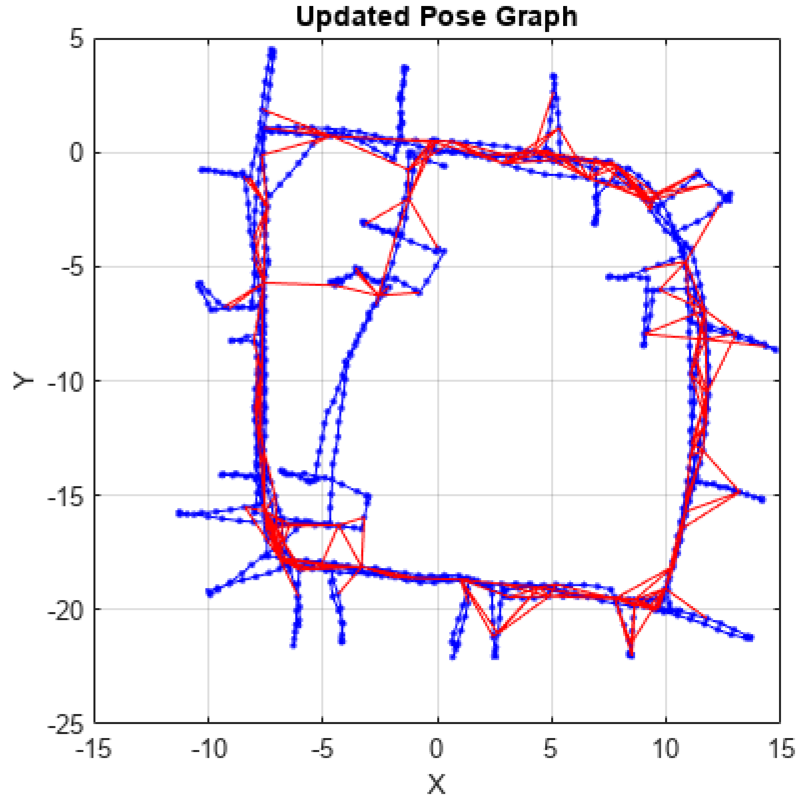



Modify the relative pose of the loop closure edge 1386 to some random values.

```
loopclosureId = 1386;
nodePair = edgeNodePairs(optimizedPG,loopclosureId);
[relPose,infoMat] = edgeConstraints(optimizedPG,loopclosureId);
relPose(2) = -5;
relPose(3) = 1.5;
addRelativePose(optimizedPG,relPose,infoMat,nodePair(1),nodePair(2));
```

Optimize the pose graph without auto loop closure trimming. Plot the optimized pose graph to see the poor adjustment of the nodes with loop closures.

```
[updatedPG,solutionInfo] = optimizePoseGraph(optimizedPG);
show(updatedPG,IDs="off");
title("Updated Pose Graph")
```




Certain loop closures should be trimmed from the pose graph. Use the `trimLoopClosures` function to trim these bad loop closures. Set the truncation threshold and maximum iterations for the trimmer parameters.

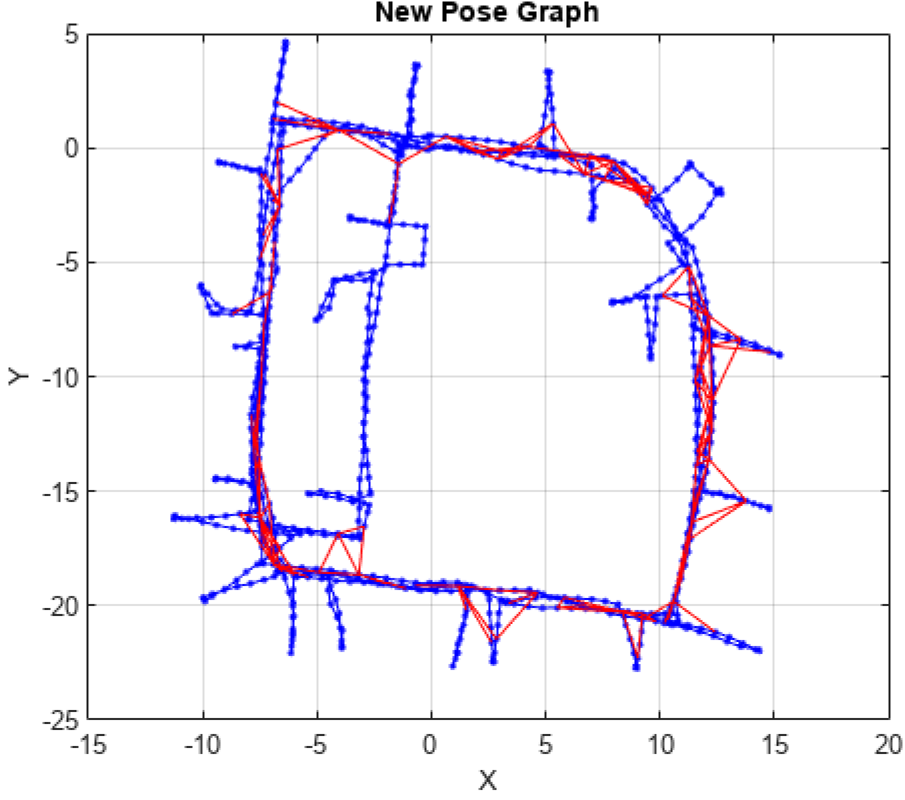
```
trimParams = struct("TruncationThreshold",0.5,"MaxIterations",100);
```

Generate solver options.

```
solverOptions = poseGraphSolverOptions("g2o-levenberg-marquardt");
```

Use the `trimLoopClosures` function with the trimmer parameters and solver options. Plot the new pose graph to see the bad loop closures were removed.

```
[newPG,trimInfo] = trimLoopClosures(updatedPG,trimParams,solverOptions);
show(newPG,IDs="off");
title("New Pose Graph")
```




## Input Arguments

**poseGraph — Pose graph**
poseGraph object | poseGraph3D object

Pose graph, specified as a poseGraph or poseGraph3D object.

**measurement — Relative pose between nodes**
[x y theta] vector | [x y z qw qx qy qz] vector

Relative pose between nodes, specified as one of the following:

For poseGraph (2-D), the pose is a [x y theta] vector, which defines a *xy*-position and orientation angle, theta.

For poseGraph3D, the pose is a [x y z qw qx qy qz] vector, which defines by an *xyz*-position and quaternion orientation, [qw qx qy qz]

**Note** Many other sources for 3-D pose graphs, including .g2o formats, specify the quaternion orientation in a different order, for example, [qx qy qz qw]. Check the source of your pose graph data before adding nodes to your poseGraph3D object.

**`infoMat` — Information matrix**
six-element vector | 21-element vector

Information matrices, specified in compact form as a six-element vector or 21-element vector.

Each vector is the compact form of the upper triangle of the square information matrix. An information matrix represents the uncertainty of the measurement. The matrix is calculated as the inverse of the covariance. If the measurement is an `[x y theta]` vector, the covariance matrix is a 3-by-3 of pairwise covariance calculations. Typically, the uncertainty is determined by the sensor model.

For `poseGraph` (2-D), each information matrix is a six-element vector. The default is `[1 0 0 1 0 1]`. For landmark nodes, the last three elements are returned as `NaN`.

For `poseGraph3D`, each information matrix is a 21-element vector. The default is `[1 0 0 0 0 1 0 0 0 0 1 0 0 0 1 0 0 1 0 1]`.

**`fromNodeID` — Node to attach from**
positive integer

Node to attach from, specified as a positive integer. This integer corresponds to the node ID of a node in `poseGraph`. When specified without `toNodeID`, `addRelativePose` creates a new node and adds an edge between the new node and the `fromNodeID` node.

**`toNodeID` — Node to attach to**
positive integer

Node to attach to, specified as a positive integer. This integer corresponds to the node ID of a node in `poseGraph`. `addRelativePose` adds an edge between this node and the `fromNodeID` node.

## Output Arguments

**`nodePair` — Edge node pair in pose graph**
two-element vector

Edge node pairs in pose graph, returned as two-element vector that lists the IDs of the two nodes that each edge connects. Multiple edges may exist between the same pair of nodes.

**`edgeID` — ID of added edge**
positive integer

ID of added edge, returned as a positive integer.

# Version History

**Introduced in R2019b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

Use this syntax when constructing `poseGraph` or `poseGraph3D` objects for code generation:

`poseGraph = poseGraph('MaxNumEdges',maxEdges,'MaxNumNodes',maxNodes)` specifies an upper bound on the number of edges and nodes allowed in the pose graph when generating code. This limit is only required when generating code.

`poseGraph = poseGraph3D('MaxNumEdges',maxEdges,'MaxNumNodes',maxNodes)`

## See Also

**Functions**
`optimizePoseGraph` | `findEdgeID` | `edgeNodePairs` | `edgeConstraints` | `nodeEstimates` | `removeEdges`

**Objects**
`poseGraph` | `poseGraph3D` | `lidarSLAM`

**Topics**
"Implement Simultaneous Localization And Mapping (SLAM) with Lidar Scans"
"Implement Online Simultaneous Localization And Mapping (SLAM) with Lidar Scans"
"Landmark SLAM Using AprilTag Markers"

# copy

Create copy of pose graph

## Syntax

```
poseGraph2 = copy(poseGraph1)
```

## Description

`poseGraph2 = copy(poseGraph1)` creates a deep copy of the pose graph object with the same properties.

## Examples

### Create Copy of Pose Graph

Create a 2-D pose graph object.

```
pg = poseGraph
```

```
pg = 
  poseGraph with properties:

               NumNodes: 1
               NumEdges: 0
    NumLoopClosureEdges: 0
     LoopClosureEdgeIDs: [1x0 double]
        LandmarkNodeIDs: []
```

Create copy of the pose graph object.

```
pgNew = copy(pg)
```

```
pgNew = 
  poseGraph with properties:

               NumNodes: 1
               NumEdges: 0
    NumLoopClosureEdges: 0
     LoopClosureEdgeIDs: [1x0 double]
        LandmarkNodeIDs: []
```

## Input Arguments

**poseGraph1 — Pose graph**
`poseGraph` object | `poseGraph3D` object

Pose graph, specified as a `poseGraph` or `poseGraph3D` object.

## Output Arguments

**`poseGraph2` — Copy of pose graph**
`poseGraph` object | `poseGraph3D` object

Copy of pose graph, returned as a `poseGraph` or `poseGraph3D` object.

# Version History

**Introduced in R2019b**

## See Also

`poseGraph` | `poseGraph3D`

# edgeConstraints

Edge constraints in pose graph

## Syntax

```
measurements = edgeConstraints(poseGraph)
[measurements,infoMats] = edgeConstraints(poseGraph)
[measurements,infoMats] = edgeConstraints(poseGraph,edgeIDs)
```

## Description

`measurements = edgeConstraints(poseGraph)` lists all edge constraints in the specified pose graph as a relative pose.

`[measurements,infoMats] = edgeConstraints(poseGraph)` also returns the information matrices for each edge. The information matrix is the inverse of the covariance of the pose measurement.

`[measurements,infoMats] = edgeConstraints(poseGraph,edgeIDs)` returns edge constraints for the specified edge IDs.

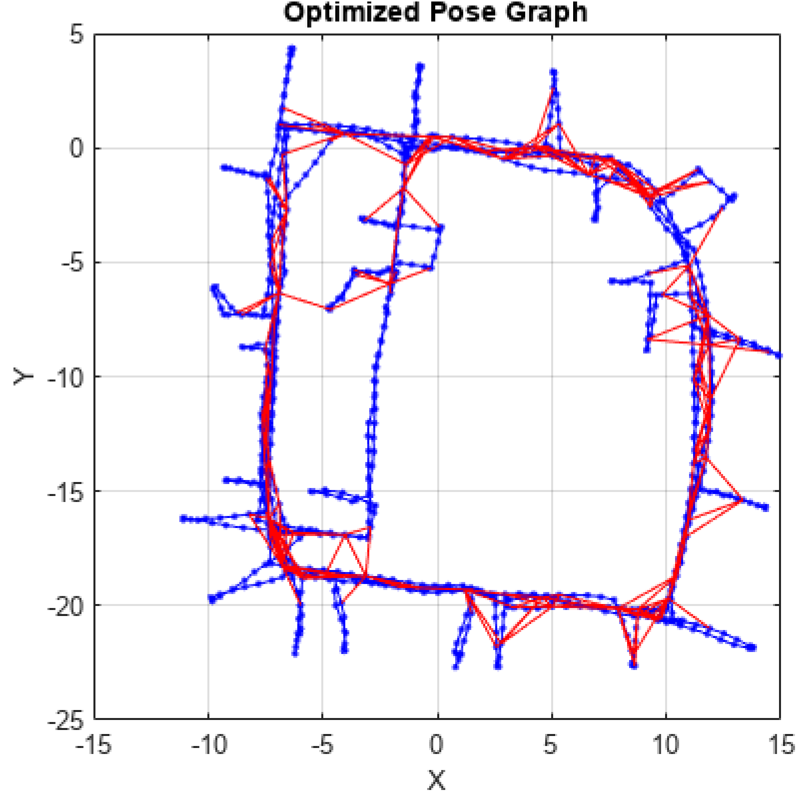
## Examples

### Identify and Remove Spurious Loop Closures from Pose Graph

This example shows how to identify and remove spurious loop closures from pose graph. To do this, you can modify the relative pose of a loop closure edge and try optimizing the pose graph with and without removing the auto spurious loop closure and compare the results.

Load the Intel Research Lab Dataset that contains a 2-D pose graph. Optimize the pose graph. Plot the pose graph with IDs off. Red lines indicate loop closures identified in the dataset.

```
load intel-2d-posegraph.mat pg
optimizedPG = optimizePoseGraph(pg);
show(optimizedPG,IDs="off");
title("Optimized Pose Graph")
```

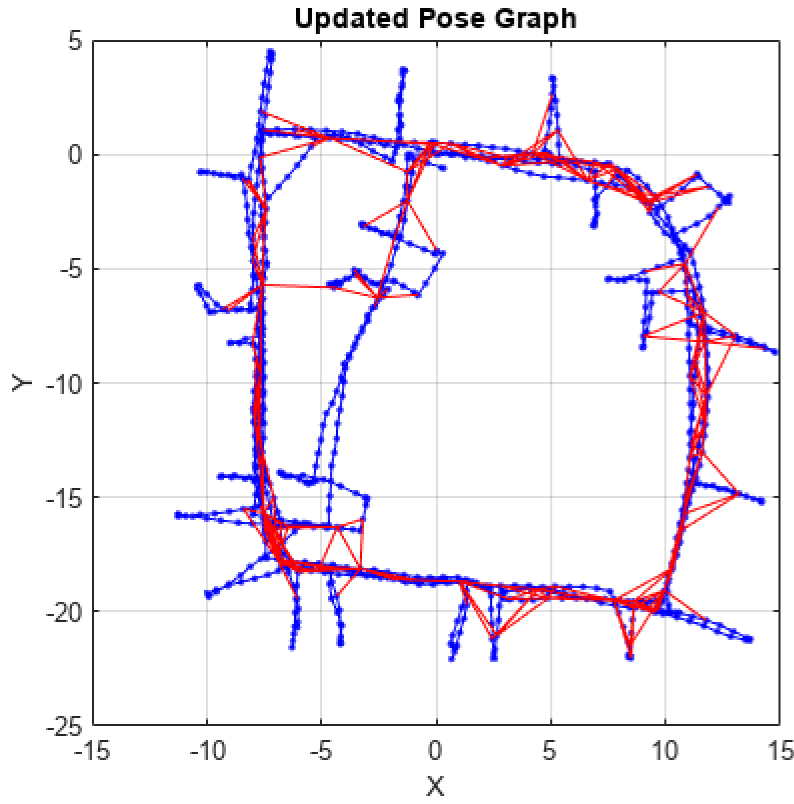



Modify the relative pose of the loop closure edge `1386` to some random values.

```
loopclosureId = 1386;
nodePair = edgeNodePairs(optimizedPG,loopclosureId);
[relPose,infoMat] = edgeConstraints(optimizedPG,loopclosureId);
relPose(2) = -5;
relPose(3) = 1.5;
addRelativePose(optimizedPG,relPose,infoMat,nodePair(1),nodePair(2));
```

Optimize the pose graph without auto loop closure trimming. Plot the optimized pose graph to see the poor adjustment of the nodes with loop closures.

```
[updatedPG,solutionInfo] = optimizePoseGraph(optimizedPG);
show(updatedPG,IDs="off");
title("Updated Pose Graph")
```




Certain loop closures should be trimmed from the pose graph. Use the `trimLoopClosures` function to trim these bad loop closures. Set the truncation threshold and maximum iterations for the trimmer parameters.

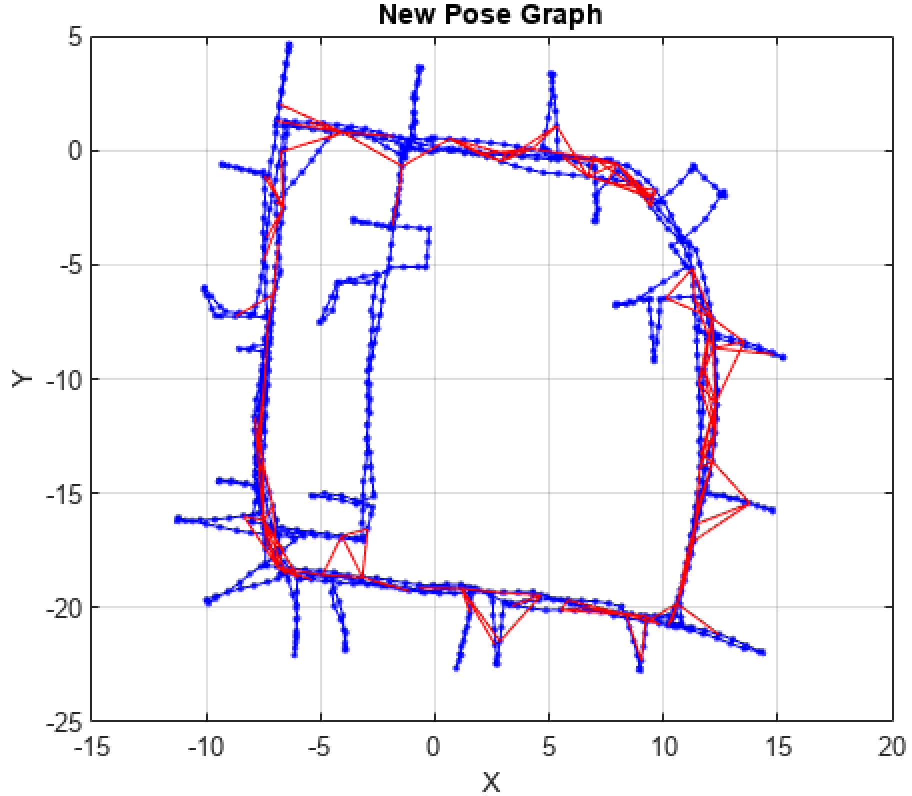
```
trimParams = struct("TruncationThreshold",0.5,"MaxIterations",100);
```

Generate solver options.

```
solverOptions = poseGraphSolverOptions("g2o-levenberg-marquardt");
```

Use the `trimLoopClosures` function with the trimmer parameters and solver options. Plot the new pose graph to see the bad loop closures were removed.

```
[newPG,trimInfo] = trimLoopClosures(updatedPG,trimParams,solverOptions);
show(newPG,IDs="off");
title("New Pose Graph")
```




## Input Arguments

**poseGraph — Pose graph**
poseGraph object | poseGraph3D object

Pose graph, specified as a poseGraph or poseGraph3D object.

**edgeIDs — Edge IDs**
vector of positive integers

Edge IDs, specified as a vector of positive integers.

## Output Arguments

**measurements — Measurements between nodes**
*n*-by-3 matrix | *n*-by-7 matrix

Measurements between nodes, returned as an *n*-by-3 matrix or *n*-by-7 matrix.

For poseGraph (2-D), each row is an [x y theta] vector, which defines the relative *xy*-position and orientation angle, theta, of a pose in the graph. For landmark positions, theta is returned as NaN.

For poseGraph3D, each row is an [x y z qw qx qy qz] vector, which defines the relative *xyz*-position and quaternion orientation, [qw qx qy qz], of a pose in the graph.

**Note** Many other sources for 3-D pose graphs, including `.g2o` formats, specify the quaternion orientation in a different order, for example, `[qx qy qz qw]`. Check the source of your pose graph data before adding nodes to your `poseGraph3D` object.

**`infoMats` — Information matrices**
*n*-by-6 matrix | *n*-by-21 matrix

Information matrices, specified in compact form as a *n*-by-6 or *n*-by-21 matrix, where *n* is the number of poses in the pose graph.

Each row is the upper triangle of the square information matrix. An information matrix represents the uncertainty of the measurement. The matrix is calculated as the inverse of the covariance. If the measurement is an `[x y theta]` vector, the covariance matrix is a 3-by-3 of pairwise covariance calculations. Typically, the uncertainty is determined by the sensor model.

For `poseGraph` (2-D), each information matrix is a six-element vector. The default is `[1 0 0 1 0 1]`. For landmark nodes, the last three elements are returned as `NaN`.

For `poseGraph3D`, each information matrix is a 21-element vector. The default is `[1 0 0 0 0 0 1 0 0 0 0 1 0 0 0 1 0 0 1 0 1]`.

# Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

Use this syntax when constructing `poseGraph` or `poseGraph3D` objects for code generation:

`poseGraph = poseGraph('MaxNumEdges',maxEdges,'MaxNumNodes',maxNodes)` specifies an upper bound on the number of edges and nodes allowed in the pose graph when generating code. This limit is only required when generating code.

## See Also

### Functions

`edgeNodePairs` | `optimizePoseGraph` | `addRelativePose` | `findEdgeID` | `nodeEstimates` | `removeEdges`

### Objects

`poseGraph` | `poseGraph3D` | `lidarSLAM`

### Topics

“Implement Simultaneous Localization And Mapping (SLAM) with Lidar Scans”
“Implement Online Simultaneous Localization And Mapping (SLAM) with Lidar Scans”

# edgeNodePairs

Edge node pairs in pose graph

## Syntax

```
nodePairs = edgeNodePairs(poseGraph)
nodePairs = edgeNodePairs(poseGraph,edgeIDs)
```

## Description

`nodePairs = edgeNodePairs(poseGraph)` returns all edges in the specified pose graph as a list of node ID pairs. Each row of the `edges` output is a pair of nodes that form an edge. Multiple edges may exist between the same pair of nodes.

`nodePairs = edgeNodePairs(poseGraph,edgeIDs)` returns edges corresponding to the specified edge IDs. Each edge in the pose graph has a unique ID even if the node pairs are the same.

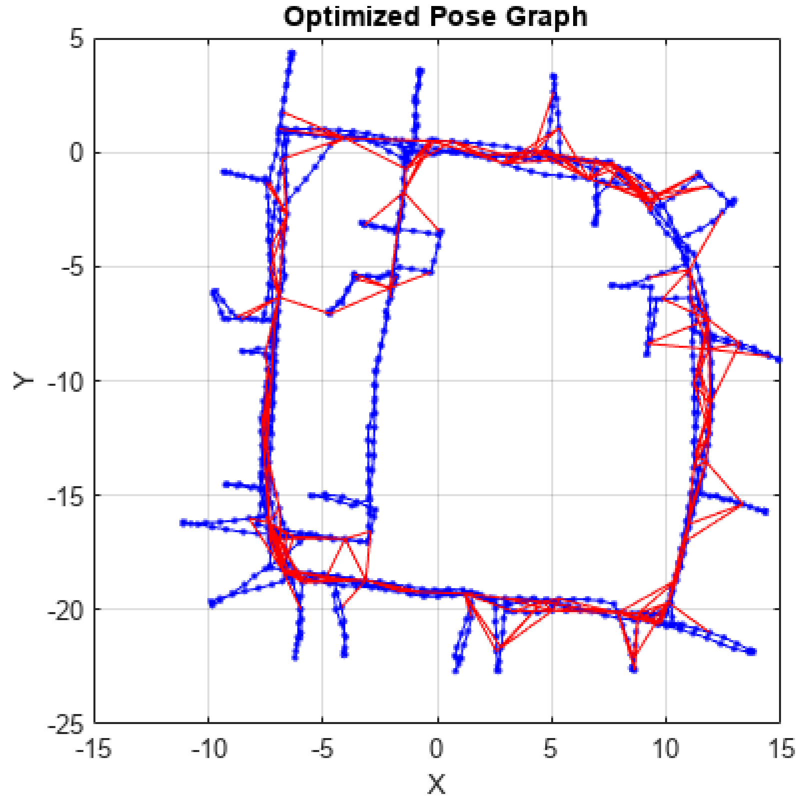
## Examples

### Identify and Remove Spurious Loop Closures from Pose Graph

This example shows how to identify and remove spurious loop closures from pose graph. To do this, you can modify the relative pose of a loop closure edge and try optimizing the pose graph with and without removing the auto spurious loop closure and compare the results.

Load the Intel Research Lab Dataset that contains a 2-D pose graph. Optimize the pose graph. Plot the pose graph with IDs off. Red lines indicate loop closures identified in the dataset.

```
load intel-2d-posegraph.mat pg
optimizedPG = optimizePoseGraph(pg);
show(optimizedPG,IDs="off");
title("Optimized Pose Graph")
```

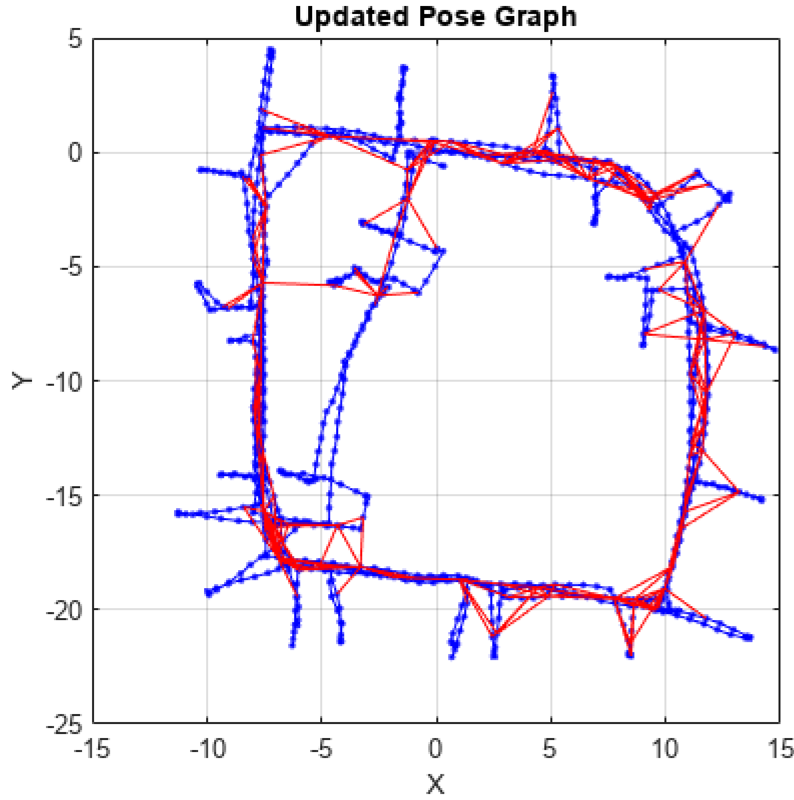



Modify the relative pose of the loop closure edge 1386 to some random values.

```
loopclosureId = 1386;
nodePair = edgeNodePairs(optimizedPG,loopclosureId);
[relPose,infoMat] = edgeConstraints(optimizedPG,loopclosureId);
relPose(2) = -5;
relPose(3) = 1.5;
addRelativePose(optimizedPG,relPose,infoMat,nodePair(1),nodePair(2));
```

Optimize the pose graph without auto loop closure trimming. Plot the optimized pose graph to see the poor adjustment of the nodes with loop closures.

```
[updatedPG,solutionInfo] = optimizePoseGraph(optimizedPG);
show(updatedPG,IDs="off");
title("Updated Pose Graph")
```




Certain loop closures should be trimmed from the pose graph. Use the `trimLoopClosures` function to trim these bad loop closures. Set the truncation threshold and maximum iterations for the trimmer parameters.

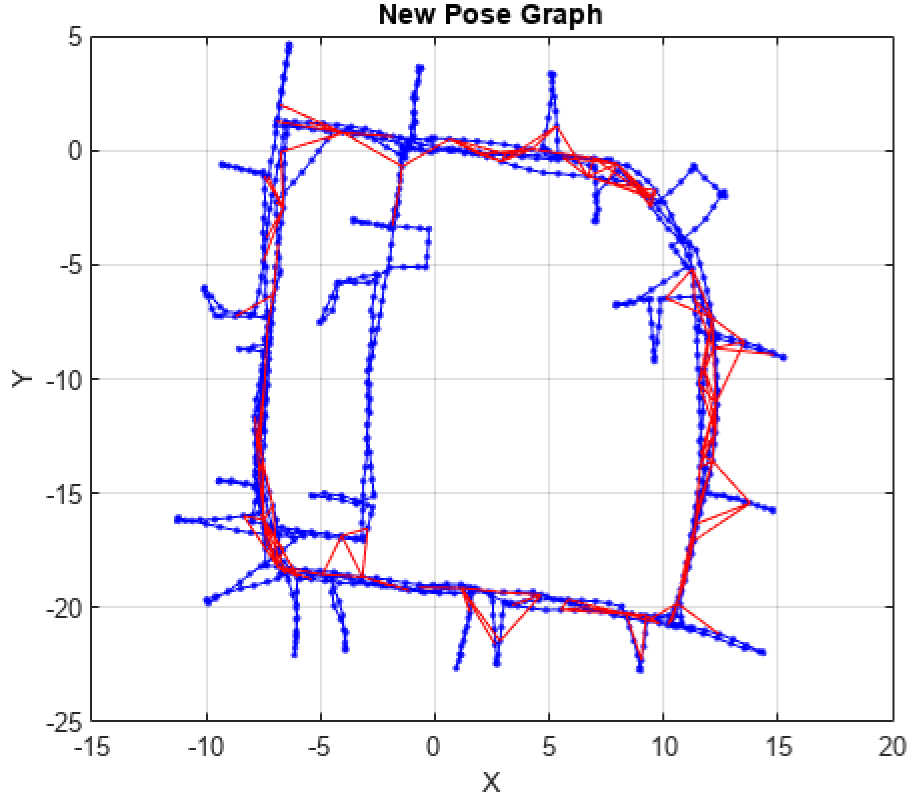
```
trimParams = struct("TruncationThreshold",0.5,"MaxIterations",100);
```

Generate solver options.

```
solverOptions = poseGraphSolverOptions("g2o-levenberg-marquardt");
```

Use the `trimLoopClosures` function with the trimmer parameters and solver options. Plot the new pose graph to see the bad loop closures were removed.

```
[newPG,trimInfo] = trimLoopClosures(updatedPG,trimParams,solverOptions);
show(newPG,IDs="off");
title("New Pose Graph")
```




## Input Arguments

**poseGraph — Pose graph**
poseGraph object | poseGraph3D object

Pose graph, specified as a poseGraph or poseGraph3D object.

**edgeIDs — Edge IDs**
vector of positive integers

Edge IDs, specified as a vector of positive integers.

## Output Arguments

**nodePairs — Edge node pairs in pose graph**
*n*-by-2 matrix

Edge node pairs in pose graph, returned as *n*-by-2 matrix that lists the IDs of the two nodes that each edge connects. Each row is a pair of nodes that form an edge. Multiple edges may exist between the same pair of nodes, so the matrix may contain duplicate entries.

# Version History

**Introduced in R2019b**

**R2019b: edgeNodePairs was renamed**
*Behavior change in future release*

The edgeNodePairs object function was renamed from edges. Use edgeNodePairs when calling the function.

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

Use this syntax when constructing poseGraph or poseGraph3D objects for code generation:

poseGraph = poseGraph('MaxNumEdges',maxEdges,'MaxNumNodes',maxNodes) specifies an upper bound on the number of edges and nodes allowed in the pose graph when generating code. This limit is only required when generating code.

## See Also

**Functions**
optimizePoseGraph | addRelativePose | findEdgeID | edgeConstraints | nodeEstimates | removeEdges

**Objects**
poseGraph | poseGraph3D | lidarSLAM

**Topics**
"Implement Simultaneous Localization And Mapping (SLAM) with Lidar Scans"
"Implement Online Simultaneous Localization And Mapping (SLAM) with Lidar Scans"

# edgeResidualErrors

Compute pose graph edge residual errors

## Syntax

```
resErrorVec = edgeResidualErrors(poseGraphObj)
```

## Description

`resErrorVec = edgeResidualErrors(poseGraphObj)` returns the residual errors for each edge in the pose graph with the current pose node estimates. The residual errors order matches the order of edge IDs in `poseGraph`.

## Examples

### Optimize and Trim Loop Closures For 2-D Pose Graphs

Optimize a pose graph based on the nodes and edge constraints. Trim loop closed based on their edge residual errors.

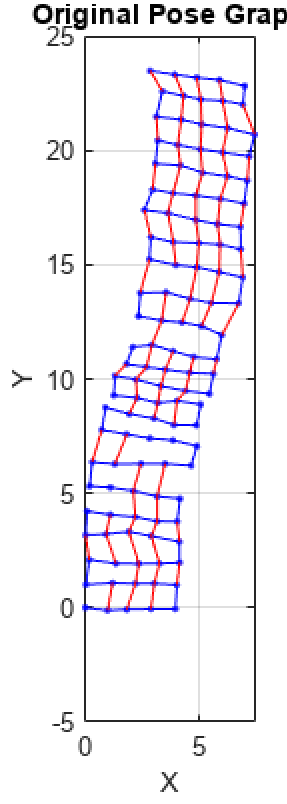
Load the data set that contains a 2-D pose graph. Inspect the `poseGraph` object to view the number of nodes and loop closures.

```
load grid-2d-posegraph.mat pg
disp(pg)
```

```
  poseGraph with properties:

               NumNodes: 120
               NumEdges: 193
    NumLoopClosureEdges: 74
     LoopClosureEdgeIDs: [120 121 122 123 124 125 126 127 128 129 130 131 132 133 134 135 136 13
        LandmarkNodeIDs: [1x0 double]
```

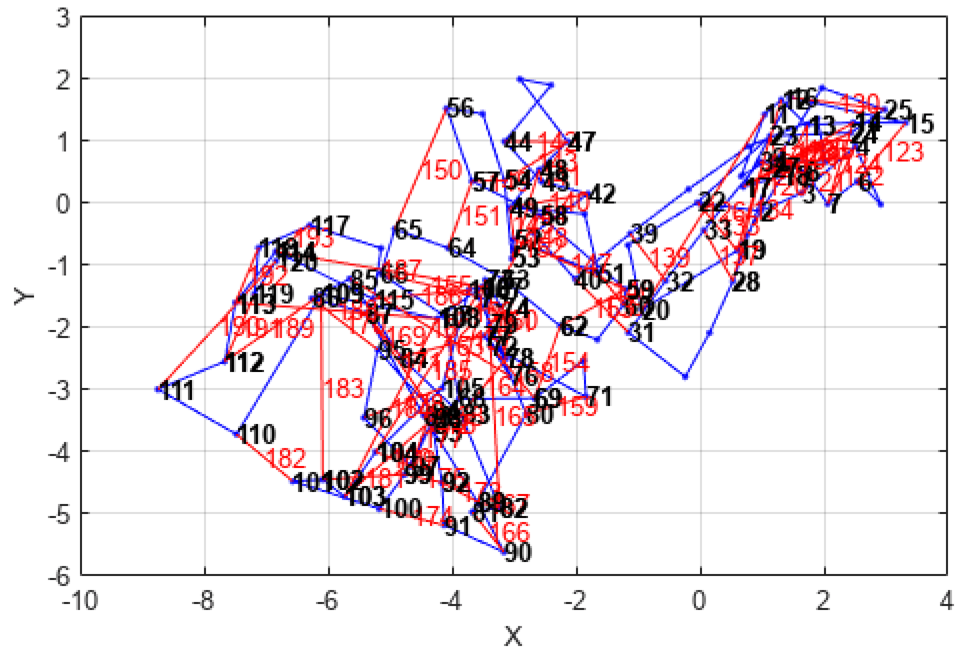
Plot the pose graph with IDs off. Red lines indicate loop closures identified in the dataset. The poses in the graph should follow a grid pattern, but show evidence of drift over time.

```
show(pg,'IDs','off');
title('Original Pose Graph')
```



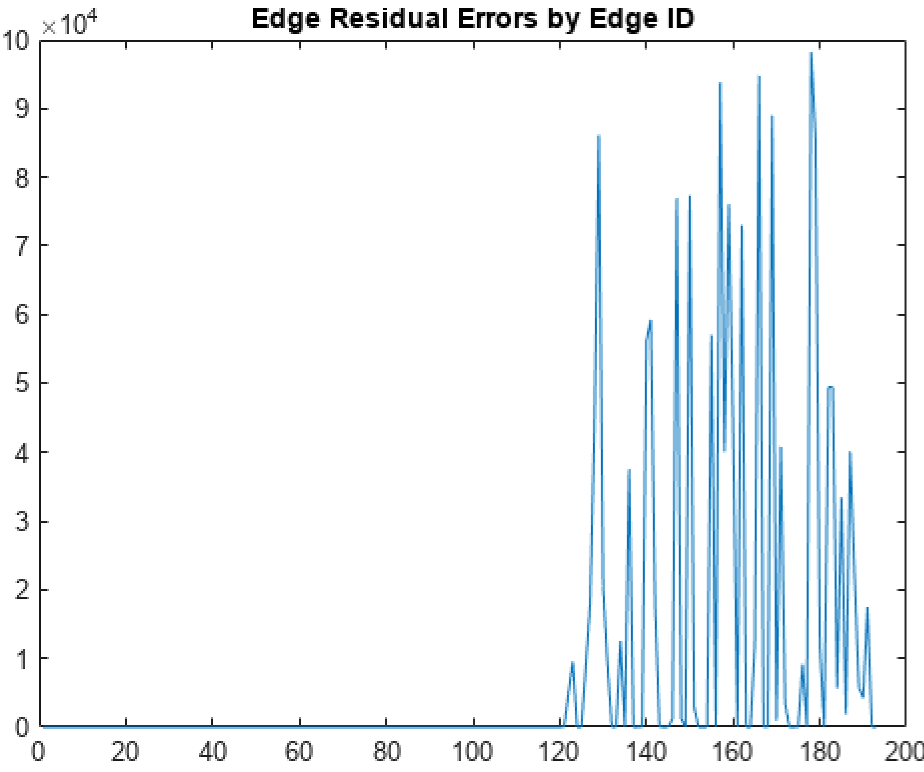

Optimize the pose graph using the `optimizePoseGraph` function. By default, this function uses the `"builtin-trust-region"` solver. Because the pose graph contains some bad loop closures, the resulting pose graph is actual not desirable.

```
pgOptim = optimizePoseGraph(pg);
figure;
show(pgOptim);
```




Look at the edge residual errors for the original pose graph. Large outlier error values at the end indicate bad loop closures.

```
resErrorVec = edgeResidualErrors(pg);
plot(resErrorVec);
title('Edge Residual Errors by Edge ID')
```




Certain loop closures should be trimmed from the pose graph based on their residual error. Use the `trimLoopClosures` function to trim these bad loop closures. Set the maximum and truncation threshold for the trimmer parameters. This threshold is set based on the measurement accuracy and should be tuned for your system.

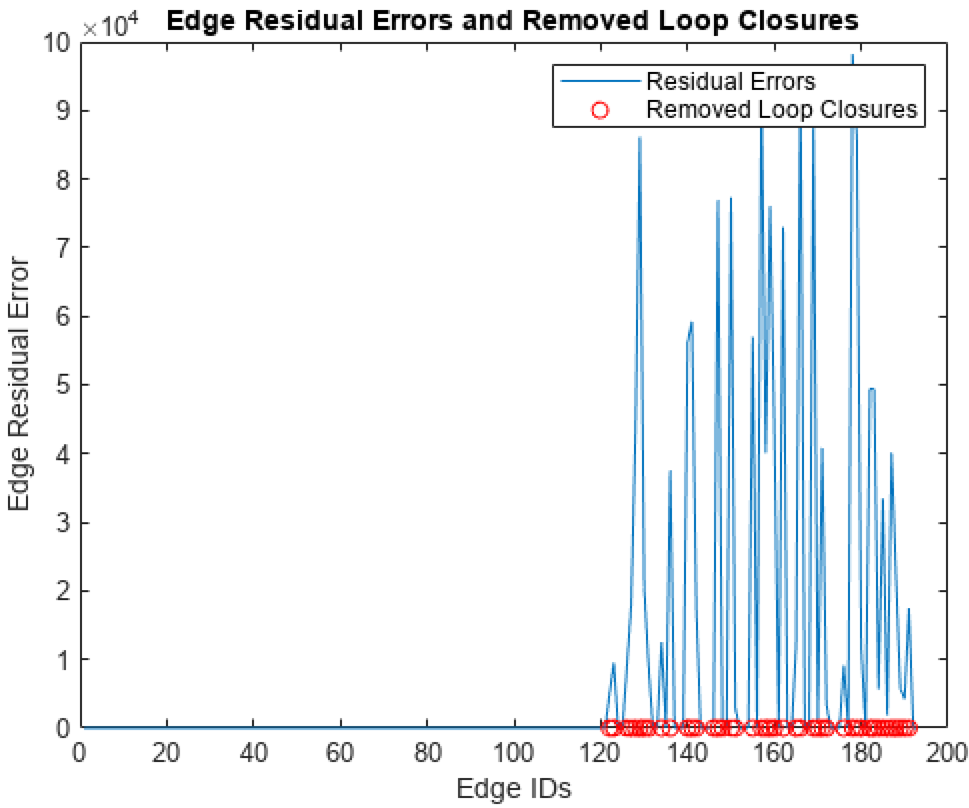
```
trimParams.MaxIterations = 100;
trimParams.TruncationThreshold = 25;

solverOptions = poseGraphSolverOptions;
```

Use the `trimLoopClosures` function with the trimmer parameters and solver options.

```
[pgNew, trimInfo, debugInfo] = trimLoopClosures(pg,trimParams,solverOptions);
```

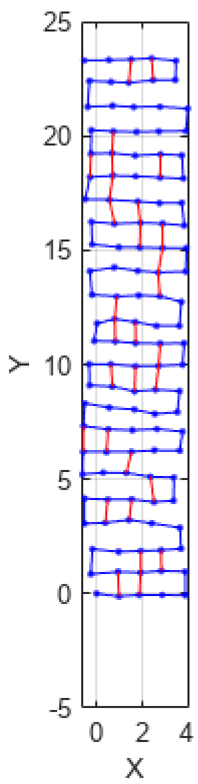
From the `trimInfo` output, plot the loop closures removed from the optimized pose graph. By plotting with the residual errors plot before, you can see the large error loop closures were removed.

```
removedLCs = trimInfo.LoopClosuresToRemove;

hold on
plot(removedLCs,zeros(length(removedLCs)),'or')
title('Edge Residual Errors and Removed Loop Closures')
legend('Residual Errors', 'Removed Loop Closures')
xlabel('Edge IDs')
ylabel('Edge Residual Error')
hold off
```




Show the new pose graph with the bad loop closures trimmed.

```
show(pgNew,"IDs","off");
```




## Input Arguments

**`poseGraphObj` — Pose graph**
`poseGraph` object | `poseGraph3D` object

Pose graph, specified as a `poseGraph` or `poseGraph3D` object.

## Output Arguments

**`resErrorVec` — Edge residual errors for pose graph**
vector of positive scalars

Edge residual errors for pose graph, specified as a vector of positive scalars.

# Version History
**Introduced in R2020b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

Use this syntax when constructing `poseGraph` or `poseGraph3D` objects for code generation:

`poseGraph = poseGraph('MaxNumEdges',maxEdges,'MaxNumNodes',maxNodes)` specifies an upper bound on the number of edges and nodes allowed in the pose graph when generating code. This limit is only required when generating code.

## See Also

**Functions**
`edgeNodePairs` | `optimizePoseGraph` | `addRelativePose` | `findEdgeID` | `nodeEstimates` | `removeEdges`

**Objects**
`poseGraph` | `poseGraph3D` | `lidarSLAM`

# findEdgeID

Find edge ID of edge

## Syntax

```
edgeID = findEdgeID(poseGraph,nodePairs)
```

## Description

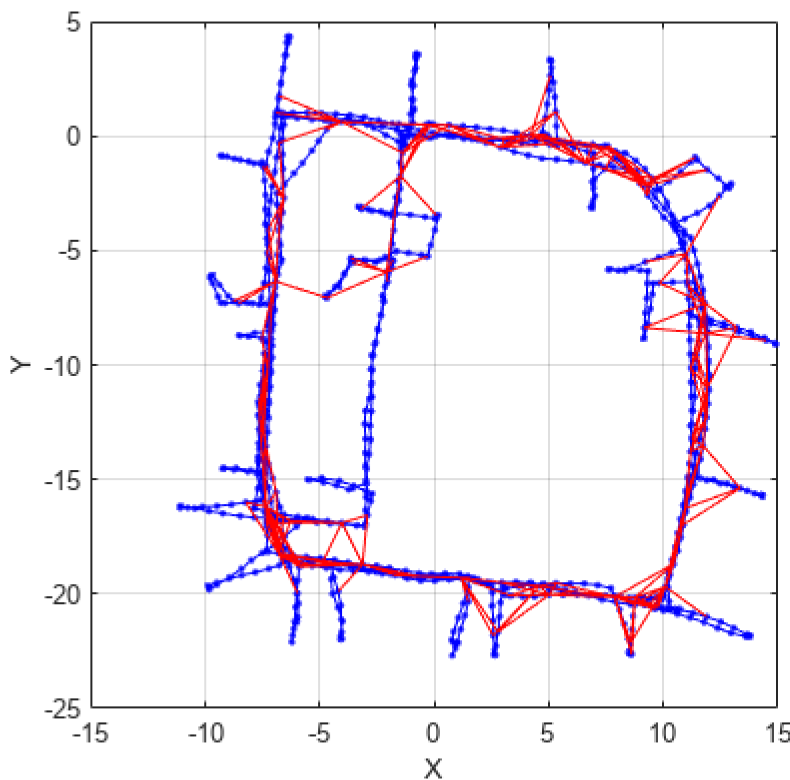
`edgeID = findEdgeID(poseGraph,nodePairs)` finds the edge ID for a specified edge. Edges are defined by the IDs of the two nodes that connect them.

## Examples

### Remove Loop Closure Edges from Pose Graph

Load the Intel Research Lab Dataset that contains a 2-D pose graph. Optimize the pose graph. Plot the pose graph with IDs off. Red lines indicate loop closures identified in the dataset.

```
load intel-2d-posegraph.mat pg
optimizedPG = optimizePoseGraph(pg);
show(optimizedPG,IDs="off");
```



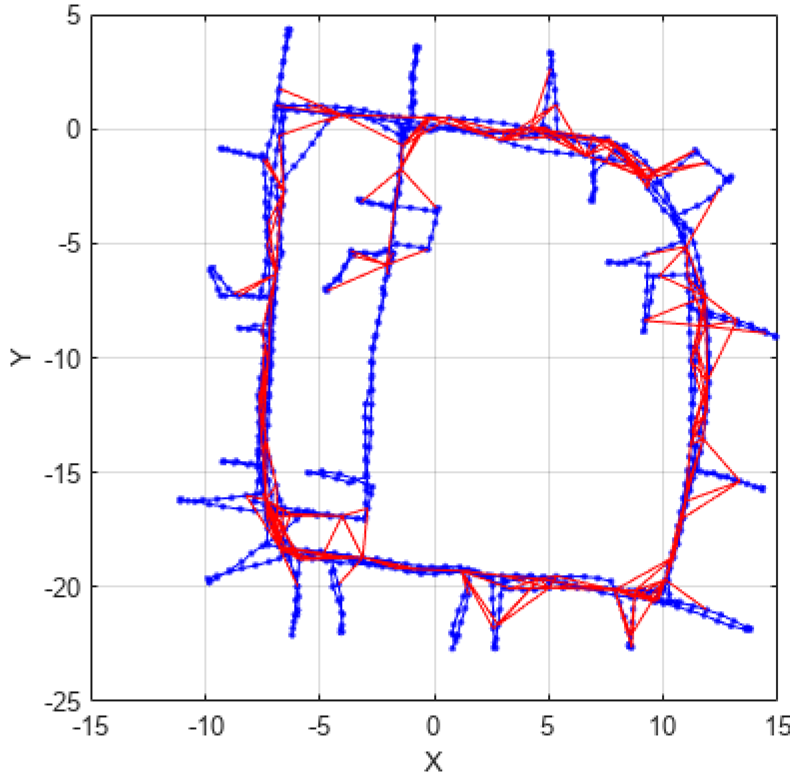
Find the loop closure edge ID for the specified edge node pair in pose graph.

```
nodePair = [133 1085];
edgeID = findEdgeID(optimizedPG,nodePair)
```

```
edgeID = 1386
```

Remove the loop closure edge from the pose graph.

```
removeEdges(optimizedPG,edgeID)
show(optimizedPG,IDs="off");
```




## Input Arguments

**poseGraph — Pose graph**
poseGraph object | poseGraph3D object

Pose graph, specified as a `poseGraph` or `poseGraph3D` object.

**nodePairs — Edge node pairs in pose graph**
two-element vector

Edge node pairs in pose graph, specified as a two-element vector that lists the IDs of the two nodes that the edge connects.

## Output Arguments

**edgeID — Edge ID**
positive integer | vector

Edge IDs, returned as a positive integer or vector of positive integers. The pose graph can contain multiple edges between each node pair, so multiple edge IDs may be returned for a single edge ID.

# Version History

**Introduced in R2019b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

Use this syntax when constructing `poseGraph` or `poseGraph3D` objects for code generation:

`poseGraph = poseGraph('MaxNumEdges',maxEdges,'MaxNumNodes',maxNodes)` specifies an upper bound on the number of edges and nodes allowed in the pose graph when generating code. This limit is only required when generating code.

## See Also

**Functions**
`optimizePoseGraph` | `addRelativePose` | `edgeNodePairs` | `edgeConstraints` | `nodeEstimates` | `removeEdges`

**Objects**
`poseGraph` | `poseGraph3D` | `lidarSLAM`

**Topics**
"Implement Simultaneous Localization And Mapping (SLAM) with Lidar Scans"
"Implement Online Simultaneous Localization And Mapping (SLAM) with Lidar Scans"

# nodeEstimates

Poses of nodes in pose graph

## Syntax

```
measurements = nodeEstimates(poseGraph)
measurements = nodeEstimates(poseGraph,nodeIDs)
```

## Description

`measurements = nodeEstimates(poseGraph)` lists all poses in the specified pose graph.

`measurements = nodeEstimates(poseGraph,nodeIDs)` lists the poses with the specified node IDs.

## Examples

### Add Landmark Point Node to Pose Graph

Create a 2-D pose graph object.

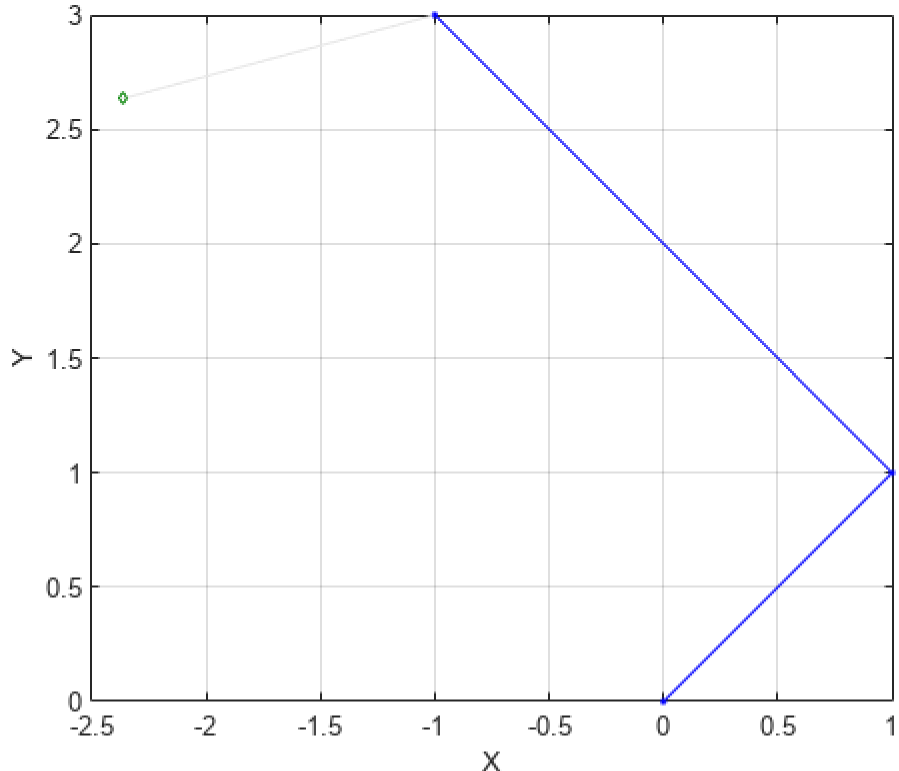
```
pg = poseGraph;
```

Add relative poses to the pose graph.

```
addRelativePose(pg,[1 1 pi/2]);
addRelativePose(pg,[2 2 pi/3]);
```

Add a landmark point node to the last pose node in the pose graph.

```
addPointLandmark(pg,[1 1]);
show(pg);
```




List all poses in the pose graph.

```
nodeEstimates(pg)
```

```
ans = 4×3

         0         0         0
    1.0000    1.0000    1.5708
   -1.0000    3.0000    2.6180
   -2.3660    2.6340       NaN
```

## Input Arguments

**poseGraph — Pose graph**
poseGraph object | poseGraph3D object

Pose graph, specified as a `poseGraph` or `poseGraph3D` object.

**nodeIDs — Node IDs**
positive integer | vector of positive integers

Node IDs, specified as a positive integer or vector of positive integers. Each node added gets an ID sequentially in the graph.

## Output Arguments

**`measurements` — Measurements between nodes**
*n*-by-3 matrix | *n*-by-7 matrix

Measurements between nodes, returned as an *n*-by-3 matrix or *n*-by-7 matrix.

For `poseGraph` (2-D), each row is an `[x y theta]` vector, which defines the relative *xy*-position and orientation angle, `theta`, of a pose in the graph. For landmark positions, `theta` is returned as `NaN`.

For `poseGraph3D`, each row is an `[x y z qw qx qy qz]` vector, which defines the relative *xyz*-position and quaternion orientation, `[qw qx qy qz]`, of a pose in the graph.

---

**Note** Many other sources for 3-D pose graphs, including `.g2o` formats, specify the quaternion orientation in a different order, for example, `[qx qy qz qw]`. Check the source of your pose graph data before adding nodes to your `poseGraph3D` object.

---

# Version History

**Introduced in R2019b**

**R2019b: `nodeEstimates` was renamed**
*Behavior change in future release*

The `nodeEstimates` object function was renamed from `nodes`. Use `nodeEstimates` when calling the function.

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

Use this syntax when constructing `poseGraph` or `poseGraph3D` objects for code generation:

`poseGraph = poseGraph('MaxNumEdges',maxEdges,'MaxNumNodes',maxNodes)` specifies an upper bound on the number of edges and nodes allowed in the pose graph when generating code. This limit is only required when generating code.

## See Also

**Functions**
`optimizePoseGraph` | `addRelativePose` | `edgeNodePairs` | `findEdgeID` | `removeEdges` | `edgeConstraints`

**Objects**
`poseGraph` | `poseGraph3D` | `lidarSLAM`

**Topics**
"Implement Simultaneous Localization And Mapping (SLAM) with Lidar Scans"
"Implement Online Simultaneous Localization And Mapping (SLAM) with Lidar Scans"

# removeEdges

Remove loop closure edges from graph

## Syntax

```
removeEdges(poseGraph,edgeIDs)
```

## Description

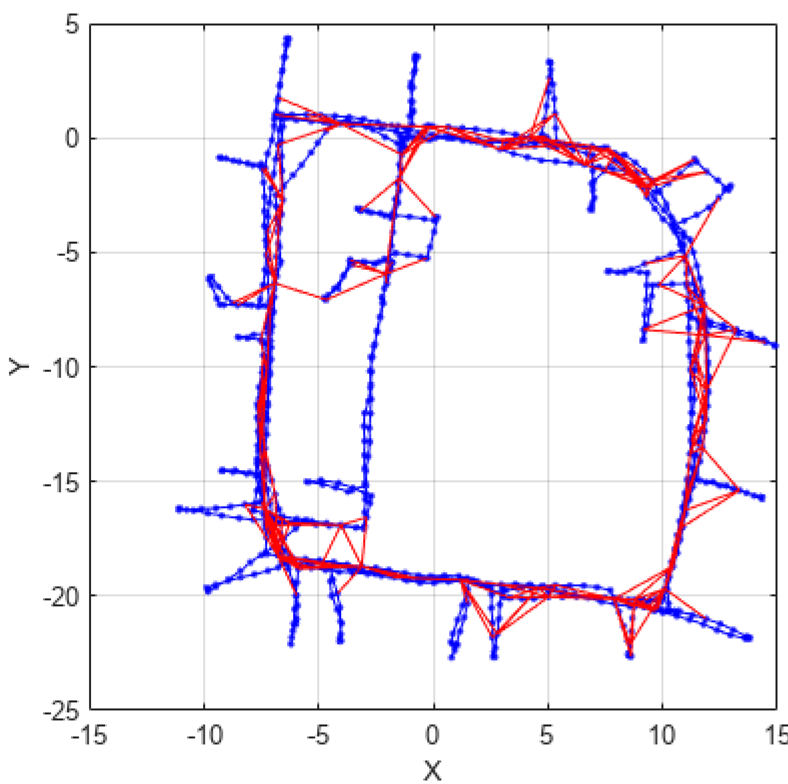
`removeEdges(poseGraph,edgeIDs)` removes loop closure edges, landmark edges, or duplicate incremental edges from the pose graph.

## Examples

### Remove Loop Closure Edges from Pose Graph

Load the Intel Research Lab Dataset that contains a 2-D pose graph. Optimize the pose graph. Plot the pose graph with IDs off. Red lines indicate loop closures identified in the dataset.

```
load intel-2d-posegraph.mat pg
optimizedPG = optimizePoseGraph(pg);
show(optimizedPG,IDs="off");
```



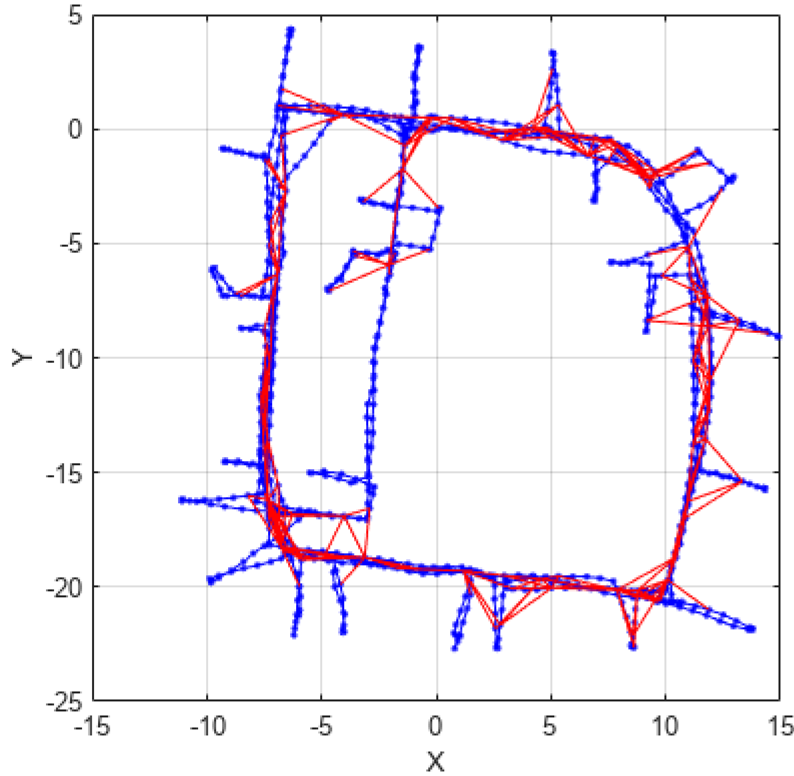
Find the loop closure edge ID for the specified edge node pair in pose graph.

```
nodePair = [133 1085];
edgeID = findEdgeID(optimizedPG,nodePair)
```

```
edgeID = 1386
```

Remove the loop closure edge from the pose graph.

```
removeEdges(optimizedPG,edgeID)
show(optimizedPG,IDs="off");
```




## Input Arguments

**poseGraph — Pose graph**
poseGraph object | poseGraph3D object

Pose graph, specified as a `poseGraph` or `poseGraph3D` object.

**edgeIDs — Edge IDs**
vector of positive integers

Edge IDs, specified as a vector of positive integers. To get edge IDs based on node pairs, see the `findEdgeID` function.

# Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

Use this syntax when constructing `poseGraph` or `poseGraph3D` objects for code generation:

`poseGraph = poseGraph('MaxNumEdges',maxEdges,'MaxNumNodes',maxNodes)` specifies an upper bound on the number of edges and nodes allowed in the pose graph when generating code. This limit is only required when generating code.

## See Also

### Functions

`optimizePoseGraph` | `findEdgeID` | `addRelativePose` | `edgeNodePairs` | `edgeConstraints` | `nodeEstimates`

### Objects

`poseGraph` | `poseGraph3D` | `lidarSLAM`

### Topics

"Implement Simultaneous Localization And Mapping (SLAM) with Lidar Scans"
"Implement Online Simultaneous Localization And Mapping (SLAM) with Lidar Scans"

# show

Plot pose graph

## Syntax

```
show(poseGraph)
show(poseGraph,Name,Value)
axes = show(___)
```

## Description

`show(poseGraph)` plots the specified pose graph in a figure.

`show(poseGraph,Name,Value)` specifies options using `Name,Value` pair arguments. For example, `'IDs','on'` plots all node and edge IDs of the pose graph.

`axes = show(___)` returns the axes handle that the pose graph is plotted to using any of previous syntaxes.

## Examples

### Optimize a 2-D Pose Graph

Optimize a pose graph based on the nodes and edge constraints. The pose graph used in this example is from the Intel Research Lab Dataset and was generated from collecting wheel odometry and a laser range finder sensor information in an indoor lab.

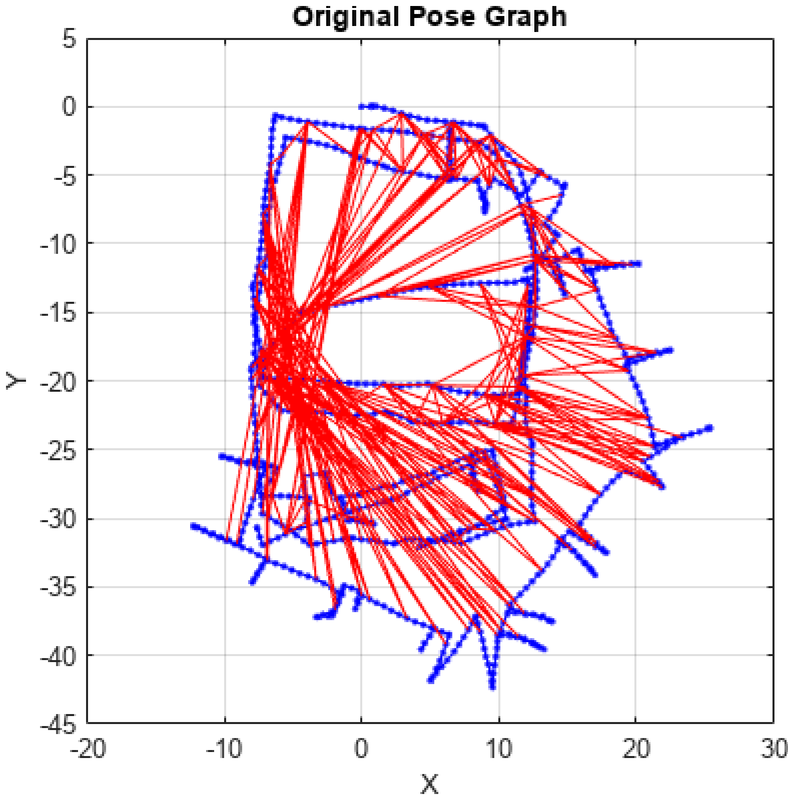
Load the Intel data set that contains a 2-D pose graph. Inspect the `poseGraph` object to view the number of nodes and loop closures.

```
load intel-2d-posegraph.mat pg
disp(pg)
```

```
  poseGraph with properties:

               NumNodes: 1228
               NumEdges: 1483
    NumLoopClosureEdges: 256
     LoopClosureEdgeIDs: [1228 1229 1230 1231 1232 1233 1234 1235 1236 1237 1238 1239 1240 1241 
        LandmarkNodeIDs: [1x0 double]
```

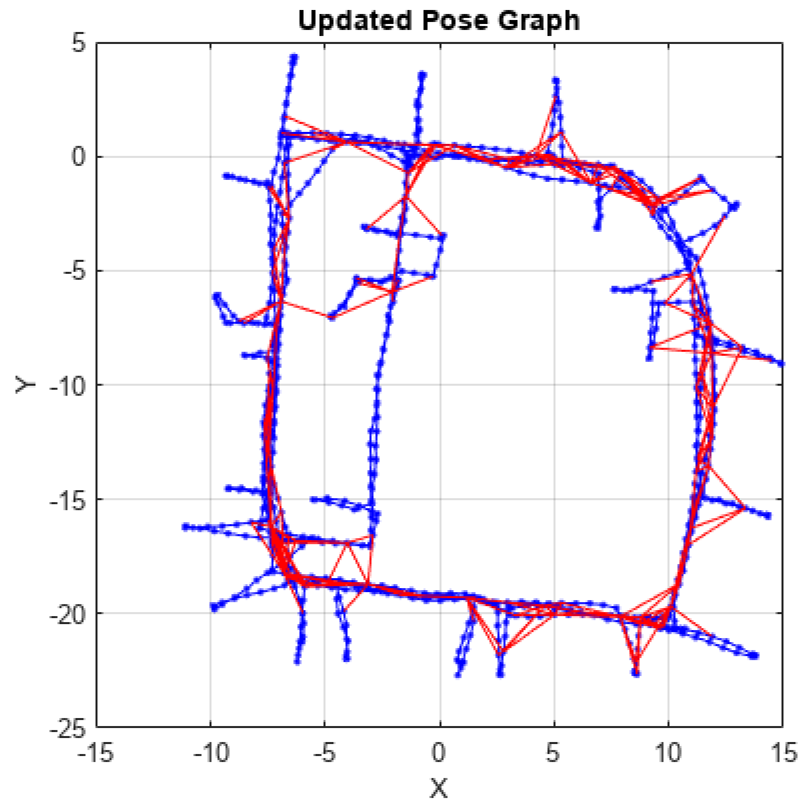
Plot the pose graph with IDs off. Red lines indicate loop closures identified in the dataset.

```
show(pg,'IDs','off');
title('Original Pose Graph')
```




Optimize the pose graph. Nodes are adjusted based on the edge constraints and loop closures. Plot the optimized pose graph to see the adjustment of the nodes with loop closures.

```
updatedPG = optimizePoseGraph(pg);
figure
show(updatedPG,'IDs','off');
title('Updated Pose Graph')
```




### Optimize a 3-D Pose Graph

Optimize a pose graph based on the nodes and edge constraints. The pose graph used in this example is taken from the MIT Dataset and was generated using information extracted from a parking garage.

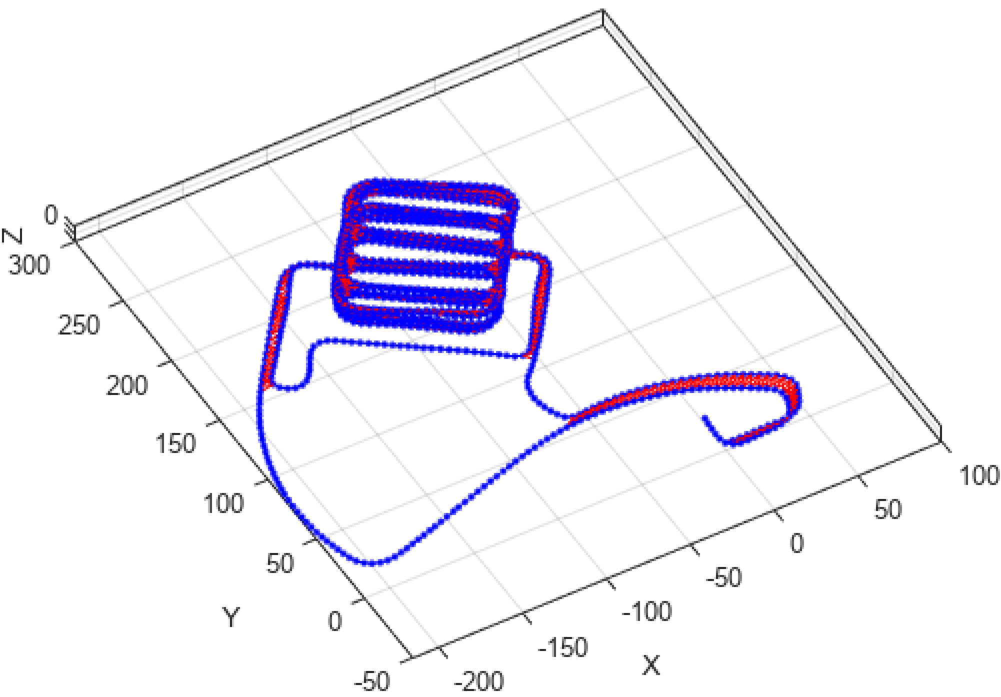
Load the pose graph from the MIT dataset. Inspect the `poseGraph3D` object to view the number of nodes and loop closures.

```
load parking-garage-posegraph.mat pg
disp(pg);
```

```
  poseGraph3D with properties:

               NumNodes: 1661
               NumEdges: 6275
    NumLoopClosureEdges: 4615
     LoopClosureEdgeIDs: [128 129 130 132 133 134 135 137 138 139 140 142 143 144 146 147 148 150
        LandmarkNodeIDs: [1x0 double]
```

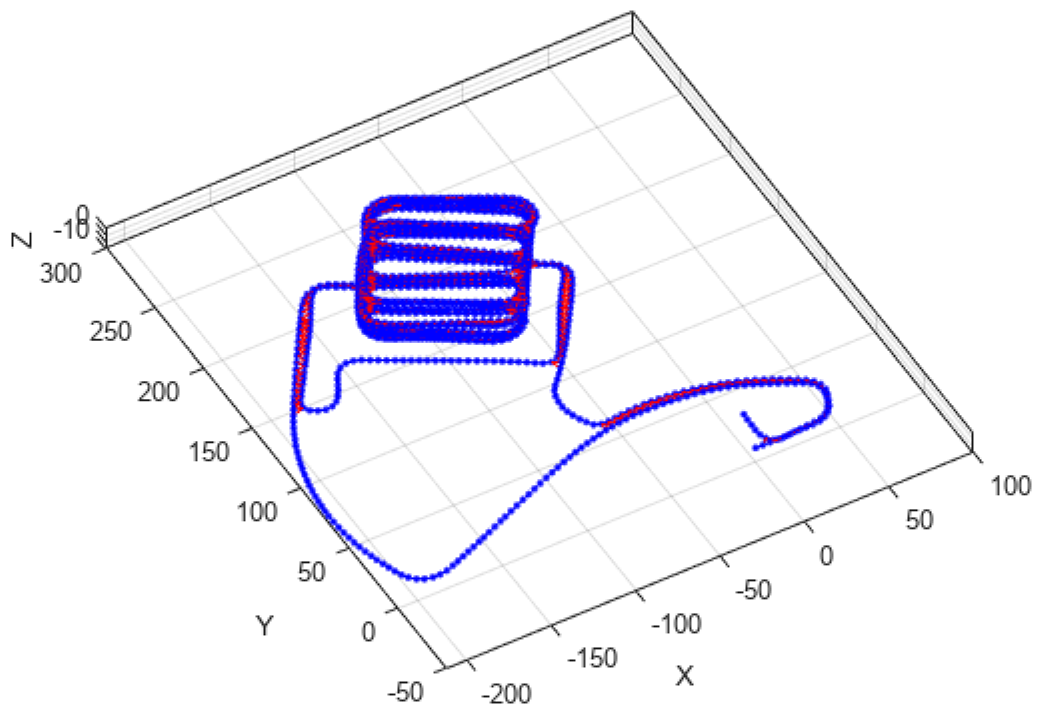
Plot the pose graph with IDs off. Red lines indicate loop closures identified in the dataset.

```
title('Original Pose Graph')
show(pg,'IDs','off');
view(-30,45)
```




Optimize the pose graph. Nodes are adjusted based on the edge constraints and loop closures. Plot the optimized pose graph to see the adjustment of the nodes with loop closures.

```
updatedPG = optimizePoseGraph(pg);
figure
title('Updated Pose Graph')
show(updatedPG,'IDs','off');
view(-30,45)
```




## Input Arguments

**poseGraph — Pose graph**
poseGraph object | poseGraph3D object

Pose graph, specified as a poseGraph or poseGraph3D object.

### Name-Value Pair Arguments

Specify optional pairs of arguments as Name1=Value1,...,NameN=ValueN, where Name is the argument name and Value is the corresponding value. Name-value arguments must appear after other arguments, but the order of the pairs does not matter.

*Before R2021a, use commas to separate each name and value, and enclose* Name *in quotes.*

Example: 'IDs','off'

**Parent — Axes used to plot pose graph**
Axes object | UIAxes object

Axes used to plot the pose graph, specified as the comma-separated pair consisting of 'Parent' and either an Axes or UIAxesobject. See axes or uiaxes.

**IDs — Display of IDs on pose graph**
'loopclosures' (default) | 'all' | 'nodes' | 'off'

Display of IDs on pose graph, specified as the comma-separated pair consisting of `'IDs'` and one of the following:

- `'all'` — Plot all node and edge IDs.
- `'nodes'` — Plot all node IDs and loop closure IDs.
- `'loopclosures'` — Plot only loop closure edge IDs.
- `'off'` — Do not plot any IDs.

## Output Arguments

**axes — Axes used to plot the map**
`Axes` object | `UIAxes` object

Axes used to plot the map, returned as either an `Axes` or `UIAxes` object. See `axes` or `uiaxes`.

# Version History

**Introduced in R2019b**

## See Also

**Functions**
`optimizePoseGraph` | `addRelativePose`

**Objects**
`poseGraph` | `poseGraph3D` | `lidarSLAM`

**Topics**
“Implement Simultaneous Localization And Mapping (SLAM) with Lidar Scans”
“Implement Online Simultaneous Localization And Mapping (SLAM) with Lidar Scans”
“Landmark SLAM Using AprilTag Markers”

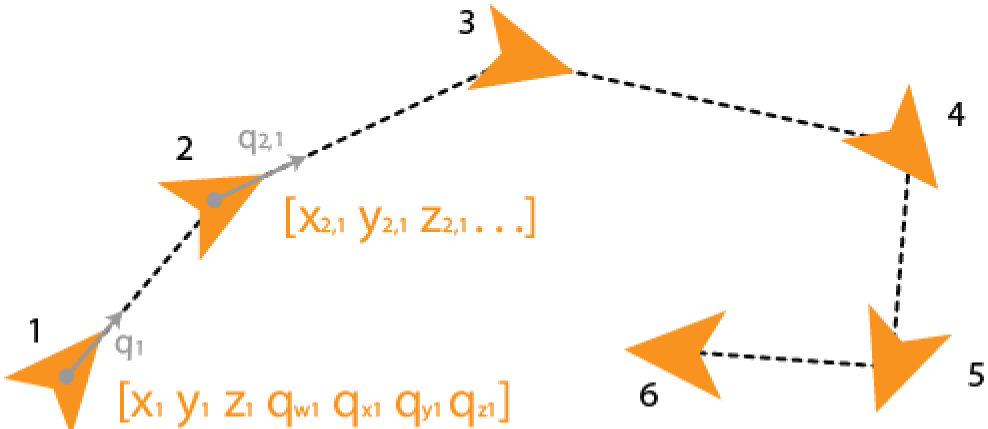
# poseGraph3D

Create 3-D pose graph

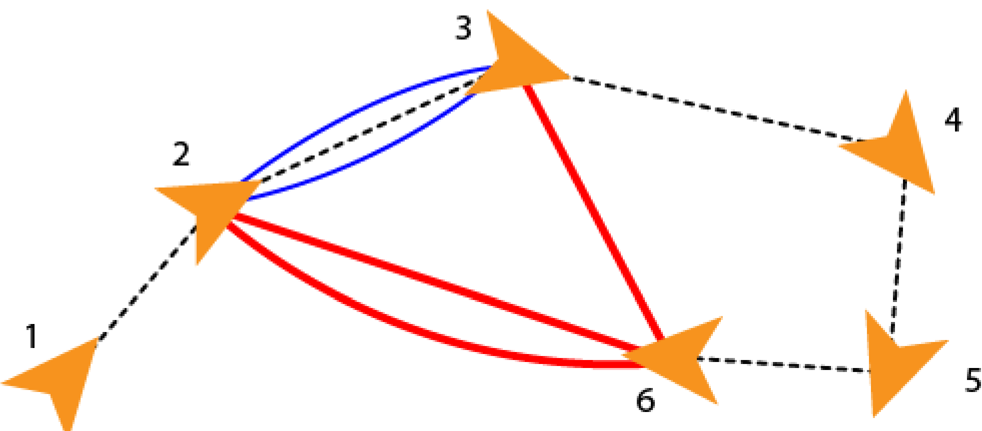
## Description

A poseGraph3D object stores information for a 3-D pose graph representation. A pose graph contains nodes connected by edges. Each node estimate is connected to the graph by edge constraints that define the relative pose between nodes and the uncertainty on that measurement.

To construct a pose graph iteratively, use the addRelativePose function to add relative pose estimates and connect them to an existing node with specified edge constraints. Pose nodes must be specified relative to a pose node. Specify the uncertainty of the measurement using an information matrix.

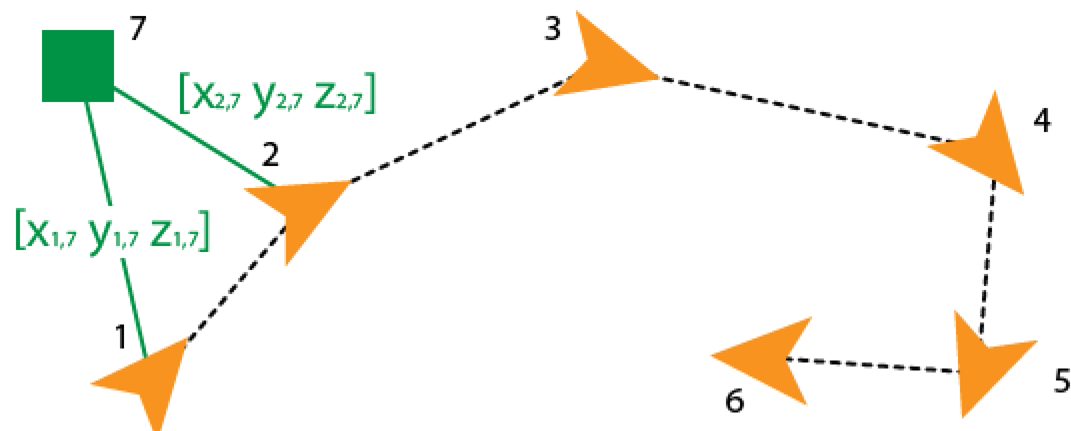



Adding an edge between two nonsequential nodes creates a *loop closure* in the graph. Multiple edges or *multiedges* between node pairs are also supported, which includes loop closures. To add additional edge constraints or loop closures, specify the node IDs using the addRelativePose function. When optimizing the pose graph, the optimizePoseGraph function finds a solution to satisfy all these edge constraints.




Loop closures and multiedges

To add landmark point nodes, use the `addPointLandmark` function. This function specifies nodes as *xyz*-points without orientation estimates. Landmarks must be specified relative to a pose node.




Point landmarks

For 2-D pose graphs, see `poseGraph`.

For an example that builds and optimizes a 3-D pose graph from real-world sensor data, see "Landmark SLAM Using AprilTag Markers".

# Creation

## Syntax

```
poseGraph = poseGraph3D
poseGraph = poseGraph3D('MaxNumEdges',maxEdges,'MaxNumNodes',maxNodes)
```

### Description

`poseGraph = poseGraph3D` creates a 3-D pose graph object. Add poses using `addRelativePose` to construct a pose graph iteratively.

`poseGraph = poseGraph3D('MaxNumEdges',maxEdges,'MaxNumNodes',maxNodes)` specifies an upper bound on the number of edges and nodes allowed in the pose graph when generating code. This limit is only required when generating code.

## Properties

**`NumNodes` — Number of nodes in pose graph**
`1` (default) | positive integer

This property is read-only.

Number of nodes in pose graph, specified as a positive integer. Each node represents a pose measurement or a point landmark measurement. To specify relative poses between nodes, use `addRelativePose`. To specify a landmark pose, use `addLandmarkPose`. To get a list of all nodes, use `edgeNodePairs`.

**`NumEdges` — Number of edges in pose graph**
`0` (default) | nonnegative integer

This property is read-only.

Number of edges in pose graph, specified as a nonnegative integer. Each edge connects two nodes in the pose graph. Loop closure edges and landmark edges are included.

**`NumLoopClosureEdges` — Number of loop closures**
`0` (default) | nonnegative integer

This property is read-only.

Number of loop closures in pose graph, specified as a nonnegative integer. To get the edge IDs of the loop closures, use the `LoopClosureEdgeIDs` property.

**`LoopClosureEdgeIDs` — Loop closure edge IDs**
vector

This property is read-only.

Loop closure edges IDs, specified as a vector of edge IDs.

**`LandmarkNodeIDs` — Landmark node IDs**
vector

This property is read-only.

Landmark node IDs, specified as a vector of IDs for each node.

## Object Functions

| | |
|---|---|
| addPointLandmark | Add landmark point node to pose graph |
| addRelativePose | Add relative pose to pose graph |
| copy | Create copy of pose graph |
| edgeNodePairs | Edge node pairs in pose graph |
| edgeConstraints | Edge constraints in pose graph |
| edgeResidualErrors | Compute pose graph edge residual errors |
| findEdgeID | Find edge ID of edge |
| nodeEstimates | Poses of nodes in pose graph |
| removeEdges | Remove loop closure edges from graph |
| show | Plot pose graph |

## Examples

### Optimize a 3-D Pose Graph

Optimize a pose graph based on the nodes and edge constraints. The pose graph used in this example is taken from the MIT Dataset and was generated using information extracted from a parking garage.

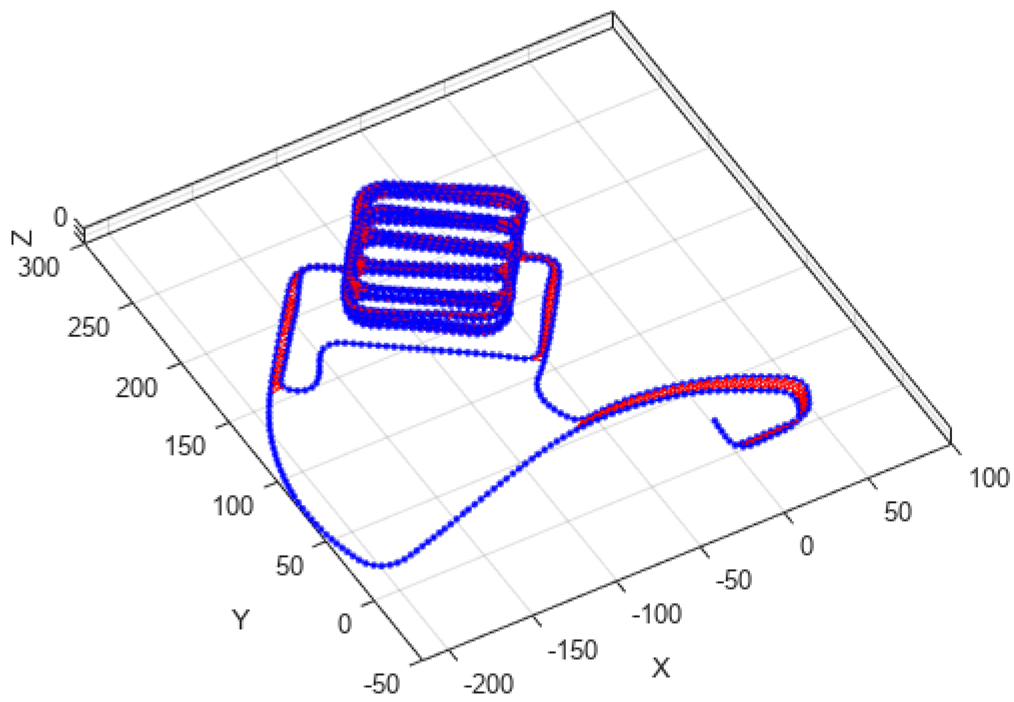
Load the pose graph from the MIT dataset. Inspect the `poseGraph3D` object to view the number of nodes and loop closures.

```
load parking-garage-posegraph.mat pg
disp(pg);
```

```
  poseGraph3D with properties:

               NumNodes: 1661
               NumEdges: 6275
    NumLoopClosureEdges: 4615
     LoopClosureEdgeIDs: [128 129 130 132 133 134 135 137 138 139 140 142 143 144 146 147 148 150
        LandmarkNodeIDs: [1x0 double]
```

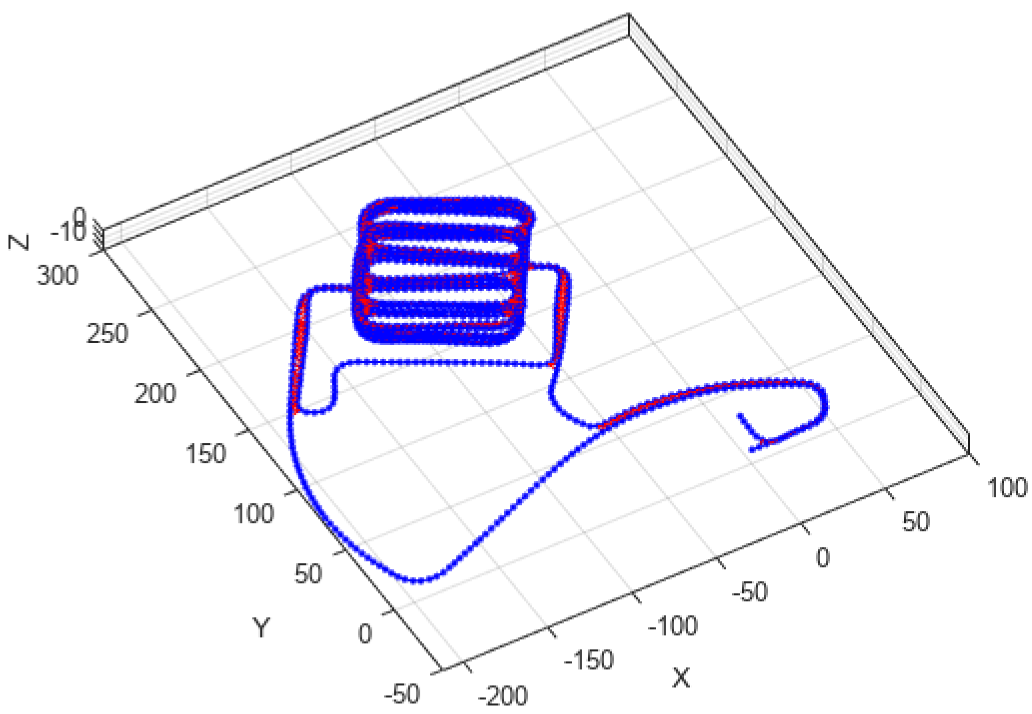
Plot the pose graph with IDs off. Red lines indicate loop closures identified in the dataset.

```
title('Original Pose Graph')
show(pg,'IDs','off');
view(-30,45)
```




Optimize the pose graph. Nodes are adjusted based on the edge constraints and loop closures. Plot the optimized pose graph to see the adjustment of the nodes with loop closures.

```
updatedPG = optimizePoseGraph(pg);
figure
title('Updated Pose Graph')
show(updatedPG,'IDs','off');
view(-30,45)
```




# Version History

**Introduced in R2019b**

## References

[1] Carlone, Luca, Roberto Tron, Kostas Daniilidis, and Frank Dellaert. "Initialization Techniques for 3D SLAM: a Survey on Rotation Estimation and its Use in Pose Graph Optimization." *2015 IEEE International Conference on Robotics and Automation (ICRA)*. 2015, pp. 4597–4604.

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

Use this syntax when constructing `poseGraph3D` objects for code generation:

`poseGraph = poseGraph3D('MaxNumEdges',maxEdges,'MaxNumNodes',maxNodes)` specifies an upper bound on the number of edges and nodes allowed in the pose graph when generating code. This limit is only required when generating code.

## See Also

**Functions**
`optimizePoseGraph` | `addRelativePose` | `addPointLandmark`

**Objects**
`poseGraph` | `lidarSLAM`

**Topics**
"Landmark SLAM Using AprilTag Markers"

# quaternion

Create a quaternion array

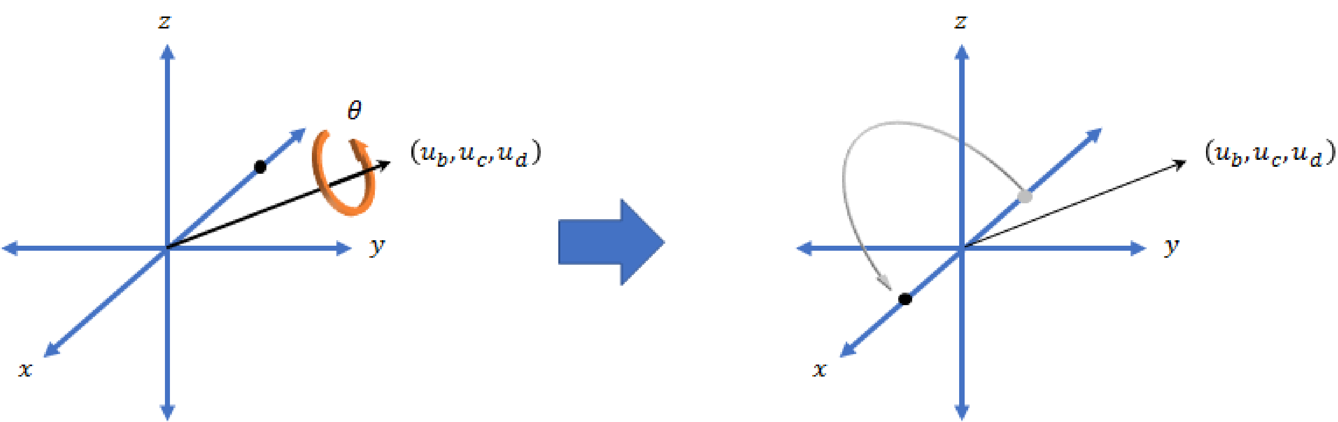
## Description

A quaternion is a four-part hyper-complex number used in three-dimensional rotations and orientations.

A quaternion number is represented in the form $a + b\text{i} + c\text{j} + d\text{k}$, where $a$, $b$, $c$, and $d$ parts are real numbers, and i, j, and k are the basis elements, satisfying the equation: $\text{i}^2 = \text{j}^2 = \text{k}^2 = \text{ijk} = -1$.

The set of quaternions, denoted by **H**, is defined within a four-dimensional vector space over the real numbers, $\mathbf{R}^4$. Every element of **H** has a unique representation based on a linear combination of the basis elements, i, j, and k.

All rotations in 3-D can be described by an axis of rotation and angle about that axis. An advantage of quaternions over rotation matrices is that the axis and angle of rotation is easy to interpret. For example, consider a point in $\mathbf{R}^3$. To rotate the point, you define an axis of rotation and an angle of rotation.




The quaternion representation of the rotation may be expressed as
$q = \cos\left(\theta/2\right) + \sin\left(\theta/2\right)(u_b\text{i} + u_c\text{j} + u_d\text{k})$, where $\theta$ is the angle of rotation and $[u_b$, $u_c$, and $u_d]$ is the axis of rotation.

## Creation

### Syntax

```
quat = quaternion()
quat = quaternion(A,B,C,D)
quat = quaternion(matrix)
quat = quaternion(RV,'rotvec')
```

```
quat = quaternion(RV,'rotvecd')
quat = quaternion(RM,'rotmat',PF)
quat = quaternion(E,'euler',RS,PF)
quat = quaternion(E,'eulerd',RS,PF)
quat = quaternion(transformation)
quat = quaternion(rotation)
```

### Description

`quat = quaternion()` creates an empty quaternion.

`quat = quaternion(A,B,C,D)` creates a quaternion array where the four quaternion parts are taken from the arrays `A`, `B`, `C`, and `D`. All the inputs must have the same size and be of the same data type.

`quat = quaternion(matrix)` creates an *N*-by-1 quaternion array from an *N*-by-4 matrix, where each column becomes one part of the quaternion.

`quat = quaternion(RV,'rotvec')` creates an *N*-by-1 quaternion array from an *N*-by-3 matrix of rotation vectors, `RV`. Each row of `RV` represents a rotation vector in radians.

`quat = quaternion(RV,'rotvecd')` creates an *N*-by-1 quaternion array from an *N*-by-3 matrix of rotation vectors, `RV`. Each row of `RV` represents a rotation vector in degrees.

`quat = quaternion(RM,'rotmat',PF)` creates an *N*-by-1 quaternion array from the 3-by-3-by-*N* array of rotation matrices, `RM`. `PF` can be either `'point'` if the Euler angles represent point rotations or `'frame'` for frame rotations.

`quat = quaternion(E,'euler',RS,PF)` creates an *N*-by-1 quaternion array from the *N*-by-3 matrix, `E`. Each row of `E` represents a set of Euler angles in radians. The angles in `E` are rotations about the axes in sequence `RS`.

`quat = quaternion(E,'eulerd',RS,PF)` creates an *N*-by-1 quaternion array from the *N*-by-3 matrix, `E`. Each row of `E` represents a set of Euler angles in degrees. The angles in `E` are rotations about the axes in sequence `RS`.

`quat = quaternion(transformation)` creates a quaternion array from the SE(3) transformation `transformation`.

`quat = quaternion(rotation)` creates an quaternion array from the SO(3) rotation `rotation`.

### Input Arguments

#### `A,B,C,D` — Quaternion parts

comma-separated arrays of the same size

Parts of a quaternion, specified as four comma-separated scalars, matrices, or multi-dimensional arrays of the same size.

Example: `quat = quaternion(1,2,3,4)` creates a quaternion of the form 1 + 2i + 3j + 4k.

Example: `quat = quaternion([1,5],[2,6],[3,7],[4,8])` creates a 1-by-2 quaternion array where `quat(1,1) = 1 + 2i + 3j + 4k` and `quat(1,2) = 5 + 6i + 7j + 8k`

Data Types: `single` | `double`

**`matrix` — Matrix of quaternion parts**
*N*-by-4 matrix

Matrix of quaternion parts, specified as an *N*-by-4 matrix. Each row represents a separate quaternion. Each column represents a separate quaternion part.

Example: `quat = quaternion(rand(10,4))` creates a 10-by-1 quaternion array.

Data Types: `single` | `double`

**RV — Matrix of rotation vectors**
*N*-by-3 matrix

Matrix of rotation vectors, specified as an *N*-by-3 matrix. Each row of RV represents the [X Y Z] elements of a rotation vector. A rotation vector is a unit vector representing the axis of rotation scaled by the angle of rotation in radians or degrees.

To use this syntax, specify the first argument as a matrix of rotation vectors and the second argument as the `'rotvec'` or `'rotvecd'`.

Example: `quat = quaternion(rand(10,3),'rotvec')` creates a 10-by-1 quaternion array.

Data Types: `single` | `double`

**RM — Rotation matrices**
3-by-3 matrix | 3-by-3-by-*N* array

Array of rotation matrices, specified by a 3-by-3 matrix or 3-by-3-by-*N* array. Each page of the array represents a separate rotation matrix.

Example: `quat = quaternion(rand(3),'rotmat','point')`

Example: `quat = quaternion(rand(3),'rotmat','frame')`

Data Types: `single` | `double`

**PF — Type of rotation matrix**
`'point'` | `'frame'`

Type of rotation matrix, specified by `'point'` or `'frame'`.

Example: `quat = quaternion(rand(3),'rotmat','point')`

Example: `quat = quaternion(rand(3),'rotmat','frame')`

Data Types: `char` | `string`

**E — Matrix of Euler angles**
*N*-by-3 matrix

Matrix of Euler angles, specified by an *N*-by-3 matrix. If using the `'euler'` syntax, specify E in radians. If using the `'eulerd'` syntax, specify E in degrees.

Example: `quat = quaternion(E,'euler','YZY','point')`

Example: `quat = quaternion(E,'euler','XYZ','frame')`

Data Types: `single` | `double`

**RS — Rotation sequence**
character vector | scalar string

Rotation sequence, specified as a three-element character vector:

- `'YZY'`
- `'YXY'`
- `'ZYZ'`
- `'ZXZ'`
- `'XYX'`
- `'XZX'`
- `'XYZ'`
- `'YZX'`
- `'ZXY'`
- `'XZY'`
- `'ZYX'`
- `'YXZ'`

Assume you want to determine the new coordinates of a point when its coordinate system is rotated using frame rotation. The point is defined in the original coordinate system as:

```
point = [sqrt(2)/2,sqrt(2)/2,0];
```

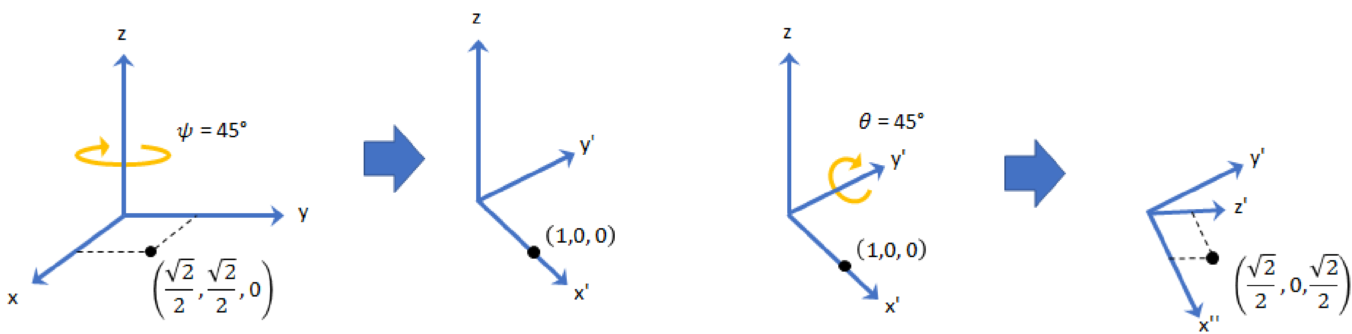
In this representation, the first column represents the *x*-axis, the second column represents the *y*-axis, and the third column represents the *z*-axis.

You want to rotate the point using the Euler angle representation [45,45,0]. Rotate the point using two different rotation sequences:

- If you create a quaternion rotator and specify the 'ZYX' sequence, the frame is first rotated 45° around the *z*-axis, then 45° around the new *y*-axis.

  ```
  quatRotator = quaternion([45,45,0],'eulerd','ZYX','frame');
  newPointCoordinate = rotateframe(quatRotator,point)
  ```

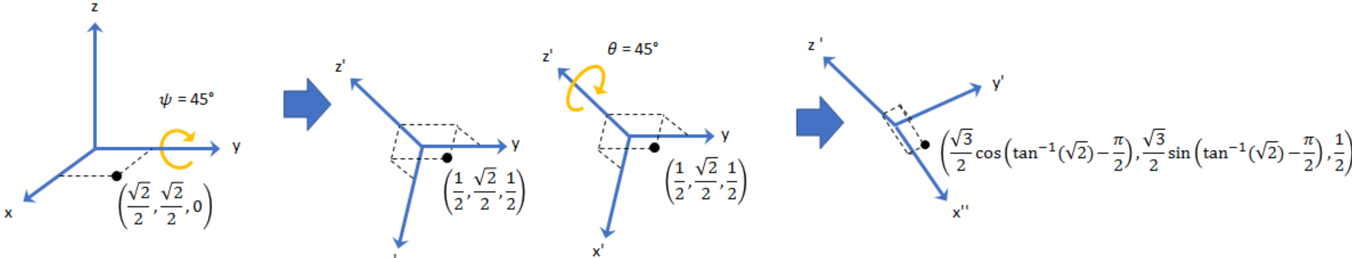
  ```
  newPointCoordinate =

      0.7071   -0.0000    0.7071
  ```




- If you create a quaternion rotator and specify the 'YZX' sequence, the frame is first rotated 45° around the *y*-axis, then 45° around the new *z*-axis.

```
quatRotator = quaternion([45,45,0],'eulerd','YZX','frame');
newPointCoordinate = rotateframe(quatRotator,point)
```

```
newPointCoordinate =

    0.8536    0.1464    0.5000
```



Data Types: char | string

**transformation — Homogeneous transformation**
se3 object | *N*-element array of se3 objects

Transformation, specified as an se3 object, or as an *N*-element array of se3 objects. *N* is the total number of transformations.

The quaternion object ignores the translational component of the transformation and converts the rotational 3-by-3 submatrix of the transformation to a quaternion.

**rotation — Orthonormal rotation**
so3 object | *N*-element array of so3 objects

Orthonormal rotation, specified as an so3 object, or as an *N*-element array of so3 objects. *N* is the total number of rotations.

## Object Functions

| | |
|---|---|
| angvel | Angular velocity from quaternion array |
| classUnderlying | Class of parts within quaternion |
| compact | Convert quaternion array to N-by-4 matrix |
| conj | Complex conjugate of quaternion |
| ' | Complex conjugate transpose of quaternion array |
| dist | Angular distance in radians |
| euler | Convert quaternion to Euler angles (radians) |
| eulerd | Convert quaternion to Euler angles (degrees) |
| exp | Exponential of quaternion array |
| .\,ldivide | Element-wise quaternion left division |
| log | Natural logarithm of quaternion array |
| meanrot | Quaternion mean rotation |
| - | Quaternion subtraction |
| * | Quaternion multiplication |
| norm | Quaternion norm |
| normalize | Quaternion normalization |
| ones | Create quaternion array with real parts set to one and imaginary parts set to zero |
| parts | Extract quaternion parts |

| | |
|---|---|
| .^,power | Element-wise quaternion power |
| prod | Product of a quaternion array |
| randrot | Uniformly distributed random rotations |
| ./,rdivide | Element-wise quaternion right division |
| rotateframe | Quaternion frame rotation |
| rotatepoint | Quaternion point rotation |
| rotmat | Convert quaternion to rotation matrix |
| rotvec | Convert quaternion to rotation vector (radians) |
| rotvecd | Convert quaternion to rotation vector (degrees) |
| slerp | Spherical linear interpolation |
| .*,times | Element-wise quaternion multiplication |
| ' | Transpose a quaternion array |
| - | Quaternion unary minus |
| zeros | Create quaternion array with all parts set to zero |

## Examples

### Create Empty Quaternion

```
quat = quaternion()
```

```
quat =

  0x0 empty quaternion array
```

By default, the underlying class of the quaternion is a double.

```
classUnderlying(quat)
```

```
ans =
'double'
```

### Create Quaternion by Specifying Individual Quaternion Parts

You can create a quaternion array by specifying the four parts as comma-separated scalars, matrices, or multidimensional arrays of the same size.

**Define quaternion parts as scalars.**

```
A = 1.1;
B = 2.1;
C = 3.1;
D = 4.1;
quatScalar = quaternion(A,B,C,D)
```

```
quatScalar = quaternion
     1.1 + 2.1i + 3.1j + 4.1k
```

**Define quaternion parts as column vectors.**

```
A = [1.1;1.2];
B = [2.1;2.2];
```

```
C = [3.1;3.2];
D = [4.1;4.2];
quatVector = quaternion(A,B,C,D)
```

```
quatVector = 2x1 quaternion array
     1.1 + 2.1i + 3.1j + 4.1k
     1.2 + 2.2i + 3.2j + 4.2k
```

**Define quaternion parts as matrices.**

```
A = [1.1,1.3; ...
     1.2,1.4];
B = [2.1,2.3; ...
     2.2,2.4];
C = [3.1,3.3; ...
     3.2,3.4];
D = [4.1,4.3; ...
     4.2,4.4];
quatMatrix = quaternion(A,B,C,D)
```

```
quatMatrix = 2x2 quaternion array
     1.1 + 2.1i + 3.1j + 4.1k     1.3 + 2.3i + 3.3j + 4.3k
     1.2 + 2.2i + 3.2j + 4.2k     1.4 + 2.4i + 3.4j + 4.4k
```

**Define quaternion parts as three dimensional arrays.**

```
A = randn(2,2,2);
B = zeros(2,2,2);
C = zeros(2,2,2);
D = zeros(2,2,2);
quatMultiDimArray = quaternion(A,B,C,D)
```

```
quatMultiDimArray = 2x2x2 quaternion array
quatMultiDimArray(:,:,1) =

     0.53767 +       0i +       0j +       0k     -2.2588 +       0i +       0j +       0k
      1.8339 +       0i +       0j +       0k     0.86217 +       0i +       0j +       0k


quatMultiDimArray(:,:,2) =

     0.31877 +       0i +       0j +       0k    -0.43359 +       0i +       0j +       0k
     -1.3077 +       0i +       0j +       0k     0.34262 +       0i +       0j +       0k
```

### Create Quaternion by Specifying Quaternion Parts Matrix

You can create a scalar or column vector of quaternions by specify an *N*-by-4 matrix of quaternion parts, where columns correspond to the quaternion parts A, B, C, and D.

Create a column vector of random quaternions.

```
quatParts = rand(3,4)
```

```
quatParts = 3×4
```

```
    0.8147    0.9134    0.2785    0.9649
    0.9058    0.6324    0.5469    0.1576
    0.1270    0.0975    0.9575    0.9706
```

```
quat = quaternion(quatParts)
```

```
quat = 3x1 quaternion array
     0.81472 + 0.91338i +  0.2785j + 0.96489k
     0.90579 + 0.63236i + 0.54688j + 0.15761k
     0.12699 + 0.09754i + 0.95751j + 0.97059k
```

To retrieve the `quatParts` matrix from quaternion representation, use `compact`.

```
retrievedquatParts = compact(quat)
```

```
retrievedquatParts = 3×4

    0.8147    0.9134    0.2785    0.9649
    0.9058    0.6324    0.5469    0.1576
    0.1270    0.0975    0.9575    0.9706
```

### Create Quaternion by Specifying Rotation Vectors

You can create an *N*-by-1 quaternion array by specifying an *N*-by-3 matrix of rotation vectors in radians or degrees. Rotation vectors are compact spatial representations that have a one-to-one relationship with normalized quaternions.

#### Rotation Vectors in Radians

Create a scalar quaternion using a rotation vector and verify the resulting quaternion is normalized.

```
rotationVector = [0.3491,0.6283,0.3491];
quat = quaternion(rotationVector,'rotvec')
```

```
quat = quaternion
     0.92124 + 0.16994i + 0.30586j + 0.16994k
```

```
norm(quat)
```

```
ans = 1.0000
```

You can convert from quaternions to rotation vectors in radians using the `rotvec` function. Recover the `rotationVector` from the quaternion, `quat`.

```
rotvec(quat)
```

```
ans = 1×3

    0.3491    0.6283    0.3491
```

### Rotation Vectors in Degrees

Create a scalar quaternion using a rotation vector and verify the resulting quaternion is normalized.

```
rotationVector = [20,36,20];
quat = quaternion(rotationVector,'rotvecd')
```

```
quat = quaternion
     0.92125 + 0.16993i + 0.30587j + 0.16993k
```

```
norm(quat)
```

```
ans = 1
```

You can convert from quaternions to rotation vectors in degrees using the `rotvecd` function. Recover the `rotationVector` from the quaternion, `quat`.

```
rotvecd(quat)
```

```
ans = 1×3

   20.0000   36.0000   20.0000
```

### Create Quaternion by Specifying Rotation Matrices

You can create an N-by-1 quaternion array by specifying a 3-by-3-by-N array of rotation matrices. Each page of the rotation matrix array corresponds to one element of the quaternion array.

Create a scalar quaternion using a 3-by-3 rotation matrix. Specify whether the rotation matrix should be interpreted as a frame or point rotation.

```
rotationMatrix = [1 0         0; ...
                  0 sqrt(3)/2 0.5; ...
                  0 -0.5      sqrt(3)/2];
quat = quaternion(rotationMatrix,'rotmat','frame')
```

```
quat = quaternion
     0.96593 + 0.25882i +       0j +       0k
```

You can convert from quaternions to rotation matrices using the `rotmat` function. Recover the `rotationMatrix` from the quaternion, `quat`.

```
rotmat(quat,'frame')
```

```
ans = 3×3

    1.0000         0         0
         0    0.8660    0.5000
         0   -0.5000    0.8660
```

### Create Quaternion by Specifying Euler Angles

You can create an *N*-by-1 quaternion array by specifying an *N*-by-3 array of Euler angles in radians or degrees.

#### Euler Angles in Radians

Use the `euler` syntax to create a scalar quaternion using a 1-by-3 vector of Euler angles in radians. Specify the rotation sequence of the Euler angles and whether the angles represent a frame or point rotation.

```
E = [pi/2,0,pi/4];
quat = quaternion(E,'euler','ZYX','frame')
```

```
quat = quaternion
     0.65328 +  0.2706i +  0.2706j + 0.65328k
```

You can convert from quaternions to Euler angles using the `euler` function. Recover the Euler angles, `E`, from the quaternion, `quat`.

```
euler(quat,'ZYX','frame')
```

```
ans = 1×3

    1.5708         0    0.7854
```

#### Euler Angles in Degrees

Use the `eulerd` syntax to create a scalar quaternion using a 1-by-3 vector of Euler angles in degrees. Specify the rotation sequence of the Euler angles and whether the angles represent a frame or point rotation.

```
E = [90,0,45];
quat = quaternion(E,'eulerd','ZYX','frame')
```

```
quat = quaternion
     0.65328 +  0.2706i +  0.2706j + 0.65328k
```

You can convert from quaternions to Euler angles in degrees using the `eulerd` function. Recover the Euler angles, `E`, from the quaternion, `quat`.

```
eulerd(quat,'ZYX','frame')
```

```
ans = 1×3

   90.0000         0   45.0000
```

### Quaternion Algebra

Quaternions form a noncommutative associative algebra over the real numbers. This example illustrates the rules of quaternion algebra.

#### Addition and Subtraction

Quaternion addition and subtraction occur part-by-part, and are commutative:

```
Q1 = quaternion(1,2,3,4)
```

```
Q1 = quaternion
     1 + 2i + 3j + 4k
```

```
Q2 = quaternion(9,8,7,6)
```

```
Q2 = quaternion
     9 + 8i + 7j + 6k
```

```
Q1plusQ2 = Q1 + Q2
```

```
Q1plusQ2 = quaternion
     10 + 10i + 10j + 10k
```

```
Q2plusQ1 = Q2 + Q1
```

```
Q2plusQ1 = quaternion
     10 + 10i + 10j + 10k
```

```
Q1minusQ2 = Q1 - Q2
```

```
Q1minusQ2 = quaternion
    -8 - 6i - 4j - 2k
```

```
Q2minusQ1 = Q2 - Q1
```

```
Q2minusQ1 = quaternion
     8 + 6i + 4j + 2k
```

You can also perform addition and subtraction of real numbers and quaternions. The first part of a quaternion is referred to as the *real* part, while the second, third, and fourth parts are referred to as the *vector*. Addition and subtraction with real numbers affect only the real part of the quaternion.

```
Q1plusRealNumber = Q1 + 5
```

```
Q1plusRealNumber = quaternion
     6 + 2i + 3j + 4k
```

```
Q1minusRealNumber = Q1 - 5
```

```
Q1minusRealNumber = quaternion
    -4 + 2i + 3j + 4k
```

### Multiplication

Quaternion multiplication is determined by the products of the basis elements and the distributive law. Recall that multiplication of the basis elements, *i*, *j*, and *k*, are not commutative, and therefore quaternion multiplication is not commutative.

```
Q1timesQ2 = Q1 * Q2
```

```
Q1timesQ2 = quaternion
    -52 + 16i + 54j + 32k
```

```
Q2timesQ1 = Q2 * Q1
```

```
Q2timesQ1 = quaternion
    -52 + 36i + 14j + 52k
```

```
isequal(Q1timesQ2,Q2timesQ1)
```

```
ans = logical
   0
```

You can also multiply a quaternion by a real number. If you multiply a quaternion by a real number, each part of the quaternion is multiplied by the real number individually:

```
Q1times5 = Q1*5
```

```
Q1times5 = quaternion
      5 + 10i + 15j + 20k
```

Multiplying a quaternion by a real number is commutative.

```
isequal(Q1*5,5*Q1)
```

```
ans = logical
   1
```

### Conjugation

The complex conjugate of a quaternion is defined such that each element of the vector portion of the quaternion is negated.

```
Q1
```

```
Q1 = quaternion
     1 + 2i + 3j + 4k
```

```
conj(Q1)
```

```
ans = quaternion
     1 - 2i - 3j - 4k
```

Multiplication between a quaternion and its conjugate is commutative:

```
isequal(Q1*conj(Q1),conj(Q1)*Q1)

ans = logical
   1
```

### Quaternion Array Manipulation

You can organize quaternions into vectors, matrices, and multidimensional arrays. Built-in MATLAB® functions have been enhanced to work with quaternions.

#### Concatenate

Quaternions are treated as individual objects during concatenation and follow MATLAB rules for array manipulation.

```
Q1 = quaternion(1,2,3,4);
Q2 = quaternion(9,8,7,6);

qVector = [Q1,Q2]

qVector = 1x2 quaternion array
     1 + 2i + 3j + 4k     9 + 8i + 7j + 6k


Q3 = quaternion(-1,-2,-3,-4);
Q4 = quaternion(-9,-8,-7,-6);

qMatrix = [qVector;Q3,Q4]

qMatrix = 2x2 quaternion array
     1 + 2i + 3j + 4k     9 + 8i + 7j + 6k
    -1 - 2i - 3j - 4k    -9 - 8i - 7j - 6k


qMultiDimensionalArray(:,:,1) = qMatrix;
qMultiDimensionalArray(:,:,2) = qMatrix

qMultiDimensionalArray = 2x2x2 quaternion array
qMultiDimensionalArray(:,:,1) =

     1 + 2i + 3j + 4k     9 + 8i + 7j + 6k
    -1 - 2i - 3j - 4k    -9 - 8i - 7j - 6k


qMultiDimensionalArray(:,:,2) =

     1 + 2i + 3j + 4k     9 + 8i + 7j + 6k
    -1 - 2i - 3j - 4k    -9 - 8i - 7j - 6k
```

#### Indexing

To access or assign elements in a quaternion array, use indexing.

```
qLoc2 = qMultiDimensionalArray(2)
```

```
qLoc2 = quaternion
    -1 - 2i - 3j - 4k
```

Replace the quaternion at index two with a quaternion one.

```
qMultiDimensionalArray(2) = ones('quaternion')
```

```
qMultiDimensionalArray = 2x2x2 quaternion array
qMultiDimensionalArray(:,:,1) =

     1 + 2i + 3j + 4k     9 + 8i + 7j + 6k
     1 + 0i + 0j + 0k    -9 - 8i - 7j - 6k


qMultiDimensionalArray(:,:,2) =

     1 + 2i + 3j + 4k     9 + 8i + 7j + 6k
    -1 - 2i - 3j - 4k    -9 - 8i - 7j - 6k
```

#### Reshape

To reshape quaternion arrays, use the `reshape` function.

```
qMatReshaped = reshape(qMatrix,4,1)
```

```
qMatReshaped = 4x1 quaternion array
     1 + 2i + 3j + 4k
    -1 - 2i - 3j - 4k
     9 + 8i + 7j + 6k
    -9 - 8i - 7j - 6k
```

#### Transpose

To transpose quaternion vectors and matrices, use the `transpose` function.

```
qMatTransposed = transpose(qMatrix)
```

```
qMatTransposed = 2x2 quaternion array
     1 + 2i + 3j + 4k    -1 - 2i - 3j - 4k
     9 + 8i + 7j + 6k    -9 - 8i - 7j - 6k
```

#### Permute

To permute quaternion vectors, matrices, and multidimensional arrays, use the `permute` function.

```
qMultiDimensionalArray
```

```
qMultiDimensionalArray = 2x2x2 quaternion array
qMultiDimensionalArray(:,:,1) =

     1 + 2i + 3j + 4k     9 + 8i + 7j + 6k
     1 + 0i + 0j + 0k    -9 - 8i - 7j - 6k


qMultiDimensionalArray(:,:,2) =
```

```
     1 + 2i + 3j + 4k     9 + 8i + 7j + 6k
    -1 - 2i - 3j - 4k    -9 - 8i - 7j - 6k
```

```
qMatPermute = permute(qMultiDimensionalArray,[3,1,2])
```

```
qMatPermute = 2x2x2 quaternion array
qMatPermute(:,:,1) =

     1 + 2i + 3j + 4k     1 + 0i + 0j + 0k
     1 + 2i + 3j + 4k    -1 - 2i - 3j - 4k


qMatPermute(:,:,2) =

     9 + 8i + 7j + 6k    -9 - 8i - 7j - 6k
     9 + 8i + 7j + 6k    -9 - 8i - 7j - 6k
```

# Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

se3 | so3

### Topics

"Rotations, Orientation, and Quaternions"
"Lowpass Filter Orientation Using Quaternion SLERP"

# angvel

Angular velocity from quaternion array

## Syntax

```
AV = angvel(Q,dt,'frame')
AV = angvel(Q,dt,'point')
[AV,qf] = angvel(Q,dt,fp,qi)
```

## Description

`AV = angvel(Q,dt,'frame')` returns the angular velocity array from an array of quaternions, `Q`. The quaternions in `Q` correspond to frame rotation. The initial quaternion is assumed to represent zero rotation.

`AV = angvel(Q,dt,'point')` returns the angular velocity array from an array of quaternions, `Q`. The quaternions in `Q` correspond to point rotation. The initial quaternion is assumed to represent zero rotation.

`[AV,qf] = angvel(Q,dt,fp,qi)` allows you to specify the initial quaternion, `qi`, and the type of rotation, `fp`. It also returns the final quaternion, `qf`.

## Examples

### Generate Angular Velocity From Quaternion Array

Create an array of quaternions.

```
eulerAngles = [(0:10:90).',zeros(numel(0:10:90),2)];
q = quaternion(eulerAngles,'eulerd','ZYX','frame');
```

Specify the time step and generate the angular velocity array.

```
dt = 1;
av = angvel(q,dt,'frame') % units in rad/s
```

```
av = 10×3

         0         0         0
         0         0    0.1743
         0         0    0.1743
         0         0    0.1743
         0         0    0.1743
         0         0    0.1743
         0         0    0.1743
         0         0    0.1743
         0         0    0.1743
         0         0    0.1743
```

## Input Arguments

**`Q` — Quaternions**
*N*-by-1 vector of quaternions

Quaternions, specified as an *N*-by-1 vector of quaternions.

Data Types: `quaternion`

**`dt` — Time step**
nonnegative scalar

Time step, specified as a nonnegative scalar.

Data Types: `single` | `double`

**`fp` — Type of rotation**
`'frame'` | `'point'`

Type of rotation, specified as `'frame'` or `'point'`.

**`qi` — Initial quaternion**
quaternion

Initial quaternion, specified as a quaternion.

Data Types: `quaternion`

## Output Arguments

**`AV` — Angular velocity**
*N*-by-3 real matrix

Angular velocity, returned as an *N*-by-3 real matrix. *N* is the number of quaternions given in the input *Q*. Each row of the matrix corresponds to an angular velocity vector.

**`qf` — Final quaternion**
quaternion

Final quaternion, returned as a quaternion. `qf` is the same as the last quaternion in the *Q* input.

Data Types: `quaternion`

# Version History
**Introduced in R2020a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also
`quaternion`

**Topics**

“Rotations, Orientation, and Quaternions”

# classUnderlying

Class of parts within quaternion

## Syntax

```
underlyingClass = classUnderlying(quat)
```

## Description

`underlyingClass = classUnderlying(quat)` returns the name of the class of the parts of the quaternion `quat`.

## Examples

### Get Underlying Class of Quaternion

A quaternion is a four-part hyper-complex number used in three-dimensional representations. The four parts of the quaternion are of data type `single` or `double`.

Create two quaternions, one with an underlying data type of `single`, and one with an underlying data type of `double`. Verify the underlying data types by calling `classUnderlying` on the quaternions.

```
qSingle = quaternion(single([1,2,3,4]))
```

```
qSingle = quaternion
     1 + 2i + 3j + 4k
```

```
classUnderlying(qSingle)
```

```
ans =
'single'
```

```
qDouble = quaternion([1,2,3,4])
```

```
qDouble = quaternion
     1 + 2i + 3j + 4k
```

```
classUnderlying(qDouble)
```

```
ans =
'double'
```

You can separate quaternions into their parts using the `parts` function. Verify the parts of each quaternion are the correct data type. Recall that `double` is the default MATLAB® type.

```
[aS,bS,cS,dS] = parts(qSingle)
```

```
aS = single
    1
```

```
bS = single
    2

cS = single
    3

dS = single
    4
```

```
[aD,bD,cD,dD] = parts(qDouble)
```

```
aD = 1

bD = 2

cD = 3

dD = 4
```

Quaternions follow the same implicit casting rules as other data types in MATLAB. That is, a quaternion with underlying data type `single` that is combined with a quaternion with underlying data type `double` results in a quaternion with underlying data type `single`. Multiply `qDouble` and `qSingle` and verify the resulting underlying data type is `single`.

```
q = qDouble*qSingle;
classUnderlying(q)
```

```
ans =
'single'
```

## Input Arguments

**`quat` — Quaternion to investigate**
scalar | vector | matrix | multi-dimensional array

Quaternion to investigate, specified as a quaternion or array of quaternions.

Data Types: `quaternion`

## Output Arguments

**`underlyingClass` — Underlying class of quaternion object**
`'single'` | `'double'`

Underlying class of quaternion, returned as the character vector `'single'` or `'double'`.

Data Types: `char`

# Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation
Generate C and C++ code using MATLAB® Coder™.

## See Also

### Functions
compact | parts

### Objects
quaternion

### Topics
"Rotations, Orientation, and Quaternions"

# compact

Convert quaternion array to *N*-by-4 matrix

## Syntax

```
matrix = compact(quat)
```

## Description

`matrix = compact(quat)` converts the quaternion array, `quat`, to an *N*-by-4 matrix. The columns are made from the four quaternion parts. The $i^{th}$ row of the matrix corresponds to `quat(i)`.

## Examples

### Convert Quaternion Array to Compact Representation of Parts

Create a scalar quaternion with random parts. Convert the parts to a 1-by-4 vector using `compact`.

```
randomParts = randn(1,4)
```

```
randomParts = 1×4

    0.5377    1.8339   -2.2588    0.8622
```

```
quat = quaternion(randomParts)
```

```
quat = quaternion
     0.53767 +  1.8339i -  2.2588j + 0.86217k
```

```
quatParts = compact(quat)
```

```
quatParts = 1×4

    0.5377    1.8339   -2.2588    0.8622
```

Create a 2-by-2 array of quaternions, then convert the representation to a matrix of quaternion parts. The output rows correspond to the linear indices of the quaternion array.

```
quatArray = [quaternion([1:4;5:8]),quaternion([9:12;13:16])]
```

```
quatArray = 2x2 quaternion array
      1 +  2i +  3j +  4k      9 + 10i + 11j + 12k
      5 +  6i +  7j +  8k     13 + 14i + 15j + 16k
```

```
quatArrayParts = compact(quatArray)
```

```
quatArrayParts = 4×4
```

```
     1     2     3     4
     5     6     7     8
     9    10    11    12
    13    14    15    16
```

## Input Arguments

### `quat` — Quaternion to convert

scalar | vector | matrix | multidimensional array

Quaternion to convert, specified as scalar, vector, matrix, or multidimensional array of quaternions.

Data Types: `quaternion`

## Output Arguments

### `matrix` — Quaternion in matrix form

*N*-by-4 matrix

Quaternion in matrix form, returned as an *N*-by-4 matrix, where *N* = `numel(quat)`.

Data Types: `single` | `double`

# Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Functions

`parts` | `classUnderlying`

### Objects

`quaternion`

### Topics

"Rotations, Orientation, and Quaternions"

# conj

Complex conjugate of quaternion

## Syntax

```
quatConjugate = conj(quat)
```

## Description

`quatConjugate = conj(quat)` returns the complex conjugate of the quaternion, `quat`.

If $q = a + b\text{i} + c\text{j} + d\text{k}$, the complex conjugate of $q$ is $q^* = a - b\text{i} - c\text{j} - d\text{k}$. Considered as a rotation operator, the conjugate performs the opposite rotation. For example,

```
q = quaternion(deg2rad([16 45 30]),'rotvec');
a = q*conj(q);
rotatepoint(a,[0,1,0])
```

```
ans =

     0     1     0
```

## Examples

### Complex Conjugate of Quaternion

Create a quaternion scalar and get the complex conjugate.

```
q = normalize(quaternion([0.9 0.3 0.3 0.25]))
```

```
q = quaternion
     0.87727 + 0.29242i + 0.29242j + 0.24369k
```

```
qConj = conj(q)
```

```
qConj = quaternion
     0.87727 - 0.29242i - 0.29242j - 0.24369k
```

Verify that a quaternion multiplied by its conjugate returns a quaternion one.

```
q*qConj
```

```
ans = quaternion
     1 + 0i + 0j + 0k
```

## Input Arguments

**`quat` — Quaternion**
scalar | vector | matrix | multidimensional array

Quaternion to conjugate, specified as a scalar, vector, matrix, or array of quaternions.

Data Types: `quaternion`

## Output Arguments

**`quatConjugate` — Quaternion conjugate**
scalar | vector | matrix | multidimensional array

Quaternion conjugate, returned as a quaternion or array of quaternions the same size as `quat`.

Data Types: `quaternion`

# Version History

**Introduced in R2019b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Functions**
`norm` | `.*,times`

**Objects**
`quaternion`

**Topics**
"Rotations, Orientation, and Quaternions"

# ctranspose, '

Complex conjugate transpose of quaternion array

## Syntax

```
quatTransposed = quat'
```

## Description

`quatTransposed = quat'` returns the complex conjugate transpose of the quaternion, `quat`.

## Examples

### Vector Complex Conjugate Transpose

Create a vector of quaternions and compute its complex conjugate transpose.

```
quat = quaternion(randn(4,4))
```

```
quat = 4x1 quaternion array
      0.53767 +  0.31877i +   3.5784j +   0.7254k
       1.8339 -   1.3077i +   2.7694j - 0.063055k
      -2.2588 -  0.43359i -   1.3499j +  0.71474k
      0.86217 +  0.34262i +   3.0349j -  0.20497k
```

```
quatTransposed = quat'
```

```
quatTransposed = 1x4 quaternion array
      0.53767 -  0.31877i -   3.5784j -   0.7254k       1.8339 +   1.3077i -   2.7694j + 0.06305
```

### Matrix Complex Conjugate Transpose

Create a matrix of quaternions and compute its complex conjugate transpose.

```
quat = [quaternion(randn(2,4)),quaternion(randn(2,4))]
```

```
quat = 2x2 quaternion array
      0.53767 -   2.2588i +  0.31877j -  0.43359k       3.5784 -   1.3499i +   0.7254j +  0.7147
       1.8339 +  0.86217i -   1.3077j +  0.34262k       2.7694 +   3.0349i - 0.063055j -  0.2049
```

```
quatTransposed = quat'
```

```
quatTransposed = 2x2 quaternion array
      0.53767 +   2.2588i -  0.31877j +  0.43359k       1.8339 -  0.86217i +   1.3077j -  0.3426
       3.5784 +   1.3499i -   0.7254j -  0.71474k       2.7694 -   3.0349i + 0.063055j +  0.2049
```

## Input Arguments

**`quat` — Quaternion to transpose**
scalar | vector | matrix

Quaternion to transpose, specified as a vector or matrix or quaternions. The complex conjugate transpose is defined for 1-D and 2-D arrays.

Data Types: `quaternion`

## Output Arguments

**`quatTransposed` — Conjugate transposed quaternion**
scalar | vector | matrix

Conjugate transposed quaternion, returned as an *N*-by-*M* array, where `quat` was specified as an *M*-by-*N* array.

Data Types: `quaternion`

# Version History

**Introduced in R2019b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Functions**
`transpose, '`

**Objects**
`quaternion`

**Topics**
"Rotations, Orientation, and Quaternions"

# dist

Angular distance in radians

## Syntax

```
distance = dist(quatA,quatB)
```

## Description

`distance = dist(quatA,quatB)` returns the angular distance in radians between two quaternions, `quatA` and `quatB`.

## Examples

### Calculate Quaternion Distance

Calculate the quaternion distance between a single quaternion and each element of a vector of quaternions. Define the quaternions using Euler angles.

```
q = quaternion([0,0,0],'eulerd','zyx','frame')
```

```
q = quaternion
     1 + 0i + 0j + 0k
```

```
qArray = quaternion([0,45,0;0,90,0;0,180,0;0,-90,0;0,-45,0],'eulerd','zyx','frame')
```

```
qArray = 5x1 quaternion array
       0.92388 +         0i +   0.38268j +         0k
       0.70711 +         0i +   0.70711j +         0k
    6.1232e-17 +         0i +         1j +         0k
       0.70711 +         0i -   0.70711j +         0k
       0.92388 +         0i -   0.38268j +         0k
```

```
quaternionDistance = rad2deg(dist(q,qArray))
```

```
quaternionDistance = 5×1

   45.0000
   90.0000
  180.0000
   90.0000
   45.0000
```

If both arguments to `dist` are vectors, the quaternion distance is calculated between corresponding elements. Calculate the quaternion distance between two quaternion vectors.

```
angles1 = [30,0,15; ...
           30,5,15; ...
```

```
           30,10,15; ...
           30,15,15];
angles2 = [30,6,15; ...
           31,11,15; ...
           30,16,14; ...
           30.5,21,15.5];

qVector1 = quaternion(angles1,'eulerd','zyx','frame');
qVector2 = quaternion(angles2,'eulerd','zyx','frame');

rad2deg(dist(qVector1,qVector2))
```

```
ans = 4×1

    6.0000
    6.0827
    6.0827
    6.0287
```

Note that a quaternion represents the same rotation as its negative. Calculate a quaternion and its negative.

```
qPositive = quaternion([30,45,-60],'eulerd','zyx','frame')
```

```
qPositive = quaternion
     0.72332 - 0.53198i + 0.20056j +  0.3919k
```

```
qNegative = -qPositive
```

```
qNegative = quaternion
    -0.72332 + 0.53198i - 0.20056j -  0.3919k
```

Find the distance between the quaternion and its negative.

```
dist(qPositive,qNegative)
```

```
ans = 0
```

The components of a quaternion may look different from the components of its negative, but both expressions represent the same rotation.

## Input Arguments

### quatA,quatB — Quaternions to calculate distance between

scalar | vector | matrix | multidimensional array

Quaternions to calculate distance between, specified as comma-separated quaternions or arrays of quaternions. `quatA` and `quatB` must have compatible sizes:

- `size(quatA) == size(quatB)`, or
- `numel(quatA) == 1`, or
- `numel(quatB) == 1`, or

- if [Adim1,…,AdimN] = size(quatA) and [Bdim1,…,BdimN] = size(quatB), then for i = 1:N, either Adimi==Bdimi or Adim==1 or Bdim==1.

  If one of the quaternion arguments contains only one quaternion, then this function returns the distances between that quaternion and every quaternion in the other argument.

Data Types: quaternion

## Output Arguments

**distance — Angular distance (radians)**
scalar | vector | matrix | multidimensional array

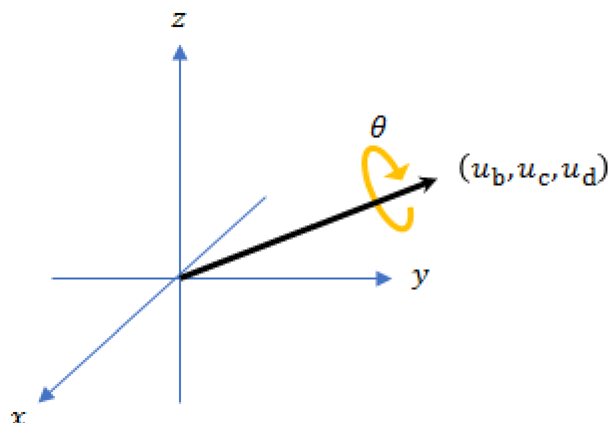
Angular distance in radians, returned as an array. The dimensions are the maximum of the union of size(quatA) and size(quatB).

Data Types: single | double

## Algorithms

The dist function returns the angular distance between two quaternions.

A quaternion may be defined by an axis $(u_b,u_c,u_d)$ and angle of rotation $\theta_q$:
$q = \cos\left(\theta_q/2\right) + \sin\left(\theta_q/2\right)(u_b\mathrm{i} + u_c\mathrm{j} + u_d\mathrm{k})$.




Given a quaternion in the form, $q = a + b\mathrm{i} + c\mathrm{j} + d\mathrm{k}$, where $a$ is the real part, you can solve for the angle of $q$ as $\theta_q = 2\cos^{-1}(a)$.

Consider two quaternions, $p$ and $q$, and the product $z = p*\mathrm{conjugate}(q)$. As $p$ approaches $q$, the angle of $z$ goes to 0, and $z$ approaches the unit quaternion.

The angular distance between two quaternions can be expressed as $\theta_z = 2\cos^{-1}(\mathrm{real}(z))$.

Using the quaternion data type syntax, the angular distance is calculated as:

```
angularDistance = 2*acos(abs(parts(p*conj(q))));
```

## Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Functions

`parts` | `conj`

### Objects

`quaternion`

### Topics

"Rotations, Orientation, and Quaternions"

# euler

Convert quaternion to Euler angles (radians)

## Syntax

`eulerAngles = euler(quat,rotationSequence,rotationType)`

## Description

`eulerAngles = euler(quat,rotationSequence,rotationType)` converts the quaternion, `quat`, to an *N*-by-3 matrix of Euler angles.

## Examples

### Convert Quaternion to Euler Angles in Radians

Convert a quaternion frame rotation to Euler angles in radians using the 'ZYX' rotation sequence.

```
quat = quaternion([0.7071 0.7071 0 0]);
eulerAnglesRandians = euler(quat,'ZYX','frame')
```

```
eulerAnglesRandians = 1×3

         0         0    1.5708
```

## Input Arguments

**`quat` — Quaternion to convert to Euler angles**
scalar | vector | matrix | multidimensional array

Quaternion to convert to Euler angles, specified as a scalar, vector, matrix, or multidimensional array of quaternions.

Data Types: `quaternion`

**`rotationSequence` — Rotation sequence**
`'ZYX'` | `'ZYZ'` | `'ZXY'` | `'ZXZ'` | `'YXZ'` | `'YXY'` | `'YZX'` | `'YZY'` | `'XYZ'` | `'XYX'` | `'XZY'` | `'XZX'`

Rotation sequence of Euler representation, specified as a character vector or string.

The rotation sequence defines the order of rotations about the axes. For example, if you specify a rotation sequence of `'YZX'`:

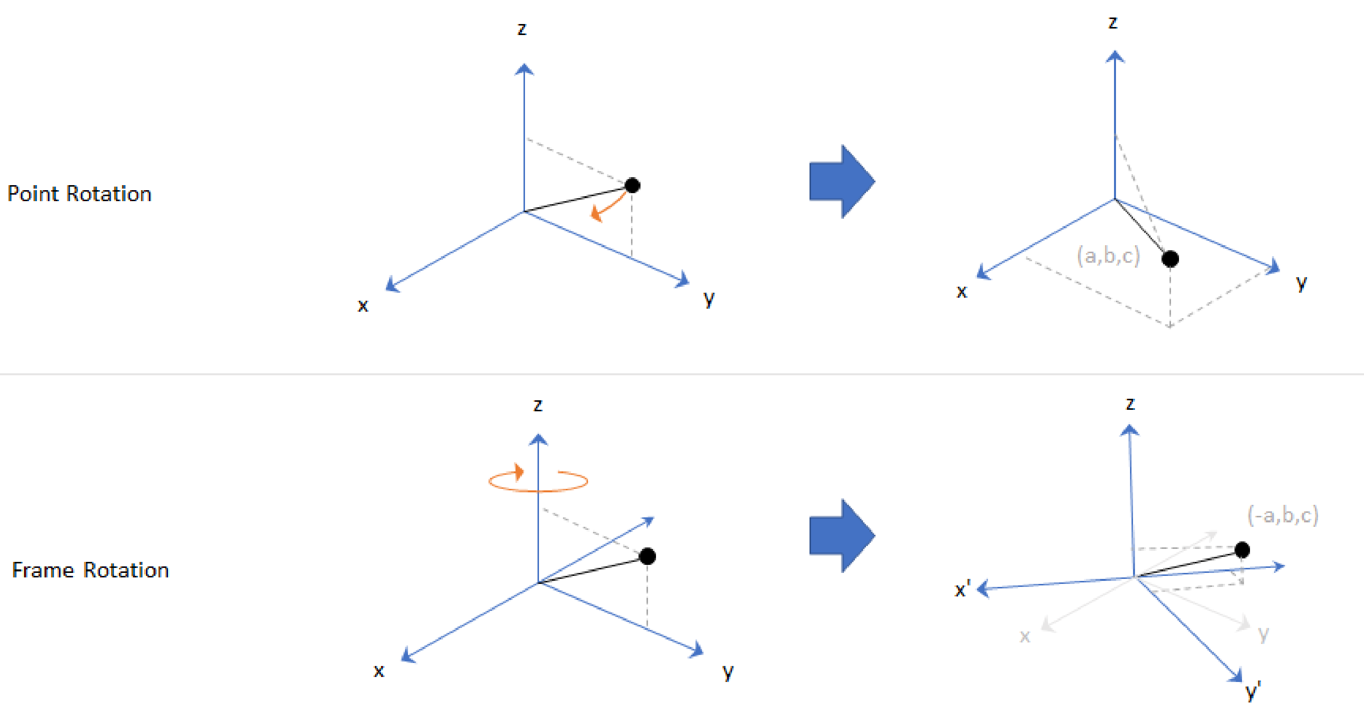
1. The first rotation is about the y-axis.
2. The second rotation is about the new z-axis.
3. The third rotation is about the new x-axis.

Data Types: `char` | `string`

**`rotationType` — Type of rotation**
`'point'` | `'frame'`

Type of rotation, specified as `'point'` or `'frame'`.

In a point rotation, the frame is static and the point moves. In a frame rotation, the point is static and the frame moves. Point rotation and frame rotation define equivalent angular displacements but in opposite directions.




Data Types: `char` | `string`

## Output Arguments

**`eulerAngles` — Euler angle representation (radians)**
*N*-by-3 matrix

Euler angle representation in radians, returned as a *N*-by-3 matrix. *N* is the number of quaternions in the `quat` argument.

For each row of `eulerAngles`, the first element corresponds to the first axis in the rotation sequence, the second element corresponds to the second axis in the rotation sequence, and the third element corresponds to the third axis in the rotation sequence.

The data type of the Euler angles representation is the same as the underlying data type of `quat`.

Data Types: `single` | `double`

# Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation
Generate C and C++ code using MATLAB® Coder™.

## See Also

### Functions
`eulerd` | `rotateframe` | `rotatepoint`

### Objects
`quaternion`

### Topics
“Rotations, Orientation, and Quaternions”

# eulerd

Convert quaternion to Euler angles (degrees)

## Syntax

`eulerAngles = eulerd(quat,rotationSequence,rotationType)`

## Description

`eulerAngles = eulerd(quat,rotationSequence,rotationType)` converts the quaternion, `quat`, to an *N*-by-3 matrix of Euler angles in degrees.

## Examples

### Convert Quaternion to Euler Angles in Degrees

Convert a quaternion frame rotation to Euler angles in degrees using the 'ZYX' rotation sequence.

```
quat = quaternion([0.7071 0.7071 0 0]);
eulerAnglesDegrees = eulerd(quat,'ZYX','frame')
```

```
eulerAnglesDegrees = 1×3

         0         0   90.0000
```

## Input Arguments

**`quat` — Quaternion to convert to Euler angles**
scalar | vector | matrix | multidimensional array

Quaternion to convert to Euler angles, specified as a scalar, vector, matrix, or multidimensional array of quaternions.

Data Types: `quaternion`

**`rotationSequence` — Rotation sequence**
`'ZYX'` | `'ZYZ'` | `'ZXY'` | `'ZXZ'` | `'YXZ'` | `'YXY'` | `'YZX'` | `'YZY'` | `'XYZ'` | `'XYX'` | `'XZY'` | `'XZX'`

Rotation sequence of Euler angle representation, specified as a character vector or string.

The rotation sequence defines the order of rotations about the axes. For example, if you specify a rotation sequence of `'YZX'`:

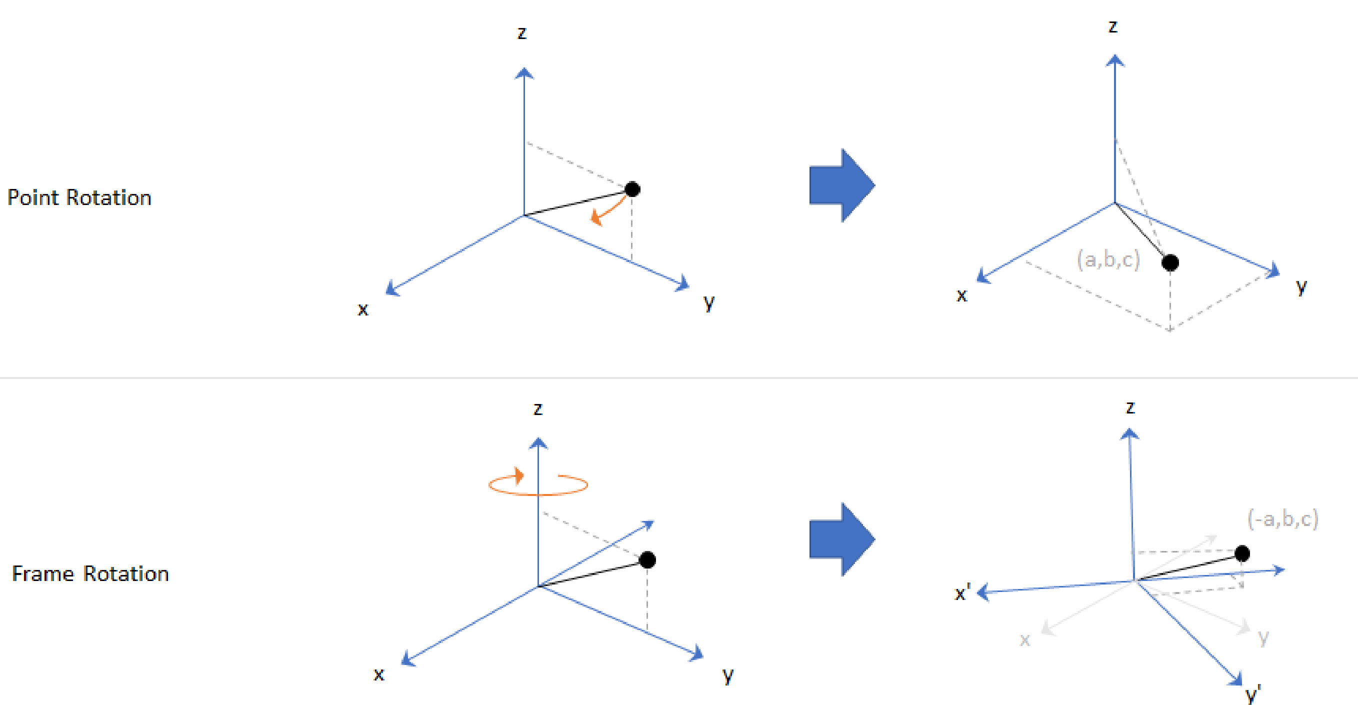
1. The first rotation is about the *y*-axis.
2. The second rotation is about the new *z*-axis.
3. The third rotation is about the new *x*-axis.

Data Types: `char` | `string`

**`rotationType` — Type of rotation**
`'point'` | `'frame'`

Type of rotation, specified as `'point'` or `'frame'`.

In a point rotation, the frame is static and the point moves. In a frame rotation, the point is static and the frame moves. Point rotation and frame rotation define equivalent angular displacements but in opposite directions.




Data Types: `char` | `string`

## Output Arguments

**`eulerAngles` — Euler angle representation (degrees)**
*N*-by-3 matrix

Euler angle representation in degrees, returned as a *N*-by-3 matrix. *N* is the number of quaternions in the `quat` argument.

For each row of `eulerAngles`, the first column corresponds to the first axis in the rotation sequence, the second column corresponds to the second axis in the rotation sequence, and the third column corresponds to the third axis in the rotation sequence.

The data type of the Euler angles representation is the same as the underlying data type of `quat`.

Data Types: `single` | `double`

# Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation
Generate C and C++ code using MATLAB® Coder™.

## See Also

### Functions
`euler` | `rotateframe` | `rotatepoint`

### Objects
`quaternion`

### Topics
“Rotations, Orientation, and Quaternions”

# exp

Exponential of quaternion array

## Syntax

```
B = exp(A)
```

## Description

`B = exp(A)` computes the exponential of the elements of the quaternion array `A`.

## Examples

### Exponential of Quaternion Array

Create a 4-by-1 quaternion array A.

```
A = quaternion(magic(4))
```

```
A = 4x1 quaternion array
     16 +  2i +  3j + 13k
      5 + 11i + 10j +  8k
      9 +  7i +  6j + 12k
      4 + 14i + 15j +  1k
```

Compute the exponential of A.

```
B = exp(A)
```

```
B = 4x1 quaternion array
     5.3525e+06 + 1.0516e+06i + 1.5774e+06j + 6.8352e+06k
        -57.359 -     89.189i -     81.081j -     64.865k
        -6799.1 +     2039.1i +     1747.8j +     3495.6k
          -6.66 +     36.931i +     39.569j +     2.6379k
```

## Input Arguments

**A — Input quaternion**
scalar | vector | matrix | multidimensional array

Input quaternion, specified as a scalar, vector, matrix, or multidimensional array.

Data Types: `quaternion`

## Output Arguments

**B — Result**
scalar | vector | matrix | multidimensional array

Result of quaternion exponential, returned as a scalar, vector, matrix, or multidimensional array.

Data Types: `quaternion`

## Algorithms

Given a quaternion $A = a + b\text{i} + c\text{j} + d\text{k} = a + \bar{v}$, the exponential is computed by

$$\exp(A) = e^{a}\left(\cos\|\bar{v}\| + \frac{\bar{v}}{\|\bar{v}\|}\sin\|\bar{v}\|\right)$$

# Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Functions

`.^,power` | `log`

### Objects

`quaternion`

### Topics

"Rotations, Orientation, and Quaternions"

# ldivide, .\

Element-wise quaternion left division

## Syntax

```
C = A.\B
```

## Description

`C = A.\B` performs quaternion element-wise division by dividing each element of quaternion `B` by the corresponding element of quaternion `A`.

## Examples

### Divide a Quaternion Array by a Real Scalar

Create a 2-by-1 quaternion array, and divide it element-by-element by a real scalar.

```
A = quaternion([1:4;5:8])
```

```
A = 2x1 quaternion array
     1 + 2i + 3j + 4k
     5 + 6i + 7j + 8k
```

```
B = 2;
C = A.\B
```

```
C = 2x1 quaternion array
     0.066667 -  0.13333i -      0.2j -  0.26667k
     0.057471 - 0.068966i -  0.08046j - 0.091954k
```

### Divide a Quaternion Array by Another Quaternion Array

Create a 2-by-2 quaternion array, and divide it element-by-element by another 2-by-2 quaternion array.

```
q1 = quaternion([1:4;2:5;4:7;5:8]);
A = reshape(q1,2,2)
```

```
A = 2x2 quaternion array
     1 + 2i + 3j + 4k     4 + 5i + 6j + 7k
     2 + 3i + 4j + 5k     5 + 6i + 7j + 8k
```

```
q2 = quaternion(magic(4));
B = reshape(q2,2,2)
```

```
B = 2x2 quaternion array
     16 +  2i +  3j + 13k      9 +  7i +  6j + 12k
      5 + 11i + 10j +  8k      4 + 14i + 15j +  1k
```

```
C = A.\B
```

```
C = 2x2 quaternion array
          2.7 -      1.9i -      0.9j -      1.7k       1.5159 -  0.37302i -  0.15079j -  0.0238
       2.2778 +  0.46296i -  0.57407j + 0.092593k       1.2471 +  0.91379i -  0.33908j -   0.109
```

## Input Arguments

**A — Divisor**
scalar | vector | matrix | multidimensional array

Divisor, specified as a quaternion, an array of quaternions, a real scalar, or an array of real numbers.

A and B must have compatible sizes. In the simplest cases, they can be the same size or one can be a scalar. Two inputs have compatible sizes if, for every dimension, the dimension sizes of the inputs are the same or one of the dimensions is 1.

Data Types: `quaternion` | `single` | `double`

**B — Dividend**
scalar | vector | matrix | multidimensional array

Dividend, specified as a quaternion, an array of quaternions, a real scalar, or an array of real numbers.

A and B must have compatible sizes. In the simplest cases, they can be the same size or one can be a scalar. Two inputs have compatible sizes if, for every dimension, the dimension sizes of the inputs are the same or one of the dimensions is 1.

Data Types: `quaternion` | `single` | `double`

## Output Arguments

**C — Result**
scalar | vector | matrix | multidimensional array

Result of quaternion division, returned as a scalar, vector, matrix, or multidimensional array.

Data Types: `quaternion`

## Algorithms

### Quaternion Division

Given a quaternion $A = a_1 + a_2\mathrm{i} + a_3\mathrm{j} + a_4\mathrm{k}$ and a real scalar $p$,

$$C = p.\backslash A = \frac{a_1}{p} + \frac{a_2}{p}\mathrm{i} + \frac{a_3}{p}\mathrm{j} + \frac{a_4}{p}\mathrm{k}$$

**Note** For a real scalar $p$, $A./p = A.\backslash p$.

### Quaternion Division by a Quaternion Scalar

Given two quaternions $A$ and $B$ of compatible sizes, then

$$C = A\,.\backslash B = A^{-1}\,.*B = \left(\frac{conj(A)}{norm(A)^2}\right).*B$$

# Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Functions

`.*,times` | `conj` | `norm` | `./,ldivide`

### Objects

`quaternion`

### Topics

"Rotations, Orientation, and Quaternions"

# log

Natural logarithm of quaternion array

## Syntax

`B = log(A)`

## Description

`B = log(A)` computes the natural logarithm of the elements of the quaternion array `A`.

## Examples

### Logarithmic Values of Quaternion Array

Create a 3-by-1 quaternion array A.

```
A = quaternion(randn(3,4))
```

```
A = 3x1 quaternion array
     0.53767 + 0.86217i - 0.43359j +  2.7694k
      1.8339 + 0.31877i + 0.34262j -  1.3499k
     -2.2588 -  1.3077i +  3.5784j +  3.0349k
```

Compute the logarithmic values of A.

```
B = log(A)
```

```
B = 3x1 quaternion array
      1.0925 + 0.40848i - 0.20543j +  1.3121k
      0.8436 + 0.14767i + 0.15872j - 0.62533k
      1.6807 - 0.53829i +   1.473j +  1.2493k
```

## Input Arguments

**A — Input array**
scalar | vector | matrix | multidimensional array

Input array, specified as a scalar, vector, matrix, or multidimensional array.

Data Types: `quaternion`

## Output Arguments

**B — Logarithm values**
scalar | vector | matrix | multidimensional array

Quaternion natural logarithm values, returned as a scalar, vector, matrix, or multidimensional array.

Data Types: `quaternion`

## Algorithms

Given a quaternion $A = a + \bar{v} = a + b\mathrm{i} + c\mathrm{j} + d\mathrm{k}$, the logarithm is computed by

$$\log(A) = \log\|A\| + \frac{\bar{v}}{\|\bar{v}\|}\arccos\frac{a}{\|A\|}$$

# Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Functions

`exp` | `.^,power`

### Objects

`quaternion`

### Topics

"Rotations, Orientation, and Quaternions"

# meanrot

Quaternion mean rotation

## Syntax

```
quatAverage = meanrot(quat)
quatAverage = meanrot(quat,dim)
quatAverage = meanrot( ___ ,nanflag)
```

## Description

`quatAverage = meanrot(quat)` returns the average rotation of the elements of `quat` along the first array dimension whose size not does equal 1.

- If `quat` is a vector, `meanrot(quat)` returns the average rotation of the elements.
- If `quat` is a matrix, `meanrot(quat)` returns a row vector containing the average rotation of each column.
- If `quat` is a multidimensional array, then `mearot(quat)` operates along the first array dimension whose size does not equal 1, treating the elements as vectors. This dimension becomes 1 while the sizes of all other dimensions remain the same.

The `meanrot` function normalizes the input quaternions, `quat`, before calculating the mean.

`quatAverage = meanrot(quat,dim)` return the average rotation along dimension `dim`. For example, if `quat` is a matrix, then `meanrot(quat,2)` is a column vector containing the mean of each row.

`quatAverage = meanrot( ___ ,nanflag)` specifies whether to include or omit `NaN` values from the calculation for any of the previous syntaxes. `meanrot(quat,'includenan')` includes all `NaN` values in the calculation while `mean(quat,'omitnan')` ignores them.

## Examples

### Quaternion Mean Rotation

Create a matrix of quaternions corresponding to three sets of Euler angles.

```
eulerAngles = [40 20 10; ...
               50 10 5; ...
               45 70 1];

quat = quaternion(eulerAngles,'eulerd','ZYX','frame');
```

Determine the average rotation represented by the quaternions. Convert the average rotation to Euler angles in degrees for readability.

```
quatAverage = meanrot(quat)
```

```
quatAverage = quaternion
      0.88863 - 0.062598i +  0.27822j +  0.35918k
```

```
eulerAverage = eulerd(quatAverage,'ZYX','frame')
```

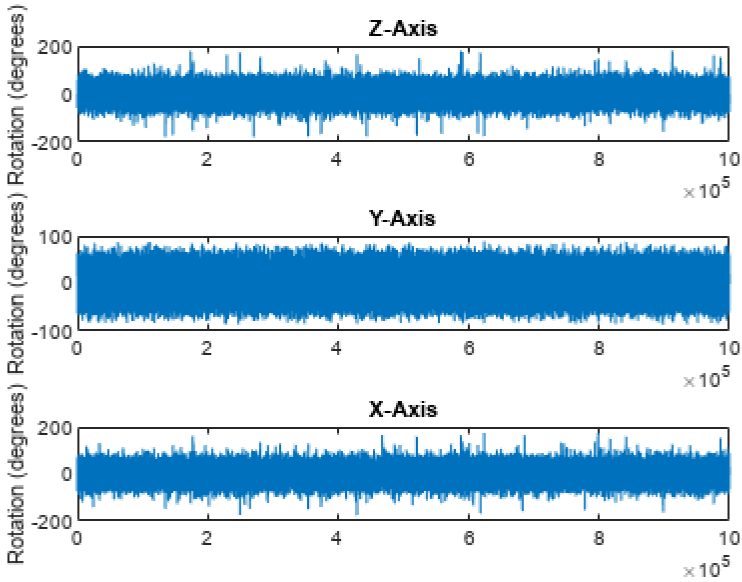
```
eulerAverage = 1×3

   45.7876   32.6452    6.0407
```

**Average Out Rotational Noise**

Use `meanrot` over a sequence of quaternions to average out additive noise.

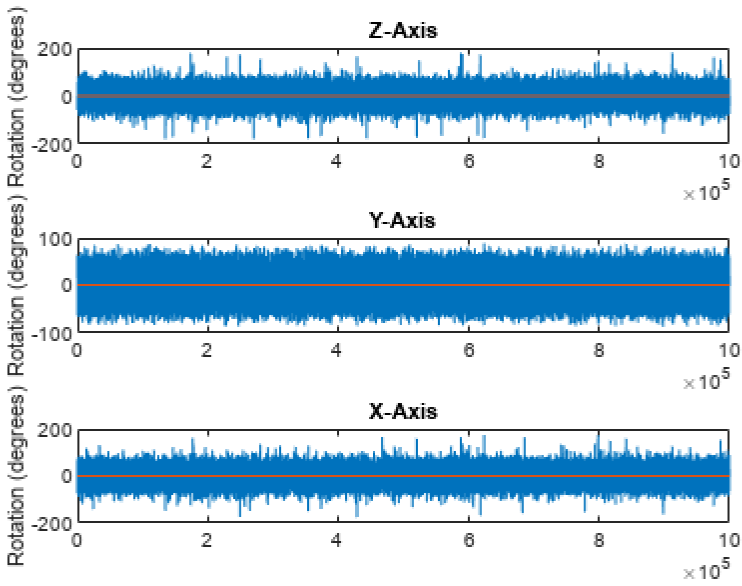
Create a vector of 1e6 quaternions whose distance, as defined by the `dist` function, from quaternion(1,0,0,0) is normally distributed. Plot the Euler angles corresponding to the noisy quaternion vector.

```
nrows = 1e6;
ax = 2*rand(nrows,3) - 1;
ax = ax./sqrt(sum(ax.^2,2));
ang = 0.5*randn(size(ax,1),1);
q = quaternion(ax.*ang ,'rotvec');

noisyEulerAngles = eulerd(q,'ZYX','frame');

figure(1)

subplot(3,1,1)
plot(noisyEulerAngles(:,1))
title('Z-Axis')
ylabel('Rotation (degrees)')
hold on

subplot(3,1,2)
plot(noisyEulerAngles(:,2))
title('Y-Axis')
ylabel('Rotation (degrees)')
hold on

subplot(3,1,3)
plot(noisyEulerAngles(:,3))
title('X-Axis')
ylabel('Rotation (degrees)')
hold on
```




Use `meanrot` to determine the average quaternion given the vector of quaternions. Convert to Euler angles and plot the results.

```
qAverage = meanrot(q);

qAverageInEulerAngles = eulerd(qAverage,'ZYX','frame');

figure(1)

subplot(3,1,1)
plot(ones(nrows,1)*qAverageInEulerAngles(:,1))
title('Z-Axis')

subplot(3,1,2)
plot(ones(nrows,1)*qAverageInEulerAngles(:,2))
title('Y-Axis')

subplot(3,1,3)
plot(ones(nrows,1)*qAverageInEulerAngles(:,3))
title('X-Axis')
```




### The `meanrot` Algorithm and Limitations

#### The `meanrot` Algorithm

The `meanrot` function outputs a quaternion that minimizes the squared Frobenius norm of the difference between rotation matrices. Consider two quaternions:

- `q0` represents no rotation.
- `q90` represents a 90 degree rotation about the *x*-axis.

```
q0 = quaternion([0 0 0],'eulerd','ZYX','frame');
q90 = quaternion([0 0 90],'eulerd','ZYX','frame');
```

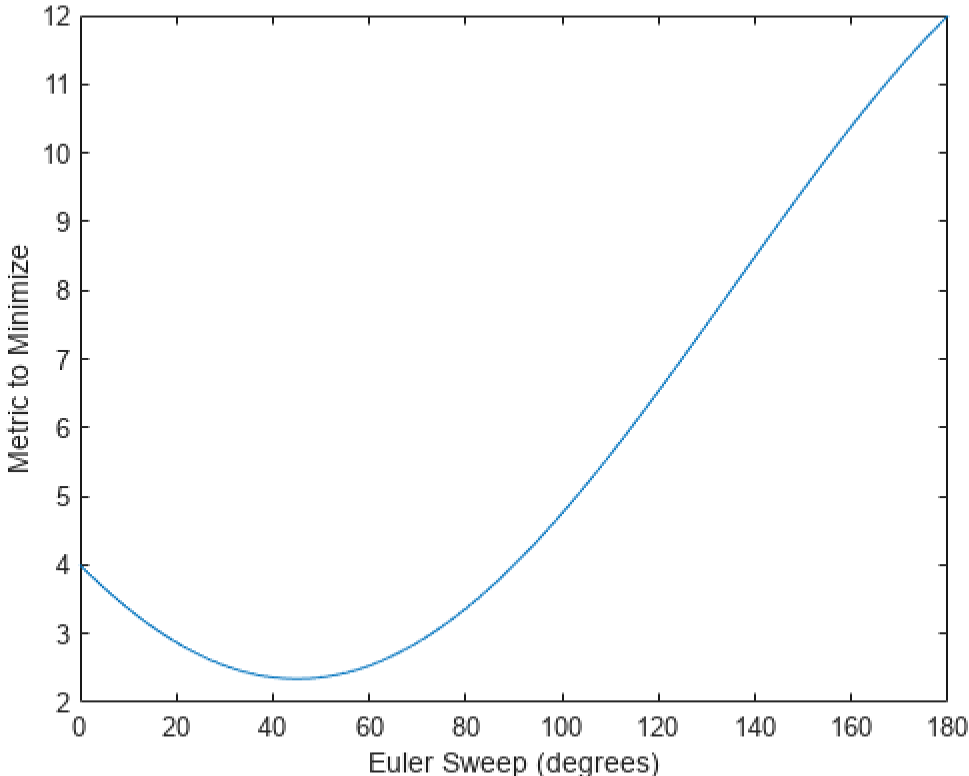
Create a quaternion sweep, `qSweep`, that represents rotations from 0 to 180 degrees about the *x*-axis.

```
eulerSweep = (0:1:180)';
qSweep = quaternion([zeros(numel(eulerSweep),2),eulerSweep], ...
    'eulerd','ZYX','frame');
```

Convert `q0`, `q90`, and `qSweep` to rotation matrices. In a loop, calculate the metric to minimize for each member of the quaternion sweep. Plot the results and return the value of the Euler sweep that corresponds to the minimum of the metric.

```
r0     = rotmat(q0,'frame');
r90    = rotmat(q90,'frame');
rSweep = rotmat(qSweep,'frame');

metricToMinimize = zeros(size(rSweep,3),1);
for i = 1:numel(qSweep)
    metricToMinimize(i) = norm((rSweep(:,:,i) - r0),'fro').^2 + ...
                          norm((rSweep(:,:,i) - r90),'fro').^2;
end
```

```
plot(eulerSweep,metricToMinimize)
xlabel('Euler Sweep (degrees)')
ylabel('Metric to Minimize')
```




```
[~,eulerIndex] = min(metricToMinimize);
eulerSweep(eulerIndex)
```

```
ans = 45
```

The minimum of the metric corresponds to the Euler angle sweep at 45 degrees. That is, `meanrot` defines the average between `quaterion([0 0 0],'ZYX','frame')` and `quaternion([0 0 90],'ZYX','frame')` as `quaternion([0 0 45],'ZYX','frame')`. Call `meanrot` with `q0` and `q90` to verify the same result.

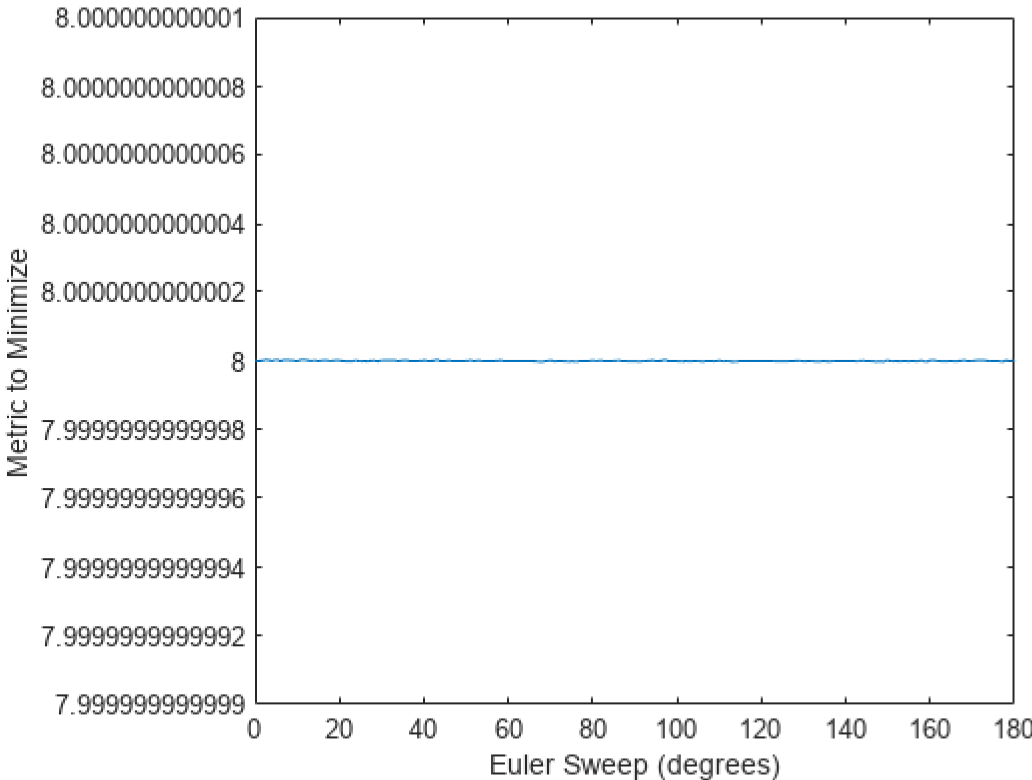
```
eulerd(meanrot([q0,q90]),'ZYX','frame')
```

```
ans = 1×3

         0         0   45.0000
```

### Limitations

The metric that `meanrot` uses to determine the mean rotation is not unique for quaternions significantly far apart. Repeat the experiment above for quaternions that are separated by 180 degrees.

```
q180 = quaternion([0 0 180],'eulerd','ZYX','frame');
r180 = rotmat(q180,'frame');

for i = 1:numel(qSweep)
    metricToMinimize(i) = norm((rSweep(:,:,i) - r0),'fro').^2 + ...
                          norm((rSweep(:,:,i) - r180),'fro').^2;
end

plot(eulerSweep,metricToMinimize)
xlabel('Euler Sweep (degrees)')
ylabel('Metric to Minimize')
```




```
[~,eulerIndex] = min(metricToMinimize);
eulerSweep(eulerIndex)
```

```
ans = 159
```

Quaternion means are usually calculated for rotations that are close to each other, which makes the edge case shown in this example unlikely in real-world applications. To average two quaternions that are significantly far apart, use the `slerp` function. Repeat the experiment using `slerp` and verify that the quaternion mean returned is more intuitive for large distances.

```
qMean = slerp(q0,q180,0.5);
q0_q180 = eulerd(qMean,'ZYX','frame')
```

```
q0_q180 = 1×3
```

```
        0         0   90.0000
```

## Input Arguments

**quat — Quaternion**
scalar | vector | matrix | multidimensional array

Quaternion for which to calculate the mean, specified as a scalar, vector, matrix, or multidimensional array of quaternions.

Data Types: `quaternion`

**dim — Dimension to operate along**
positive integer scalar

Dimension to operate along, specified as a positive integer scalar. If no value is specified, then the default is the first array dimension whose size does not equal 1.

Dimension `dim` indicates the dimension whose length reduces to 1. The `size(quatAverage,dim)` is `1`, while the sizes of all other dimensions remain the same.

Data Types: `double` | `single`

**nanflag — NaN condition**
`'includenan'` (default) | `'omitnan'`

`NaN` condition, specified as one of these values:

- `'includenan'` –– Include `NaN` values when computing the mean rotation, resulting in `NaN`.
- `'omitnan'` –– Ignore all `NaN` values in the input.

Data Types: `char` | `string`

## Output Arguments

**quatAverage — Quaternion average rotation**
scalar | vector | matrix | multidimensional array

Quaternion average rotation, returned as a scalar, vector, matrix, or multidimensional array.

Data Types: `single` | `double`

## Algorithms

`meanrot` determines a quaternion mean, $\bar{q}$, according to [1]. $\bar{q}$ is the quaternion that minimizes the squared Frobenius norm of the difference between rotation matrices:

$$\bar{q} = \arg \min_{q \in S^3} \sum_{i=1}^{n} \|A(q) - A(q_i)\|_F^2$$

# Version History

**Introduced in R2019b**

## References

[1] Markley, F. Landis, Yang Chen, John Lucas Crassidis, and Yaakov Oshman. "Average Quaternions." *Journal of Guidance, Control, and Dynamics*. Vol. 30, Issue 4, 2007, pp. 1193-1197.

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Functions**
`dist` | `slerp`

**Objects**
`quaternion`

**Topics**
"Rotations, Orientation, and Quaternions"

# minus, -

Quaternion subtraction

## Syntax

```
C = A - B
```

## Description

`C = A - B` subtracts quaternion `B` from quaternion `A` using quaternion subtraction. Either `A` or `B` may be a real number, in which case subtraction is performed with the real part of the quaternion argument.

## Examples

### Subtract a Quaternion from a Quaternion

Quaternion subtraction is defined as the subtraction of the corresponding parts of each quaternion. Create two quaternions and perform subtraction.

```
Q1 = quaternion([1,0,-2,7]);
Q2 = quaternion([1,2,3,4]);

Q1minusQ2 = Q1 - Q2
```

```
Q1minusQ2 = quaternion
     0 - 2i - 5j + 3k
```

### Subtract a Real Number from a Quaternion

Addition and subtraction of real numbers is defined for quaternions as acting on the real part of the quaternion. Create a quaternion and then subtract 1 from the real part.

```
Q = quaternion([1,1,1,1])
```

```
Q = quaternion
     1 + 1i + 1j + 1k
```

```
Qminus1 = Q - 1
```

```
Qminus1 = quaternion
     0 + 1i + 1j + 1k
```

## Input Arguments

**A — Input**
scalar | vector | matrix | multidimensional array

Input, specified as a quaternion, array of quaternions, real number, or array of real numbers.

Data Types: `quaternion` | `single` | `double`

**B — Input**
scalar | vector | matrix | multidimensional array

Input, specified as a quaternion, array of quaternions, real number, or array of real numbers.

Data Types: `quaternion` | `single` | `double`

## Output Arguments

**C — Result**
scalar | vector | matrix | multidimensional array

Result of quaternion subtraction, returned as a scalar, vector, matrix, or multidimensional array of quaternions.

Data Types: `quaternion`

# Version History

**Introduced in R2019b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Functions**
`-,uminus` | `.*,times` | `*,mtimes`

**Objects**
`quaternion`

**Topics**
"Rotations, Orientation, and Quaternions"

# mtimes, *

Quaternion multiplication

## Syntax

```
quatC = A*B
```

## Description

`quatC = A*B` implements quaternion multiplication if either `A` or `B` is a quaternion. Either `A` or `B` must be a scalar.

You can use quaternion multiplication to compose rotation operators:

- To compose a sequence of frame rotations, multiply the quaternions in the order of the desired sequence of rotations. For example, to apply a *p* quaternion followed by a *q* quaternion, multiply in the order *pq*. The rotation operator becomes $(pq)^*v(pq)$, where *v* represents the object to rotate specified in quaternion form. * represents conjugation.
- To compose a sequence of point rotations, multiply the quaternions in the reverse order of the desired sequence of rotations. For example, to apply a *p* quaternion followed by a *q* quaternion, multiply in the reverse order, *qp*. The rotation operator becomes $(qp)v(qp)^*$.

## Examples

### Multiply Quaternion Scalar and Quaternion Vector

Create a 4-by-1 column vector, `A`, and a scalar, `b`. Multiply `A` times `b`.

```
A = quaternion(randn(4,4))
```

```
A = 4x1 quaternion array
      0.53767 +  0.31877i +   3.5784j +   0.7254k
       1.8339 -   1.3077i +   2.7694j - 0.063055k
      -2.2588 -  0.43359i -   1.3499j +  0.71474k
      0.86217 +  0.34262i +   3.0349j -  0.20497k
```

```
b = quaternion(randn(1,4))
```

```
b = quaternion
    -0.12414 +  1.4897i +   1.409j +  1.4172k
```

```
C = A*b
```

```
C = 4x1 quaternion array
      -6.6117 +   4.8105i +  0.94224j -   4.2097k
      -2.0925 +   6.9079i +   3.9995j -   3.3614k
       1.8155 -   6.2313i -    1.336j -     1.89k
      -4.6033 +   5.8317i + 0.047161j -    2.791k
```

## Input Arguments

**A — Input**
scalar | vector | matrix | multidimensional array

Input to multiply, specified as a quaternion, array of quaternions, real scalar, or array of real scalars.

If B is nonscalar, then A must be scalar.

Data Types: quaternion | single | double

**B — Input**
scalar | vector | matrix | multidimensional array

Input to multiply, specified as a quaternion, array of quaternions, real scalar, or array of real scalars.

If A is nonscalar, then B must be scalar.

Data Types: quaternion | single | double

## Output Arguments

**quatC — Quaternion product**
scalar | vector | matrix | multidimensional array

Quaternion product, returned as a quaternion or array of quaternions.

Data Types: quaternion

## Algorithms

### Quaternion Multiplication by a Real Scalar

Given a quaternion

$$q = a_{\mathrm{q}} + b_{\mathrm{q}}\mathrm{i} + c_{\mathrm{q}}\mathrm{j} + d_{\mathrm{q}}\mathrm{k},$$

the product of $q$ and a real scalar $\beta$ is

$$\beta q = \beta a_{\mathrm{q}} + \beta b_{\mathrm{q}}\mathrm{i} + \beta c_{\mathrm{q}}\mathrm{j} + \beta d_{\mathrm{q}}\mathrm{k}$$

### Quaternion Multiplication by a Quaternion Scalar

The definition of the basis elements for quaternions,

$$\mathrm{i}^2 = \mathrm{j}^2 = \mathrm{k}^2 = \mathrm{ijk} = -1\,,$$

can be expanded to populate a table summarizing quaternion basis element multiplication:

| | **1** | **i** | **j** | **k** |
|---|---|---|---|---|
| **1** | 1 | i | j | k |
| **i** | i | −1 | k | −j |

| **j** | j | −k | −1 | i |
|---|---|---|---|---|
| **k** | k | j | −i | −1 |

When reading the table, the rows are read first, for example: ij = k and ji = −k.

Given two quaternions, $q = a_q + b_q\mathrm{i} + c_q\mathrm{j} + d_q\mathrm{k}$, and $p = a_p + b_p\mathrm{i} + c_p\mathrm{j} + d_p\mathrm{k}$, the multiplication can be expanded as:

$$\begin{aligned} z = pq &= \left(a_p + b_p\mathrm{i} + c_p\mathrm{j} + d_p\mathrm{k}\right)\left(a_q + b_q\mathrm{i} + c_q\mathrm{j} + d_q\mathrm{k}\right) \\ &= a_pa_q + a_pb_q\mathrm{i} + a_pc_q\mathrm{j} + a_pd_q\mathrm{k} \\ &\quad + b_pa_q\mathrm{i} + b_pb_q\mathrm{i}^2 + b_pc_q\mathrm{ij} + b_pd_q\mathrm{ik} \\ &\quad + c_pa_q\mathrm{j} + c_pb_q\mathrm{ji} + c_pc_q\mathrm{j}^2 + c_pd_q\mathrm{jk} \\ &\quad + d_pa_qk + d_pb_q\mathrm{ki} + d_pc_q\mathrm{kj} + d_pd_q\mathrm{k}^2 \end{aligned}$$

You can simplify the equation using the quaternion multiplication table:

$$\begin{aligned} z = pq &= a_pa_q + a_pb_q\mathrm{i} + a_pc_q\mathrm{j} + a_pd_q\mathrm{k} \\ &\quad + b_pa_q\mathrm{i} - b_pb_q + b_pc_q\mathrm{k} - b_pd_q\mathrm{j} \\ &\quad + c_pa_q\mathrm{j} - c_pb_q\mathrm{k} - c_pc_q + c_pd_q\mathrm{i} \\ &\quad + d_pa_qk + d_pb_q\mathrm{j} - d_pc_q\mathrm{i} - d_pd_q \end{aligned}$$

# Version History

**Introduced in R2019b**

## References

[1] Kuipers, Jack B. *Quaternions and Rotation Sequences: A Primer with Applications to Orbits, Aerospace, and Virtual Reality*. Princeton, NJ: Princeton University Press, 2007.

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Functions

`.*`,`times`

### Objects

`quaternion`

### Topics

“Rotations, Orientation, and Quaternions”

# norm

Quaternion norm

## Syntax

```
N = norm(quat)
```

## Description

`N = norm(quat)` returns the norm of the quaternion, `quat`.

Given a quaternion of the form $Q = a + b\text{i} + c\text{j} + d\text{k}$, the norm of the quaternion is defined as $\text{norm}(Q) = \sqrt{a^2 + b^2 + c^2 + d^2}$.

## Examples

### Calculate Quaternion Norm

Create a scalar quaternion and calculate its norm.

```
quat = quaternion(1,2,3,4);
norm(quat)
```

```
ans = 5.4772
```

The quaternion norm is defined as the square root of the sum of the quaternion parts squared. Calculate the quaternion norm explicitly to verify the result of the `norm` function.

```
[a,b,c,d] = parts(quat);
sqrt(a^2+b^2+c^2+d^2)
```

```
ans = 5.4772
```

## Input Arguments

**`quat` — Quaternion**
scalar | vector | matrix | multidimensional array

Quaternion for which to calculate the norm, specified as a scalar, vector, matrix, or multidimensional array of quaternions.

Data Types: `quaternion`

## Output Arguments

**`N` — Quaternion norm**
scalar | vector | matrix | multidimensional array

Quaternion norm. If the input `quat` is an array, the output is returned as an array the same size as `quat`. Elements of the array are real numbers with the same data type as the underlying data type of the quaternion, `quat`.

Data Types: `single` | `double`

# Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Functions

`normalize` | `parts` | `conj`

### Objects

`quaternion`

### Topics

"Rotations, Orientation, and Quaternions"

# normalize

Quaternion normalization

## Syntax

```
quatNormalized = normalize(quat)
```

## Description

`quatNormalized = normalize(quat)` normalizes the quaternion.

Given a quaternion of the form $Q = a + b\text{i} + c\text{j} + d\text{k}$, the normalized quaternion is defined as $Q/\sqrt{a^2 + b^2 + c^2 + d^2}$.

## Examples

### Normalize Elements of Quaternion Vector

Quaternions can represent rotations when normalized. You can use `normalize` to normalize a scalar, elements of a matrix, or elements of a multi-dimensional array of quaternions. Create a column vector of quaternions, then normalize them.

```
quatArray = quaternion([1,2,3,4; ...
                        2,3,4,1; ...
                        3,4,1,2]);
quatArrayNormalized = normalize(quatArray)
```

```
quatArrayNormalized = 3x1 quaternion array
     0.18257 + 0.36515i + 0.54772j +  0.7303k
     0.36515 + 0.54772i +  0.7303j + 0.18257k
     0.54772 +  0.7303i + 0.18257j + 0.36515k
```

## Input Arguments

**quat — Quaternion to normalize**
scalar | vector | matrix | multidimensional array

Quaternion to normalize, specified as a scalar, vector, matrix, or multidimensional array of quaternions.

Data Types: `quaternion`

## Output Arguments

**quatNormalized — Normalized quaternion**
scalar | vector | matrix | multidimensional array

Normalized quaternion, returned as a quaternion or array of quaternions the same size as `quat`.

Data Types: `quaternion`

# Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Functions

`norm` | `.*,times` | `conj`

### Objects

`quaternion`

### Topics

"Rotations, Orientation, and Quaternions"

# ones

Create quaternion array with real parts set to one and imaginary parts set to zero

## Syntax

```
quatOnes = ones('quaternion')
quatOnes = ones(n,'quaternion')
quatOnes = ones(sz,'quaternion')
quatOnes = ones(sz1,...,szN,'quaternion')

quatOnes = ones( ___ ,'like',prototype,'quaternion')
```

## Description

`quatOnes = ones('quaternion')` returns a scalar quaternion with the real part set to 1 and the imaginary parts set to 0.

Given a quaternion of the form $Q = a + b\text{i} + c\text{j} + d\text{k}$, a quaternion one is defined as $Q = 1 + 0\text{i} + 0\text{j} + 0\text{k}$.

`quatOnes = ones(n,'quaternion')` returns an `n`-by-`n` quaternion matrix with the real parts set to 1 and the imaginary parts set to 0.

`quatOnes = ones(sz,'quaternion')` returns an array of quaternion ones where the size vector, `sz`, defines `size(qOnes)`.

Example: `ones([1,4,2],'quaternion')` returns a 1-by-4-by-2 array of quaternions with the real parts set to `1` and the imaginary parts set to `0`.

`quatOnes = ones(sz1,...,szN,'quaternion')` returns a `sz1`-by-...-by-`szN` array of ones where `sz1,…,szN` indicates the size of each dimension.

`quatOnes = ones( ___ ,'like',prototype,'quaternion')` specifies the underlying class of the returned quaternion array to be the same as the underlying class of the quaternion prototype.

## Examples

### Quaternion Scalar One

Create a quaternion scalar one.

```
quatOnes = ones('quaternion')
```

```
quatOnes = quaternion
     1 + 0i + 0j + 0k
```

### Square Matrix of Quaternion Ones

Create an n-by-n matrix of quaternion ones.

```
n = 3;
quatOnes = ones(n,'quaternion')
```

```
quatOnes = 3x3 quaternion array
     1 + 0i + 0j + 0k     1 + 0i + 0j + 0k     1 + 0i + 0j + 0k
     1 + 0i + 0j + 0k     1 + 0i + 0j + 0k     1 + 0i + 0j + 0k
     1 + 0i + 0j + 0k     1 + 0i + 0j + 0k     1 + 0i + 0j + 0k
```

### Multidimensional Array of Quaternion Ones

Create a multidimensional array of quaternion ones by defining array dimensions in order. In this example, you create a 3-by-1-by-2 array. You can specify dimensions using a row vector or comma-separated integers. Specify the dimensions using a row vector and display the results:

```
dims = [3,1,2];
quatOnesSyntax1 = ones(dims,'quaternion')
```

```
quatOnesSyntax1 = 3x1x2 quaternion array
quatOnesSyntax1(:,:,1) =

     1 + 0i + 0j + 0k
     1 + 0i + 0j + 0k
     1 + 0i + 0j + 0k


quatOnesSyntax1(:,:,2) =

     1 + 0i + 0j + 0k
     1 + 0i + 0j + 0k
     1 + 0i + 0j + 0k
```

Specify the dimensions using comma-separated integers, and then verify the equivalency of the two syntaxes:

```
quatOnesSyntax2 = ones(3,1,2,'quaternion');
isequal(quatOnesSyntax1,quatOnesSyntax2)
```

```
ans = logical
   1
```

### Underlying Class of Quaternion Ones

A quaternion is a four-part hyper-complex number used in three-dimensional rotations and orientations. You can specify the underlying data type of the parts as `single` or `double`. The default is `double`.

Create a quaternion array of ones with the underlying data type set to `single`.

```
quatOnes = ones(2,'like',single(1),'quaternion')
```

```
quatOnes = 2x2 quaternion array
     1 + 0i + 0j + 0k     1 + 0i + 0j + 0k
     1 + 0i + 0j + 0k     1 + 0i + 0j + 0k
```

Verify the underlying class using the `classUnderlying` function.

```
classUnderlying(quatOnes)
```

```
ans =
'single'
```

## Input Arguments

### n — Size of square quaternion matrix

integer value

Size of square quaternion matrix, specified as an integer value.

If `n` is zero or negative, then `quatOnes` is returned as an empty matrix.

Example: `ones(4,'quaternion')` returns a 4-by-4 matrix of quaternions with the real parts set to `1` and the imaginary parts set to `0`.

Data Types: `single` | `double` | `int8` | `int16` | `int32` | `int64` | `uint8` | `uint16` | `uint32` | `uint64`

### sz — Output size

row vector of integer values

Output size, specified as a row vector of integer values. Each element of `sz` indicates the size of the corresponding dimension in `quatOnes`. If the size of any dimension is `0` or negative, then `quatOnes` is returned as an empty array.

Data Types: `single` | `double` | `int8` | `int16` | `int32` | `int64` | `uint8` | `uint16` | `uint32` | `uint64`

### prototype — Quaternion prototype

variable

Quaternion prototype, specified as a variable.

Example: `ones(2,'like',quat,'quaternion')` returns a 2-by-2 matrix of quaternions with the same underlying class as the prototype quaternion, `quat`.

Data Types: `quaternion`

### sz1,...,szN — Size of each dimension

two or more integer values

Size of each dimension, specified as two or more integers. If the size of any dimension is `0` or negative, then `quatOnes` is returned as an empty array.

Example: `ones(2,3,'quaternion')` returns a 2-by-3 matrix of quaternions with the real parts set to `1` and the imaginary parts set to `0`.

Data Types: `single` | `double` | `int8` | `int16` | `int32` | `int64` | `uint8` | `uint16` | `uint32` | `uint64`

## Output Arguments

**`quatOnes` — Quaternion ones**
scalar | vector | matrix | multidimensional array

Quaternion ones, returned as a scalar, vector, matrix, or multidimensional array of quaternions.

Given a quaternion of the form $Q = a + b\text{i} + c\text{j} + d\text{k}$, a quaternion one is defined as $Q = 1 + 0\text{i} + 0\text{j} + 0\text{k}$.

Data Types: `quaternion`

# Version History

**Introduced in R2019b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Functions**
`zeros`

**Objects**
`quaternion`

**Topics**
"Rotations, Orientation, and Quaternions"

# parts

Extract quaternion parts

## Syntax

```
[a,b,c,d] = parts(quat)
```

## Description

`[a,b,c,d] = parts(quat)` returns the parts of the quaternion array as arrays, each the same size as `quat`.

## Examples

### Convert Quaternion to Matrix of Quaternion Parts

Convert a quaternion representation to parts using the `parts` function.

Create a two-element column vector of quaternions by specifying the parts.

```
quat = quaternion([1:4;5:8])
```

```
quat = 2x1 quaternion array
     1 + 2i + 3j + 4k
     5 + 6i + 7j + 8k
```

Recover the parts from the quaternion matrix using the `parts` function. The parts are returned as separate output arguments, each the same size as the input 2-by-1 column vector of quaternions.

```
[qA,qB,qC,qD] = parts(quat)
```

```
qA = 2×1

     1
     5

qB = 2×1

     2
     6

qC = 2×1

     3
     7

qD = 2×1
```

```
    4
    8
```

## Input Arguments

**quat — Quaternion**
scalar | vector | matrix | multidimensional array

Quaternion, specified as a quaternion or array of quaternions.

Data Types: quaternion

## Output Arguments

**[a,b,c,d] — Quaternion parts**
scalar | vector | matrix | multidimensional array

Quaternion parts, returned as four arrays: a, b, c, and d. Each part is the same size as quat.

Data Types: single | double

# Version History

**Introduced in R2019b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Functions**
classUnderlying | compact

**Objects**
quaternion

**Topics**
"Rotations, Orientation, and Quaternions"

# power, .^

Element-wise quaternion power

## Syntax

```
C = A.^b
```

## Description

`C = A.^b` raises each element of `A` to the corresponding power in `b`.

## Examples

### Raise a Quaternion to a Real Scalar Power

Create a quaternion and raise it to a real scalar power.

```
A = quaternion(1,2,3,4)
```

```
A = quaternion
     1 + 2i + 3j + 4k
```

```
b = 3;
C = A.^b
```

```
C = quaternion
     -86 -  52i -  78j - 104k
```

### Raise a Quaternion Array to Powers from a Multidimensional Array

Create a 2-by-1 quaternion array and raise it to powers from a 2-D array.

```
A = quaternion([1:4;5:8])
```

```
A = 2x1 quaternion array
     1 + 2i + 3j + 4k
     5 + 6i + 7j + 8k
```

```
b = [1 0 2; 3 2 1]
```

```
b = 2×3

     1     0     2
     3     2     1
```

```
C = A.^b
```

```
C = 2x3 quaternion array
        1 +    2i +    3j +    4k        1 +    0i +    0j +    0k      -28 +    4i +    6j +
    -2110 -  444i -  518j -  592k     -124 +   60i +   70j +   80k        5 +    6i +    7j +
```

## Input Arguments

### A — Base

scalar | vector | matrix | multidimensional array

Base, specified as a scalar, vector, matrix, or multidimensional array.

Data Types: `quaternion` | `single` | `double`

### b — Exponent

scalar | vector | matrix | multidimensional array

Exponent, specified as a real scalar, vector, matrix, or multidimensional array.

Data Types: `single` | `double`

## Output Arguments

### C — Result

scalar | vector | matrix | multidimensional array

Each element of quaternion A raised to the corresponding power in b, returned as a scalar, vector, matrix, or multidimensional array.

Data Types: `quaternion`

## Algorithms

The polar representation of a quaternion $A = a + b\text{i} + c\text{j} + d\text{k}$ is given by

$$A = \|A\|(\cos\theta + \widehat{u}\sin\theta)$$

where $\theta$ is the angle of rotation, and $\hat{u}$ is the unit quaternion.

Quaternion $A$ raised by a real exponent $b$ is given by

$$P = A\,.\hat{}\,b = \|A\|^b(\cos(b\theta) + \widehat{u}\sin(b\theta))$$

# Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

**Functions**
`log` | `exp`

**Objects**
`quaternion`

**Topics**
"Rotations, Orientation, and Quaternions"

# prod

Product of a quaternion array

## Syntax

```
quatProd = prod(quat)
quatProd = prod(quat,dim)
```

## Description

`quatProd = prod(quat)` returns the quaternion product of the elements of the array.

`quatProd = prod(quat,dim)` calculates the quaternion product along dimension `dim`.

## Examples

### Product of Quaternions in Each Column

Create a 3-by-3 array whose elements correspond to their linear indices.

```
A = reshape(quaternion(randn(9,4)),3,3)
```

```
A = 3x3 quaternion array
      0.53767 +   2.7694i +    1.409j -  0.30344k      0.86217 +   0.7254i -   1.2075j +   0.888
       1.8339 -   1.3499i +   1.4172j +  0.29387k      0.31877 - 0.063055i +  0.71724j -   1.147
      -2.2588 +   3.0349i +   0.6715j -  0.78728k      -1.3077 +  0.71474i +   1.6302j -   1.068
```

Find the product of the quaternions in each column. The length of the first dimension is `1`, and the length of the second dimension matches `size(A,2)`.

```
B = prod(A)
```

```
B = 1x3 quaternion array
    -19.837 -  9.1521i +  15.813j -  19.918k     -5.4708 - 0.28535i +   3.077j -  1.2295k
```

### Product of Specified Dimension of Quaternion Array

You can specify which dimension of a quaternion array to take the product of.

Create a 2-by-2-by-2 quaternion array.

```
A = reshape(quaternion(randn(8,4)),2,2,2);
```

Find the product of the elements in each page of the array. The length of the first dimension matches `size(A,1)`, the length of the second dimension matches `size(A,2)`, and the length of the third dimension is `1`.

```
dim = 3;
B = prod(A,dim)

B = 2x2 quaternion array
     -2.4847 +  1.1659i - 0.37547j +  2.8068k     0.28786 - 0.29876i - 0.51231j -  4.2972k
     0.38986 -  3.6606i -  2.0474j -   6.047k      -1.741 - 0.26782i +  5.4346j +  4.1452k
```

## Input Arguments

**quat — Quaternion**
scalar | vector | matrix | multidimensional array

Quaternion, specified as scalar, vector, matrix, or multidimensional array of quaternions.

Example: `qProd = prod(quat)` calculates the quaternion product along the first non-singleton dimension of `quat`.

Data Types: `quaternion`

**dim — Dimension**
first non-singleton dimension (default) | positive integer

Dimension along which to calculate the quaternion product, specified as a positive integer. If `dim` is not specified, `prod` operates along the first non-singleton dimension of `quat`.

Data Types: `single` | `double` | `int8` | `int16` | `int32` | `int64` | `uint8` | `uint16` | `uint32` | `uint64`

## Output Arguments

**quatProd — Quaternion product**
positive integer

Quaternion product, returned as quaternion array with one less non-singleton dimension than `quat`.

For example, if `quat` is a 2-by-2-by-5 array,

- `prod(quat,1)` returns a 1-by-2-by-5 array.
- `prod(quat,2)` returns a 2-by-1-by-5 array.
- `prod(quat,3)` returns a 2-by-2 array.

Data Types: `quaternion`

# Version History

**Introduced in R2019b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Functions**
mtimes | .*,times

**Objects**
quaternion

**Topics**
"Rotations, Orientation, and Quaternions"

# rdivide, ./

Element-wise quaternion right division

## Syntax

```
C = A./B
```

## Description

`C = A./B` performs quaternion element-wise division by dividing each element of quaternion `A` by the corresponding element of quaternion `B`.

## Examples

### Divide a Quaternion Array by a Real Scalar

Create a 2-by-1 quaternion array, and divide it element-by-element by a real scalar.

```
A = quaternion([1:4;5:8])
```

```
A = 2x1 quaternion array
     1 + 2i + 3j + 4k
     5 + 6i + 7j + 8k
```

```
B = 2;
C = A./B
```

```
C = 2x1 quaternion array
     0.5 +   1i + 1.5j +   2k
     2.5 +   3i + 3.5j +   4k
```

### Divide a Quaternion Array by Another Quaternion Array

Create a 2-by-2 quaternion array, and divide it element-by-element by another 2-by-2 quaternion array.

```
q1 = quaternion(magic(4));
A = reshape(q1,2,2)
```

```
A = 2x2 quaternion array
     16 +  2i +  3j + 13k      9 +  7i +  6j + 12k
      5 + 11i + 10j +  8k      4 + 14i + 15j +  1k
```

```
q2 = quaternion([1:4;3:6;2:5;4:7]);
B = reshape(q2,2,2)
```

```
B = 2x2 quaternion array
     1 + 2i + 3j + 4k     2 + 3i + 4j + 5k
     3 + 4i + 5j + 6k     4 + 5i + 6j + 7k
```

```
C = A./B
```

```
C = 2x2 quaternion array
          2.7 -      0.1i -      2.1j -      1.7k       2.2778 + 0.092593i -  0.46296j -  0.5740
       1.8256 - 0.081395i +  0.45349j -  0.24419k       1.4524 -      0.5i +   1.0238j -   0.261
```

## Input Arguments

**A — Dividend**
scalar | vector | matrix | multidimensional array

Dividend, specified as a quaternion, an array of quaternions, a real scalar, or an array of real numbers.

A and B must have compatible sizes. In the simplest cases, they can be the same size or one can be a scalar. Two inputs have compatible sizes if, for every dimension, the dimension sizes of the inputs are the same or one of the dimensions is 1.

Data Types: quaternion | single | double

**B — Divisor**
scalar | vector | matrix | multidimensional array

Divisor, specified as a quaternion, an array of quaternions, a real scalar, or an array of real numbers.

A and B must have compatible sizes. In the simplest cases, they can be the same size or one can be a scalar. Two inputs have compatible sizes if, for every dimension, the dimension sizes of the inputs are the same or one of the dimensions is 1.

Data Types: quaternion | single | double

## Output Arguments

**C — Result**
scalar | vector | matrix | multidimensional array

Result of quaternion division, returned as a scalar, vector, matrix, or multidimensional array.

Data Types: quaternion

## Algorithms

### Quaternion Division

Given a quaternion $A = a_1 + a_2\mathrm{i} + a_3\mathrm{j} + a_4\mathrm{k}$ and a real scalar p,

$$C = A\,./p = \frac{a_1}{p} + \frac{a_2}{p}\mathrm{i} + \frac{a_3}{p}\mathrm{j} + \frac{a_4}{p}\mathrm{k}$$

**Note** For a real scalar $p$, $A./p = A.\backslash p$.

### Quaternion Division by a Quaternion Scalar

Given two quaternions $A$ and $B$ of compatible sizes,

$$C = A./B = A.*B^{-1} = A.*\left(\frac{conj(B)}{norm(B)^2}\right)$$

## Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Functions

`conj` | `./,ldivide` | `norm` | `.*,times`

### Objects

`quaternion`

### Topics

"Rotations, Orientation, and Quaternions"

# randrot

Uniformly distributed random rotations

## Syntax

```
R = randrot
R = randrot(m)
R = randrot(m1,...,mN)
R = randrot([m1,...,mN])
```

## Description

`R = randrot` returns a unit quaternion drawn from a uniform distribution of random rotations.

`R = randrot(m)` returns an `m`-by-`m` matrix of unit quaternions drawn from a uniform distribution of random rotations.

`R = randrot(m1,...,mN)` returns an `m1`-by-...-by-`mN` array of random unit quaternions, where `m1`, ..., `mN` indicate the size of each dimension. For example, `randrot(3,4)` returns a 3-by-4 matrix of random unit quaternions.

`R = randrot([m1,...,mN])` returns an `m1`-by-...-by-`mN` array of random unit quaternions, where `m1`,..., `mN` indicate the size of each dimension. For example, `randrot([3,4])` returns a 3-by-4 matrix of random unit quaternions.

## Examples

### Matrix of Random Rotations

Generate a 3-by-3 matrix of uniformly distributed random rotations.

```
r = randrot(3)
```

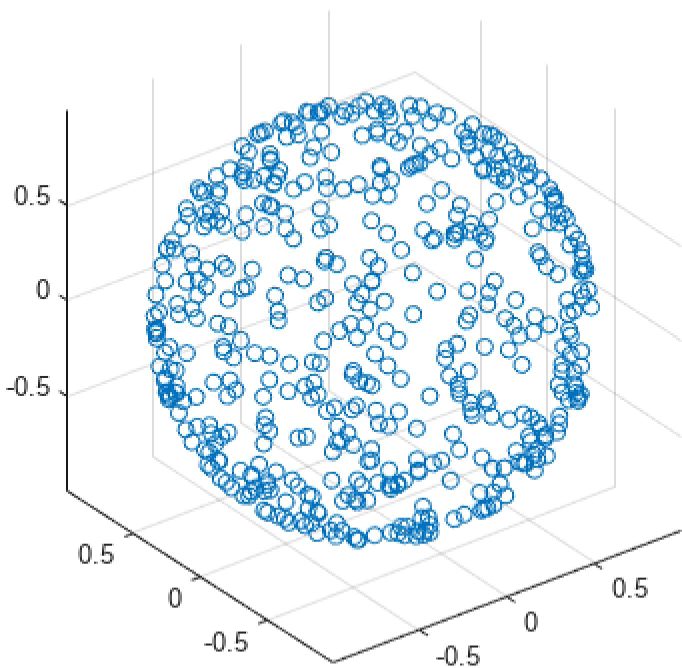
```
r = 3x3 quaternion array
      0.17446 +  0.59506i -  0.73295j +  0.27976k      0.69704 - 0.060589i +  0.68679j -  0.19695
      0.21908 -  0.89875i -    0.298j +  0.23548k    -0.049744 +  0.59691i +  0.56459j +  0.56786
       0.6375 +  0.49338i -  0.24049j +  0.54068k       0.2979 -  0.53568i +  0.31819j +  0.72323
```

### Create Uniform Distribution of Random Rotations

Create a vector of 500 random quaternions. Use `rotatepoint` to visualize the distribution of the random rotations applied to point (1, 0, 0).

```
q = randrot(500,1);

pt = rotatepoint(q, [1 0 0]);
```

```
figure
scatter3(pt(:,1), pt(:,2), pt(:,3))
axis equal
```




## Input Arguments

**m — Size of square matrix**
integer

Size of square quaternion matrix, specified as an integer value. If m is 0 or negative, then R is returned as an empty matrix.

Data Types: single | double | int8 | int16 | int32 | int64 | uint8 | uint16 | uint32 | uint64

**m1,...,mN — Size of each dimension**
two or more integer values

Size of each dimension, specified as two or more integer values. If the size of any dimension is 0 or negative, then R is returned as an empty array.

Example: randrot(2,3) returns a 2-by-3 matrix of random quaternions.

Data Types: single | double | int8 | int16 | int32 | int64 | uint8 | uint16 | uint32 | uint64

**[m1,...,mN] — Vector of size of each dimension**
row vector of integer values

Vector of size of each dimension, specified as a row vector of two or more integer values. If the size of any dimension is `0` or negative, then `R` is returned as an empty array.

Example: `randrot([2,3])` returns a 2-by-3 matrix of random quaternions.

Data Types: `single` | `double` | `int8` | `int16` | `int32` | `int64` | `uint8` | `uint16` | `uint32` | `uint64`

## Output Arguments

**R — Random quaternions**
scalar | vector | matrix | multidimensional array

Random quaternions, returned as a quaternion or array of quaternions.

Data Types: `quaternion`

# Version History

**Introduced in R2019b**

## References

[1] Shoemake, K. "Uniform Random Rotations." *Graphics Gems III* (K. David, ed.). New York: Academic Press, 1992.

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

`quaternion`

**Topics**
“Rotations, Orientation, and Quaternions”

# rotateframe

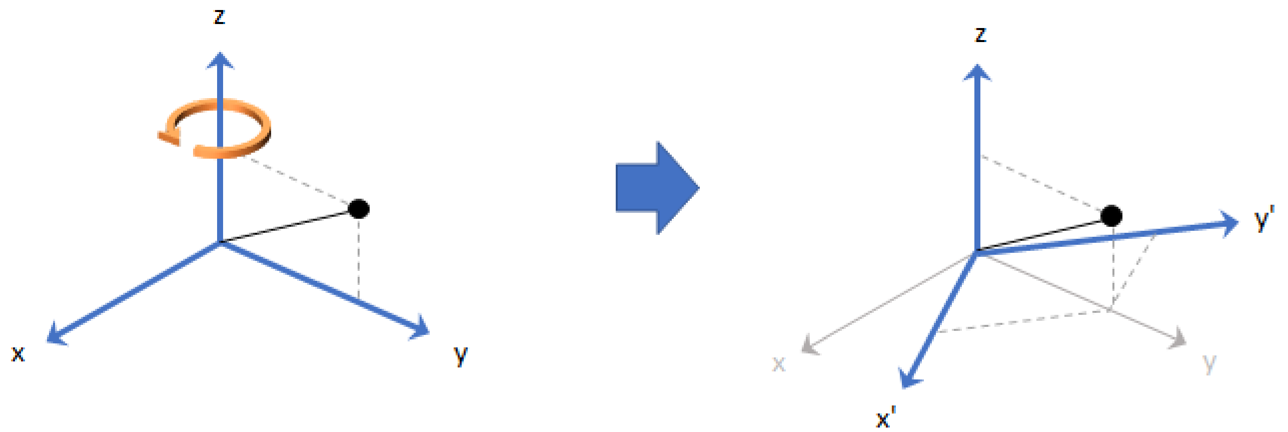
Quaternion frame rotation

## Syntax

```
rotationResult = rotateframe(quat,cartesianPoints)
```

## Description

`rotationResult = rotateframe(quat,cartesianPoints)` rotates the frame of reference for the Cartesian points using the quaternion, `quat`. The elements of the quaternion are normalized before use in the rotation.

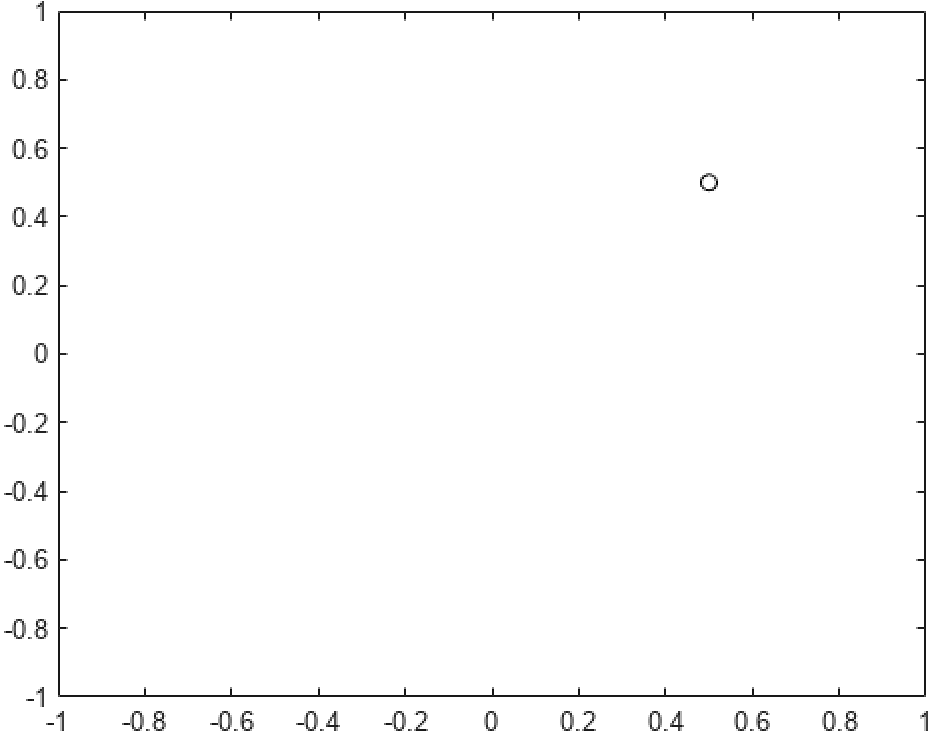



## Examples

### Rotate Frame Using Quaternion Vector

Define a point in three dimensions. The coordinates of a point are always specified in the order *x*, *y*, and *z*. For convenient visualization, define the point on the *x*-*y* plane.

```
x = 0.5;
y = 0.5;
z = 0;
plot(x,y,'ko')
hold on
axis([-1 1 -1 1])
```



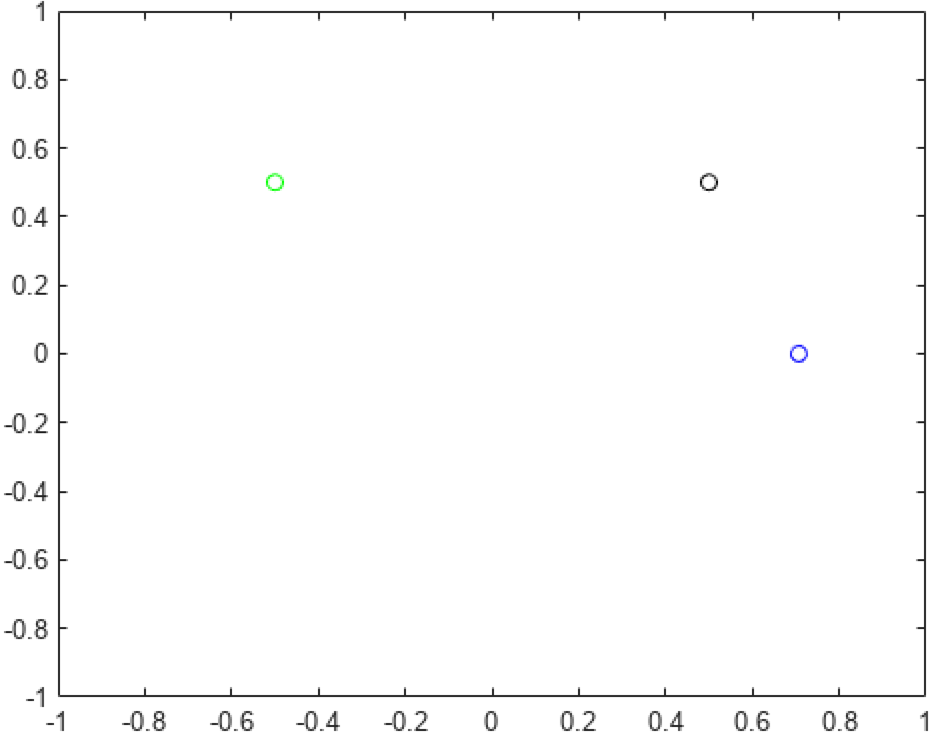

Create a quaternion vector specifying two separate rotations, one to rotate the frame 45 degrees and another to rotate the point -90 degrees about the *z*-axis. Use `rotateframe` to perform the rotations.

```
quat = quaternion([0,0,pi/4; ...
                   0,0,-pi/2],'euler','XYZ','frame');

rereferencedPoint = rotateframe(quat,[x,y,z])
```

```
rereferencedPoint = 2×3

    0.7071   -0.0000         0
   -0.5000    0.5000         0
```

Plot the rereferenced points.

```
plot(rereferencedPoint(1,1),rereferencedPoint(1,2),'bo')
plot(rereferencedPoint(2,1),rereferencedPoint(2,2),'go')
```




**Rereference Group of Points using Quaternion**

Define two points in three-dimensional space. Define a quaternion to rereference the points by first rotating the reference frame about the *z*-axis 30 degrees and then about the new *y*-axis 45 degrees.

```
a = [1,0,0];
b = [0,1,0];
quat = quaternion([30,45,0],'eulerd','ZYX','point');
```

Use `rotateframe` to reference both points using the quaternion rotation operator. Display the result.

```
rP = rotateframe(quat,[a;b])
```

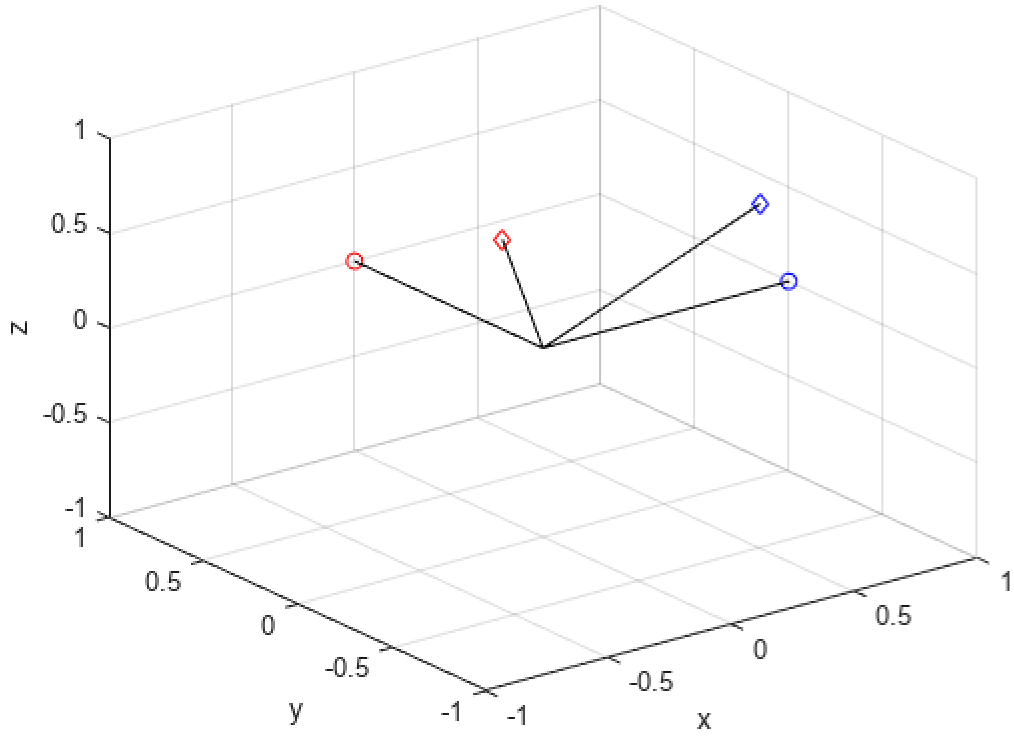
```
rP = 2×3

    0.6124   -0.3536    0.7071
    0.5000    0.8660   -0.0000
```

Visualize the original orientation and the rotated orientation of the points. Draw lines from the origin to each of the points for visualization purposes.

```
plot3(a(1),a(2),a(3),'bo');
```

```
hold on
```

```
grid on
axis([-1 1 -1 1 -1 1])
xlabel('x')
ylabel('y')
zlabel('z')

plot3(b(1),b(2),b(3),'ro');
plot3(rP(1,1),rP(1,2),rP(1,3),'bd')
plot3(rP(2,1),rP(2,2),rP(2,3),'rd')

plot3([0;rP(1,1)],[0;rP(1,2)],[0;rP(1,3)],'k')
plot3([0;rP(2,1)],[0;rP(2,2)],[0;rP(2,3)],'k')
plot3([0;a(1)],[0;a(2)],[0;a(3)],'k')
plot3([0;b(1)],[0;b(2)],[0;b(3)],'k')
```




## Input Arguments

**quat — Quaternion that defines rotation**
scalar | vector

Quaternion that defines rotation, specified as a scalar quaternion or vector of quaternions.

Data Types: `quaternion`

**`cartesianPoints` — Three-dimensional Cartesian points**
1-by-3 vector | *N*-by-3 matrix

Three-dimensional Cartesian points, specified as a 1-by-3 vector or $N$-by-3 matrix.

Data Types: `single` | `double`

## Output Arguments

### `rotationResult` — Re-referenced Cartesian points

vector | matrix

Cartesian points defined in reference to rotated reference frame, returned as a vector or matrix the same size as `cartesianPoints`.

The data type of the re-referenced Cartesian points is the same as the underlying data type of `quat`.

Data Types: `single` | `double`

## Algorithms

Quaternion frame rotation re-references a point specified in $\mathbf{R}^3$ by rotating the original frame of reference according to a specified quaternion:

$$L_q(u) = q^* u q$$

where $q$ is the quaternion, * represents conjugation, and $u$ is the point to rotate, specified as a quaternion.

For convenience, the `rotateframe` function takes a point in $\mathbf{R}^3$ and returns a point in $\mathbf{R}^3$. Given a function call with some arbitrary quaternion, $q = a + b\text{i} + c\text{j} + d\text{k}$, and arbitrary coordinate, $[x,y,z]$,

```
point = [x,y,z];
rereferencedPoint = rotateframe(q,point)
```

the `rotateframe` function performs the following operations:

1. Converts point $[x,y,z]$ to a quaternion:

   $$u_q = 0 + xi + yj + zk$$

2. Normalizes the quaternion, $q$:

   $$q_n = \frac{q}{\sqrt{a^2 + b^2 + c^2 + d^2}}$$

3. Applies the rotation:

   $$v_q = q^* u_q q$$

4. Converts the quaternion output, $v_q$, back to $\mathbf{R}^3$

# Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Functions

`rotatepoint`

### Objects

`quaternion`

### Topics

"Rotations, Orientation, and Quaternions"

# rotatepoint

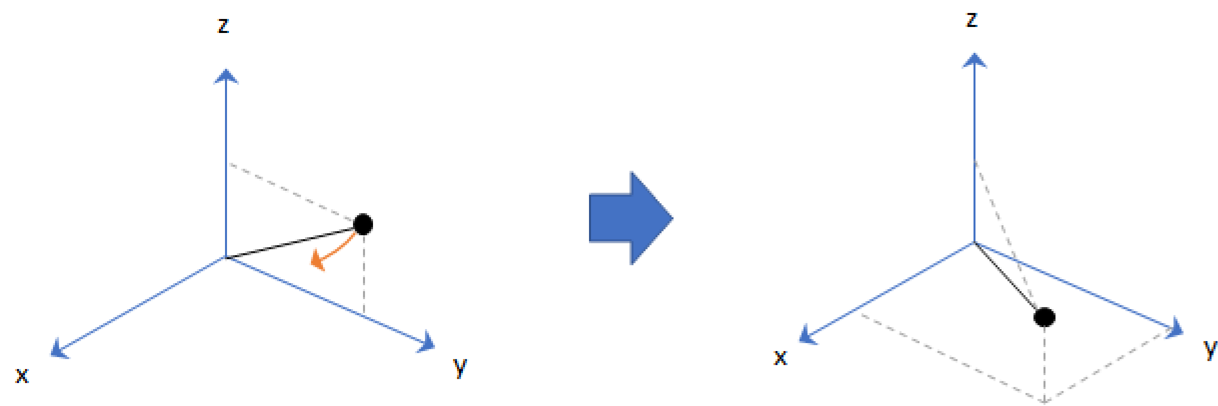
Quaternion point rotation

## Syntax

```
rotationResult = rotatepoint(quat,cartesianPoints)
```

## Description

`rotationResult = rotatepoint(quat,cartesianPoints)` rotates the Cartesian points using the quaternion, `quat`. The elements of the quaternion are normalized before use in the rotation.

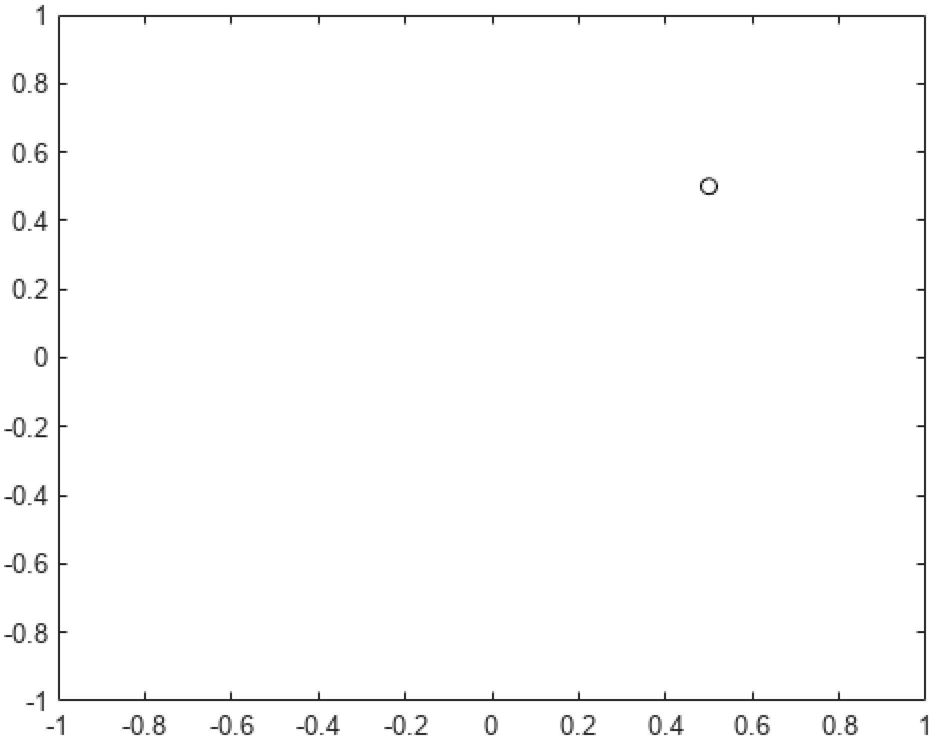



## Examples

### Rotate Point Using Quaternion Vector

Define a point in three dimensions. The coordinates of a point are always specified in order *x*, *y*, *z*. For convenient visualization, define the point on the *x*-*y* plane.

```
x = 0.5;
y = 0.5;
z = 0;

plot(x,y,'ko')
hold on
axis([-1 1 -1 1])
```



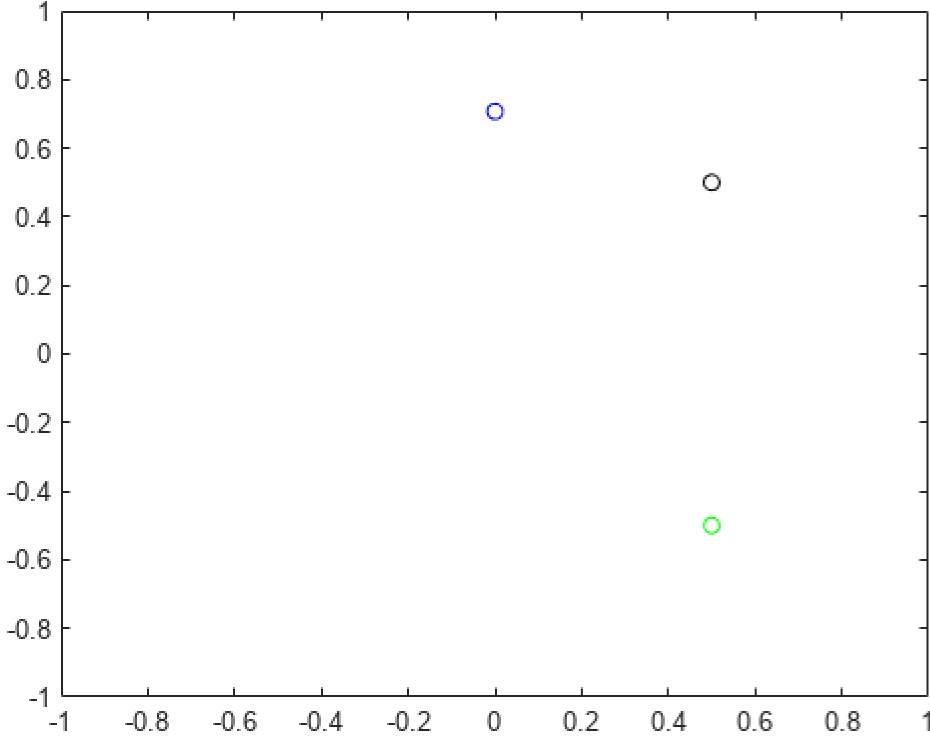

Create a quaternion vector specifying two separate rotations, one to rotate the point 45 and another to rotate the point -90 degrees about the *z*-axis. Use `rotatepoint` to perform the rotation.

```
quat = quaternion([0,0,pi/4; ...
                   0,0,-pi/2],'euler','XYZ','point');

rotatedPoint = rotatepoint(quat,[x,y,z])
```

```
rotatedPoint = 2×3

   -0.0000    0.7071         0
    0.5000   -0.5000         0
```

Plot the rotated points.

```
plot(rotatedPoint(1,1),rotatedPoint(1,2),'bo')
plot(rotatedPoint(2,1),rotatedPoint(2,2),'go')
```




**Rotate Group of Points Using Quaternion**

Define two points in three-dimensional space. Define a quaternion to rotate the point by first rotating about the *z*-axis 30 degrees and then about the new *y*-axis 45 degrees.

```
a = [1,0,0];
b = [0,1,0];
quat = quaternion([30,45,0],'eulerd','ZYX','point');
```

Use `rotatepoint` to rotate both points using the quaternion rotation operator. Display the result.

```
rP = rotatepoint(quat,[a;b])
```

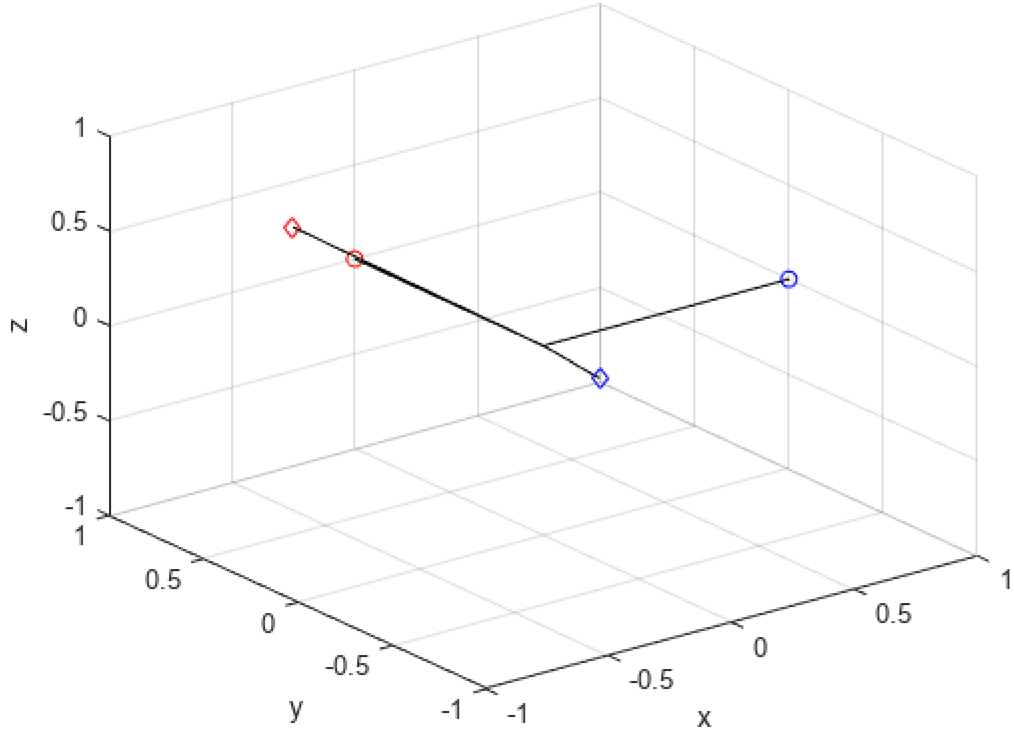
```
rP = 2×3

    0.6124    0.5000   -0.6124
   -0.3536    0.8660    0.3536
```

Visualize the original orientation and the rotated orientation of the points. Draw lines from the origin to each of the points for visualization purposes.

```
plot3(a(1),a(2),a(3),'bo');
```

```
hold on
```

```
grid on
axis([-1 1 -1 1 -1 1])
xlabel('x')
ylabel('y')
zlabel('z')

plot3(b(1),b(2),b(3),'ro');
plot3(rP(1,1),rP(1,2),rP(1,3),'bd')
plot3(rP(2,1),rP(2,2),rP(2,3),'rd')

plot3([0;rP(1,1)],[0;rP(1,2)],[0;rP(1,3)],'k')
plot3([0;rP(2,1)],[0;rP(2,2)],[0;rP(2,3)],'k')
plot3([0;a(1)],[0;a(2)],[0;a(3)],'k')
plot3([0;b(1)],[0;b(2)],[0;b(3)],'k')
```




## Input Arguments

### quat — Quaternion that defines rotation

scalar | vector

Quaternion that defines rotation, specified as a scalar quaternion, row vector of quaternions, or column vector of quaternions.

Data Types: `quaternion`

**`cartesianPoints` — Three-dimensional Cartesian points**
1-by-3 vector | *N*-by-3 matrix

Three-dimensional Cartesian points, specified as a 1-by-3 vector or *N*-by-3 matrix.

Data Types: `single` | `double`

## Output Arguments

**`rotationResult` — Repositioned Cartesian points**
vector | matrix

Rotated Cartesian points defined using the quaternion rotation, returned as a vector or matrix the same size as `cartesianPoints`.

Data Types: `single` | `double`

## Algorithms

Quaternion point rotation rotates a point specified in $\mathbf{R}^3$ according to a specified quaternion:

$$L_q(u) = quq^*$$

where $q$ is the quaternion, * represents conjugation, and $u$ is the point to rotate, specified as a quaternion.

For convenience, the `rotatepoint` function takes in a point in $\mathbf{R}^3$ and returns a point in $\mathbf{R}^3$. Given a function call with some arbitrary quaternion, $q = a + b\text{i} + c\text{j} + d\text{k}$, and arbitrary coordinate, $[x,y,z]$, for example,

```
rereferencedPoint = rotatepoint(q,[x,y,z])
```

the `rotatepoint` function performs the following operations:

1. Converts point $[x,y,z]$ to a quaternion:

   $$u_q = 0 + xi + yj + zk$$

2. Normalizes the quaternion, $q$:

   $$q_n = \frac{q}{\sqrt{a^2 + b^2 + c^2 + d^2}}$$

3. Applies the rotation:

   $$v_q = qu_qq^*$$

4. Converts the quaternion output, $v_q$, back to $\mathbf{R}^3$

# Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation
Generate C and C++ code using MATLAB® Coder™.

## See Also

### Functions
`rotateframe`

### Objects
`quaternion`

### Topics
"Rotations, Orientation, and Quaternions"

# rotmat

Convert quaternion to rotation matrix

## Syntax

```
rotationMatrix = rotmat(quat,rotationType)
```

## Description

`rotationMatrix = rotmat(quat,rotationType)` converts the quaternion, `quat`, to an equivalent rotation matrix representation.

## Examples

### Convert Quaternion to Rotation Matrix for Point Rotation

Define a quaternion for use in point rotation.

```
theta = 45;
gamma = 30;
quat = quaternion([0,theta,gamma],'eulerd','ZYX','point')
```

```
quat = quaternion
       0.8924 +  0.23912i +  0.36964j + 0.099046k
```

Convert the quaternion to a rotation matrix.

```
rotationMatrix = rotmat(quat,'point')
```

```
rotationMatrix = 3×3

    0.7071   -0.0000    0.7071
    0.3536    0.8660   -0.3536
   -0.6124    0.5000    0.6124
```

To verify the rotation matrix, directly create two rotation matrices corresponding to the rotations about the *y*- and *x*-axes. Multiply the rotation matrices and compare to the output of `rotmat`.

```
theta = 45;
gamma = 30;

ry = [cosd(theta)   0           sind(theta) ; ...
      0             1           0           ; ...
     -sind(theta)   0           cosd(theta)];

rx = [1             0           0           ;      ...
      0             cosd(gamma) -sind(gamma) ;     ...
      0             sind(gamma) cosd(gamma)];

rotationMatrixVerification = rx*ry
```

```
rotationMatrixVerification = 3×3

    0.7071         0    0.7071
    0.3536    0.8660   -0.3536
   -0.6124    0.5000    0.6124
```

### Convert Quaternion to Rotation Matrix for Frame Rotation

Define a quaternion for use in frame rotation.

```
theta = 45;
gamma = 30;
quat = quaternion([0,theta,gamma],'eulerd','ZYX','frame')
```

```
quat = quaternion
       0.8924 +  0.23912i +  0.36964j - 0.099046k
```

Convert the quaternion to a rotation matrix.

```
rotationMatrix = rotmat(quat,'frame')
```

```
rotationMatrix = 3×3

    0.7071   -0.0000   -0.7071
    0.3536    0.8660    0.3536
    0.6124   -0.5000    0.6124
```

To verify the rotation matrix, directly create two rotation matrices corresponding to the rotations about the *y*- and *x*-axes. Multiply the rotation matrices and compare to the output of `rotmat`.

```
theta = 45;
gamma = 30;

ry = [cosd(theta)   0           -sind(theta) ; ...
      0             1           0            ; ...
     sind(theta)   0           cosd(theta)];

rx = [1             0           0           ;      ...
      0             cosd(gamma) sind(gamma) ;     ...
      0             -sind(gamma) cosd(gamma)];

rotationMatrixVerification = rx*ry
```

```
rotationMatrixVerification = 3×3

    0.7071         0   -0.7071
    0.3536    0.8660    0.3536
    0.6124   -0.5000    0.6124
```

### Convert Quaternion Vector to Rotation Matrices

Create a 3-by-1 normalized quaternion vector.

```
qVec = normalize(quaternion(randn(3,4)));
```

Convert the quaternion array to rotation matrices. The pages of `rotmatArray` correspond to the linear index of `qVec`.

```
rotmatArray = rotmat(qVec,'frame');
```

Assume `qVec` and `rotmatArray` correspond to a sequence of rotations. Combine the quaternion rotations into a single representation, then apply the quaternion rotation to arbitrarily initialized Cartesian points.

```
loc = normalize(randn(1,3));
quat = prod(qVec);
rotateframe(quat,loc)
```

```
ans = 1×3

    0.9524    0.5297    0.9013
```

Combine the rotation matrices into a single representation, then apply the rotation matrix to the same initial Cartesian points. Verify the quaternion rotation and rotation matrix result in the same orientation.

```
totalRotMat = eye(3);
for i = 1:size(rotmatArray,3)
    totalRotMat = rotmatArray(:,:,i)*totalRotMat;
end
totalRotMat*loc'
```

```
ans = 3×1

    0.9524
    0.5297
    0.9013
```

## Input Arguments

**quat — Quaternion to convert**
scalar | vector | matrix | multidimensional array

Quaternion to convert, specified as a scalar, vector, matrix, or multidimensional array.

Data Types: `quaternion`

**`rotationType` — Type or rotation**
`'frame'` | `'point'`

Type of rotation represented by the `rotationMatrix` output, specified as `'frame'` or `'point'`.

Data Types: `char` | `string`

## Output Arguments

**`rotationMatrix` — Rotation matrix representation**
3-by-3 matrix | 3-by-3-by-*N* multidimensional array

Rotation matrix representation, returned as a 3-by-3 matrix or 3-by-3-by-*N* multidimensional array.

- If `quat` is a scalar, `rotationMatrix` is returned as a 3-by-3 matrix.
- If `quat` is non-scalar, `rotationMatrix` is returned as a 3-by-3-by-*N* multidimensional array, where `rotationMatrix(:,:,i)` is the rotation matrix corresponding to `quat(i)`.

The data type of the rotation matrix is the same as the underlying data type of `quat`.

Data Types: `single` | `double`

## Algorithms

Given a quaternion of the form

$$q = a + bi + cj + dk,$$

the equivalent rotation matrix for frame rotation is defined as

$$\begin{bmatrix} 2a^2-1+2b^2 & 2bc+2ad & 2bd-2ac \\ 2bc-2ad & 2a^2-1+2c^2 & 2cd+2ab \\ 2bd+2ac & 2cd-2ab & 2a^2-1+2d^2 \end{bmatrix}.$$

The equivalent rotation matrix for point rotation is the transpose of the frame rotation matrix:

$$\begin{bmatrix} 2a^2-1+2b^2 & 2bc-2ad & 2bd+2ac \\ 2bc+2ad & 2a^2-1+2c^2 & 2cd-2ab \\ 2bd-2ac & 2cd+2ab & 2a^2-1+2d^2 \end{bmatrix}.$$

# Version History

**Introduced in R2019b**

## References

[1] Kuipers, Jack B. *Quaternions and Rotation Sequences: A Primer with Applications to Orbits, Aerospace, and Virtual Reality*. Princeton, NJ: Princeton University Press, 2007.

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Functions**
`rotvec` | `rotvecd` | `euler` | `eulerd`

**Objects**
`quaternion`

**Topics**
"Rotations, Orientation, and Quaternions"

# rotvec

Convert quaternion to rotation vector (radians)

## Syntax

`rotationVector = rotvec(quat)`

## Description

`rotationVector = rotvec(quat)` converts the quaternion array, `quat`, to an *N*-by-3 matrix of equivalent rotation vectors in radians. The elements of `quat` are normalized before conversion.

## Examples

### Convert Quaternion to Rotation Vector in Radians

Convert a random quaternion scalar to a rotation vector in radians

```
quat = quaternion(randn(1,4));
rotvec(quat)
```

```
ans = 1×3

    1.6866   -2.0774    0.7929
```

## Input Arguments

**`quat` — Quaternion to convert**
scalar | vector | matrix | multidimensional array

Quaternion to convert, specified as scalar quaternion, vector, matrix, or multidimensional array of quaternions.

Data Types: `quaternion`

## Output Arguments

**`rotationVector` — Rotation vector (radians)**
*N*-by-3 matrix

Rotation vector representation, returned as an *N*-by-3 matrix of rotations vectors, where each row represents the [X Y Z] angles of the rotation vectors in radians. The *i*th row of `rotationVector` corresponds to the element `quat(i)`.

The data type of the rotation vector is the same as the underlying data type of `quat`.

Data Types: `single` | `double`

## Algorithms

All rotations in 3-D can be represented by a three-element axis of rotation and a rotation angle, for a total of four elements. If the rotation axis is constrained to be unit length, the rotation angle can be distributed over the vector elements to reduce the representation to three elements.

Recall that a quaternion can be represented in axis-angle form

$$q = \cos\left(\theta/2\right) + \sin\left(\theta/2\right)(\mathrm{x}\mathrm{i} + y\mathrm{j} + z\mathrm{k}),$$

where $\theta$ is the angle of rotation and $[x,y,z]$ represent the axis of rotation.

Given a quaternion of the form

$$q = a + bi + cj + dk,$$

you can solve for the rotation angle using the axis-angle form of quaternions:

$$\theta = 2\cos^{-1}(a).$$

Assuming a normalized axis, you can rewrite the quaternion as a rotation vector without loss of information by distributing $\theta$ over the parts $b$, $c$, and $d$. The rotation vector representation of $q$ is

$$q_{\mathrm{rv}} = \frac{\theta}{\sin\left(\theta/2\right)}[b, c, d].$$

# Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Functions

`rotvecd` | `euler` | `eulerd`

### Objects

`quaternion`

### Topics

“Rotations, Orientation, and Quaternions”

# rotvecd

Convert quaternion to rotation vector (degrees)

## Syntax

`rotationVector = rotvecd(quat)`

## Description

`rotationVector = rotvecd(quat)` converts the quaternion array, `quat`, to an *N*-by-3 matrix of equivalent rotation vectors in degrees. The elements of `quat` are normalized before conversion.

## Examples

### Convert Quaternion to Rotation Vector in Degrees

Convert a random quaternion scalar to a rotation vector in degrees.

```
quat = quaternion(randn(1,4));
rotvecd(quat)
```

```
ans = 1×3

   96.6345 -119.0274   45.4312
```

## Input Arguments

**`quat` — Quaternion to convert**
scalar | vector | matrix | multidimensional array

Quaternion to convert, specified as scalar, vector, matrix, or multidimensional array of quaternions.

Data Types: `quaternion`

## Output Arguments

**`rotationVector` — Rotation vector (degrees)**
*N*-by-3 matrix

Rotation vector representation, returned as an *N*-by-3 matrix of rotation vectors, where each row represents the [*x y z*] angles of the rotation vectors in degrees. The *i*th row of `rotationVector` corresponds to the element `quat(i)`.

The data type of the rotation vector is the same as the underlying data type of `quat`.

Data Types: `single` | `double`

## Algorithms

All rotations in 3-D can be represented by four elements: a three-element axis of rotation and a rotation angle. If the rotation axis is constrained to be unit length, the rotation angle can be distributed over the vector elements to reduce the representation to three elements.

Recall that a quaternion can be represented in axis-angle form

$$q = \cos\left(\theta/2\right) + \sin\left(\theta/2\right)(\mathrm{xi} + y\mathrm{j} + z\mathrm{k}),$$

where $\theta$ is the angle of rotation in degrees, and $[x,y,z]$ represent the axis of rotation.

Given a quaternion of the form

$$q = a + bi + cj + dk\ ,$$

you can solve for the rotation angle using the axis-angle form of quaternions:

$$\theta = 2\cos^{-1}(a)\ .$$

Assuming a normalized axis, you can rewrite the quaternion as a rotation vector without loss of information by distributing $\theta$ over the parts $b$, $c$, and $d$. The rotation vector representation of $q$ is

$$q_{\mathrm{rv}} = \frac{\theta}{\sin\left(\theta/2\right)}[b, c, d]\ .$$

# Version History

**Introduced in R2019b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Functions**
`rotvec` | `euler` | `eulerd`

**Objects**
`quaternion`

**Topics**
"Rotations, Orientation, and Quaternions"

# slerp

Spherical linear interpolation

## Syntax

```
q0 = slerp(q1,q2,T)
```

## Description

`q0 = slerp(q1,q2,T)` spherically interpolates between `q1` and `q2` by the interpolation coefficient `T`. The function always chooses the shorter interpolation path between `q1` and `q2`.

## Examples

### Interpolate Between Two Quaternions

Create two quaternions with the following interpretation:

1. `a` = 45 degree rotation around the *z*-axis
2. `c` = -45 degree rotation around the *z*-axis

```
a = quaternion([45,0,0],'eulerd','ZYX','frame');
c = quaternion([-45,0,0],'eulerd','ZYX','frame');
```

Call `slerp` with the quaternions `a` and `c` and specify an interpolation coefficient of 0.5.

```
interpolationCoefficient = 0.5;

b = slerp(a,c,interpolationCoefficient);
```

The output of `slerp`, `b`, represents an average rotation of `a` and `c`. To verify, convert `b` to Euler angles in degrees.

```
averageRotation = eulerd(b,'ZYX','frame')
```

```
averageRotation = 1×3

     0     0     0
```

The interpolation coefficient is specified as a normalized value between `0` and `1`, inclusive. An interpolation coefficient of `0` corresponds to the `a` quaternion, and an interpolation coefficient of `1` corresponds to the `c` quaternion. Call `slerp` with coefficients `0` and `1` to confirm.

```
b = slerp(a,c,[0,1]);
eulerd(b,'ZYX','frame')
```

```
ans = 2×3

   45.0000         0         0
```

```
  -45.0000         0         0
```

You can create smooth paths between quaternions by specifying arrays of equally spaced interpolation coefficients.

```
path = 0:0.1:1;
```

```
interpolatedQuaternions = slerp(a,c,path);
```

For quaternions that represent rotation only about a single axis, specifying interpolation coefficients as equally spaced results in quaternions equally spaced in Euler angles. Convert `interpolatedQuaternions` to Euler angles and verify that the difference between the angles in the path is constant.

```
k = eulerd(interpolatedQuaternions,'ZYX','frame');
abc = abs(diff(k))
```

```
abc = 10×3

    9.0000         0         0
    9.0000         0         0
    9.0000         0         0
    9.0000         0         0
    9.0000         0         0
    9.0000         0         0
    9.0000         0         0
    9.0000         0         0
    9.0000         0         0
    9.0000         0         0
```

Alternatively, you can use the `dist` function to verify that the distance between the interpolated quaternions is consistent. The `dist` function returns angular distance in radians; convert to degrees for easy comparison.

```
def = rad2deg(dist(interpolatedQuaternions(2:end),interpolatedQuaternions(1:end-1)))
```

```
def = 1×10

    9.0000    9.0000    9.0000    9.0000    9.0000    9.0000    9.0000    9.0000    9.0000    9.0
```

### SLERP Minimizes Great Circle Path

The SLERP algorithm interpolates along a great circle path connecting two quaternions. This example shows how the SLERP algorithm minimizes the great circle path.

Define four quaternions:

1. `q0` - quaternion indicating no rotation from the global frame
2. `q179` - quaternion indicating a 179 degree rotation about the *z*-axis
3. `q180` - quaternion indicating a 180 degree rotation about the *z*-axis

**4** `q181` - quaternion indicating a 181 degree rotation about the *z*-axis

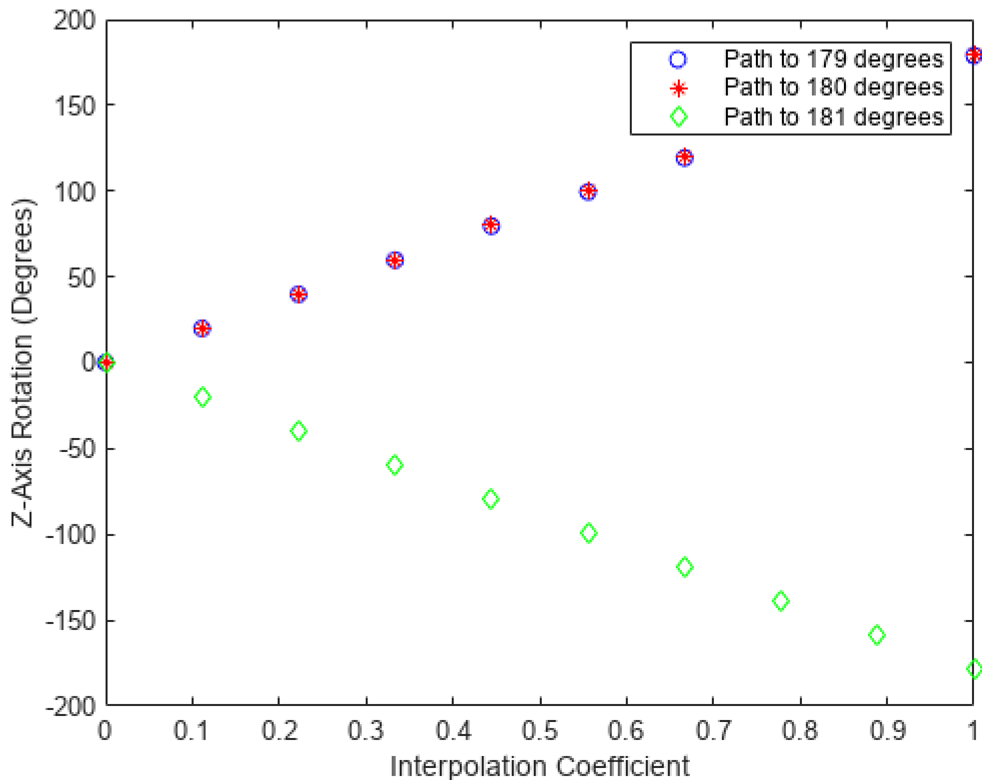
```
q0 = ones(1,'quaternion');

q179 = quaternion([179,0,0],'eulerd','ZYX','frame');

q180 = quaternion([180,0,0],'eulerd','ZYX','frame');

q181 = quaternion([181,0,0],'eulerd','ZYX','frame');
```

Use `slerp` to interpolate between `q0` and the three quaternion rotations. Specify that the paths are traveled in 10 steps.

```
T = linspace(0,1,10);

q179path = slerp(q0,q179,T);
q180path = slerp(q0,q180,T);
q181path = slerp(q0,q181,T);
```

Plot each path in terms of Euler angles in degrees.

```
q179pathEuler = eulerd(q179path,'ZYX','frame');
q180pathEuler = eulerd(q180path,'ZYX','frame');
q181pathEuler = eulerd(q181path,'ZYX','frame');

plot(T,q179pathEuler(:,1),'bo', ...
     T,q180pathEuler(:,1),'r*', ...
     T,q181pathEuler(:,1),'gd');
legend('Path to 179 degrees', ...
       'Path to 180 degrees', ...
       'Path to 181 degrees')
xlabel('Interpolation Coefficient')
ylabel('Z-Axis Rotation (Degrees)')
```




The path between q0 and q179 is clockwise to minimize the great circle distance. The path between q0 and q181 is counterclockwise to minimize the great circle distance. The path between q0 and q180 can be either clockwise or counterclockwise, depending on numerical rounding.

#### Show Interpolated Quaternions on Sphere

Create two quaternions.

```
q1 = quaternion([75,-20,-10],'eulerd','ZYX','frame');
q2 = quaternion([-45,20,30],'eulerd','ZYX','frame');
```

Define the interpolation coefficient.

```
T = 0:0.01:1;
```

Obtain the interpolated quaternions.

```
quats = slerp(q1,q2,T);
```

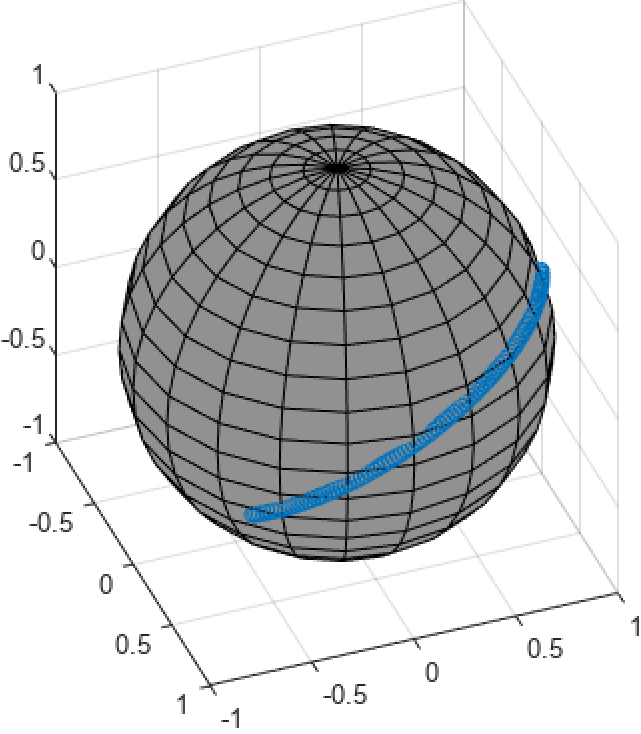
Obtain the corresponding rotate points.

```
pts = rotatepoint(quats,[1 0 0]);
```

Show the interpolated quaternions on a unit sphere.

```
figure
[X,Y,Z] = sphere;
```

```
surf(X,Y,Z,'FaceColor',[0.57 0.57 0.57])
hold on;

scatter3(pts(:,1),pts(:,2),pts(:,3))
view([69.23 36.60])
axis equal
```




Note that the interpolated quaternions follow the shorter path from `q1` to `q2`.

## Input Arguments

### q1 — Quaternion

scalar | vector | matrix | multidimensional array

Quaternion to interpolate, specified as a scalar, vector, matrix, or multidimensional array of quaternions.

`q1`, `q2`, and `T` must have compatible sizes. In the simplest cases, they can be the same size or any one can be a scalar. Two inputs have compatible sizes if, for every dimension, the dimension sizes of the inputs are either the same or one of them is 1.

Data Types: `quaternion`

### q2 — Quaternion

scalar | vector | matrix | multidimensional array

Quaternion to interpolate, specified as a scalar, vector, matrix, or multidimensional array of quaternions.

`q1`, `q2`, and `T` must have compatible sizes. In the simplest cases, they can be the same size or any one can be a scalar. Two inputs have compatible sizes if, for every dimension, the dimension sizes of the inputs are either the same or one of the dimension sizes is 1.

Data Types: `quaternion`

**`T` — Interpolation coefficient**
scalar | vector | matrix | multidimensional array

Interpolation coefficient, specified as a scalar, vector, matrix, or multidimensional array of numbers with each element in the range [0,1].

`q1`, `q2`, and `T` must have compatible sizes. In the simplest cases, they can be the same size or any one can be a scalar. Two inputs have compatible sizes if, for every dimension, the dimension sizes of the inputs are either the same or one of the dimension sizes is 1.

Data Types: `single` | `double`

## Output Arguments

**`q0` — Interpolated quaternion**
scalar | vector | matrix | multidimensional array

Interpolated quaternion, returned as a scalar, vector, matrix, or multidimensional array.

Data Types: `quaternion`

## Algorithms

Quaternion **s**pherical **l**inear int**erp**olation (SLERP) is an extension of linear interpolation along a plane to spherical interpolation in three dimensions. The algorithm was first proposed in [1]. Given two quaternions, $q_1$ and $q_2$, SLERP interpolates a new quaternion, $q_0$, along the great circle that connects $q_1$ and $q_2$. The interpolation coefficient, $T$, determines how close the output quaternion is to either $q_1$ and $q_2$.

The SLERP algorithm can be described in terms of sinusoids:

$$q_0 = \frac{\sin((1-T)\theta)}{\sin(\theta)}q_1 + \frac{\sin(T\theta)}{\sin(\theta)}q_2$$

where $q_1$ and $q_2$ are normalized quaternions, and $\theta$ is half the angular distance between $q_1$ and $q_2$.

# Version History

**Introduced in R2019b**

## References

[1] Shoemake, Ken. "Animating Rotation with Quaternion Curves." *ACM SIGGRAPH Computer Graphics* Vol. 19, Issue 3, 1985, pp. 245–254.

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Functions**
`dist` | `meanrot`

**Objects**
`quaternion`

**Topics**
"Lowpass Filter Orientation Using Quaternion SLERP"
"Rotations, Orientation, and Quaternions"

# times, .*

Element-wise quaternion multiplication

## Syntax

```
quatC = A.*B
```

## Description

`quatC = A.*B` returns the element-by-element quaternion multiplication of quaternion arrays.

You can use quaternion multiplication to compose rotation operators:

- To compose a sequence of frame rotations, multiply the quaternions in the same order as the desired sequence of rotations. For example, to apply a *p* quaternion followed by a *q* quaternion, multiply in the order *pq*. The rotation operator becomes $(pq)^{*}v(pq)$, where *v* represents the object to rotate in quaternion form. * represents conjugation.
- To compose a sequence of point rotations, multiply the quaternions in the reverse order of the desired sequence of rotations. For example, to apply a *p* quaternion followed by a *q* quaternion, multiply in the reverse order, *qp*. The rotation operator becomes $(qp)v(qp)^{*}$.

## Examples

### Multiply Two Quaternion Vectors

Create two vectors, `A` and `B`, and multiply them element by element.

```
A = quaternion([1:4;5:8]);
B = A;
C = A.*B
```

```
C = 2x1 quaternion array
     -28 +   4i +   6j +   8k
    -124 +  60i +  70j +  80k
```

### Multiply Two Quaternion Arrays

Create two 3-by-3 arrays, `A` and `B`, and multiply them element by element.

```
A = reshape(quaternion(randn(9,4)),3,3);
B = reshape(quaternion(randn(9,4)),3,3);
C = A.*B
```

```
C = 3x3 quaternion array
     0.60169 +  2.4332i -  2.5844j + 0.51646k    -0.49513 +  1.1722i +  4.4401j -   1.217k      2
     -4.2329 +  2.4547i +  3.7768j + 0.77484k    -0.65232 - 0.43112i -  1.4645j - 0.90073k     -
```

```
    -4.4159 +  2.1926i +  1.9037j -  4.0303k     -2.0232 +  0.4205i - 0.17288j +  3.8529k     -2
```

Note that quaternion multiplication is not commutative:

```
isequal(C,B.*A)
```

```
ans = logical
   0
```

#### Multiply Quaternion Row and Column Vectors

Create a row vector a and a column vector b, then multiply them. The 1-by-3 row vector and 4-by-1 column vector combine to produce a 4-by-3 matrix with all combinations of elements multiplied.

```
a = [zeros('quaternion'),ones('quaternion'),quaternion(randn(1,4))]
```

```
a = 1x3 quaternion array
           0 +       0i +       0j +       0k             1 +       0i +       0j +       0k     0
```

```
b = quaternion(randn(4,4))
```

```
b = 4x1 quaternion array
      0.31877 +   3.5784i +   0.7254j -  0.12414k
      -1.3077 +   2.7694i - 0.063055j +   1.4897k
     -0.43359 -   1.3499i +  0.71474j +    1.409k
      0.34262 +   3.0349i -  0.20497j +   1.4172k
```

```
a.*b
```

```
ans = 4x3 quaternion array
            0 +       0i +         0j +        0k      0.31877 +   3.5784i +   0.7254j -  0.1241
            0 +       0i +         0j +        0k      -1.3077 +   2.7694i - 0.063055j +   1.489
            0 +       0i +         0j +        0k     -0.43359 -   1.3499i +  0.71474j +    1.40
            0 +       0i +         0j +        0k      0.34262 +   3.0349i -  0.20497j +   1.417
```

## Input Arguments

**A — Array to multiply**
scalar | vector | matrix | multidimensional array

Array to multiply, specified as a quaternion, an array of quaternions, a real scalar, or an array of real numbers.

A and B must have compatible sizes. In the simplest cases, they can be the same size or one can be a scalar. Two inputs have compatible sizes if, for every dimension, the dimension sizes of the inputs are the same or one of them is 1.

Data Types: quaternion | single | double

**B — Array to multiply**
scalar | vector | matrix | multidimensional array

Array to multiply, specified as a quaternion, an array of quaternions, a real scalar, or an array of real numbers.

A and B must have compatible sizes. In the simplest cases, they can be the same size or one can be a scalar. Two inputs have compatible sizes if, for every dimension, the dimension sizes of the inputs are the same or one of them is 1.

Data Types: quaternion | single | double

## Output Arguments

**quatC — Quaternion product**
scalar | vector | matrix | multidimensional array

Quaternion product, returned as a scalar, vector, matrix, or multidimensional array.

Data Types: quaternion

## Algorithms

### Quaternion Multiplication by a Real Scalar

Given a quaternion,

$$q = a_{\mathrm{q}} + b_{\mathrm{q}}\mathrm{i} + c_{\mathrm{q}}\mathrm{j} + d_{\mathrm{q}}\mathrm{k},$$

the product of $q$ and a real scalar $\beta$ is

$$\beta q = \beta a_{\mathrm{q}} + \beta b_{\mathrm{q}}\mathrm{i} + \beta c_{\mathrm{q}}\mathrm{j} + \beta d_{\mathrm{q}}\mathrm{k}$$

### Quaternion Multiplication by a Quaternion Scalar

The definition of the basis elements for quaternions,

$$\mathrm{i}^2 = \mathrm{j}^2 = \mathrm{k}^2 = \mathrm{ijk} = -1\,,$$

can be expanded to populate a table summarizing quaternion basis element multiplication:

| | **1** | **i** | **j** | **k** |
|---|---|---|---|---|
| **1** | 1 | i | j | k |
| **i** | i | −1 | k | −j |
| **j** | j | −k | −1 | i |
| **k** | k | j | −i | −1 |

When reading the table, the rows are read first, for example: ij = k and ji = −k.

Given two quaternions, $q = a_{\mathrm{q}} + b_{\mathrm{q}}\mathrm{i} + c_{\mathrm{q}}\mathrm{j} + d_{\mathrm{q}}\mathrm{k}$, and $p = a_{\mathrm{p}} + b_{\mathrm{p}}\mathrm{i} + c_{\mathrm{p}}\mathrm{j} + d_{\mathrm{p}}\mathrm{k}$, the multiplication can be expanded as:

$$
\begin{aligned}
z = pq = & \left(a_p + b_p\mathrm{i} + c_p\mathrm{j} + d_p\mathrm{k}\right)\left(a_q + b_q\mathrm{i} + c_q\mathrm{j} + d_q\mathrm{k}\right) \\
= & \ a_pa_q + a_pb_q\mathrm{i} + a_pc_q\mathrm{j} + a_pd_q\mathrm{k} \\
& + b_pa_q\mathrm{i} + b_pb_q\mathrm{i}^2 + b_pc_q\mathrm{ij} + b_pd_q\mathrm{ik} \\
& + c_pa_q\mathrm{j} + c_pb_q\mathrm{ji} + c_pc_q\mathrm{j}^2 + c_pd_q\mathrm{jk} \\
& + d_pa_qk + d_pb_q\mathrm{ki} + d_pc_q\mathrm{kj} + d_pd_q\mathrm{k}^2
\end{aligned}
$$

You can simplify the equation using the quaternion multiplication table.

$$
\begin{aligned}
z = pq \ = & \ a_pa_q + a_pb_q\mathrm{i} + a_pc_q\mathrm{j} + a_pd_q\mathrm{k} \\
& + b_pa_q\mathrm{i} - b_pb_q + b_pc_q\mathrm{k} - b_pd_q\mathrm{j} \\
& + c_pa_q\mathrm{j} - c_pb_q\mathrm{k} - c_pc_q + c_pd_q\mathrm{i} \\
& + d_pa_qk + d_pb_q\mathrm{j} - d_pc_q\mathrm{i} - d_pd_q
\end{aligned}
$$

# Version History

**Introduced in R2019b**

## References

[1] Kuipers, Jack B. *Quaternions and Rotation Sequences: A Primer with Applications to Orbits, Aerospace, and Virtual Reality*. Princeton, NJ: Princeton University Press, 2007.

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Functions

`prod` | `mtimes, *`

### Objects

`quaternion`

### Topics

"Rotations, Orientation, and Quaternions"

# transpose, .'

Transpose a quaternion array

## Syntax

```
Y = quat.'
```

## Description

`Y = quat.'` returns the non-conjugate transpose of the quaternion array, `quat`.

## Examples

### Vector Transpose

Create a vector of quaternions and compute its nonconjugate transpose.

```
quat = quaternion(randn(4,4))
```

```
quat = 4x1 quaternion array
      0.53767 +  0.31877i +   3.5784j +   0.7254k
       1.8339 -   1.3077i +   2.7694j - 0.063055k
      -2.2588 -  0.43359i -   1.3499j +  0.71474k
      0.86217 +  0.34262i +   3.0349j -  0.20497k
```

```
quatTransposed = quat.'
```

```
quatTransposed = 1x4 quaternion array
      0.53767 +  0.31877i +   3.5784j +   0.7254k       1.8339 -   1.3077i +   2.7694j - 0.06305
```

### Matrix Transpose

Create a matrix of quaternions and compute its nonconjugate transpose.

```
quat = [quaternion(randn(2,4)),quaternion(randn(2,4))]
```

```
quat = 2x2 quaternion array
      0.53767 -   2.2588i +  0.31877j -  0.43359k       3.5784 -   1.3499i +   0.7254j +  0.7147
       1.8339 +  0.86217i -   1.3077j +  0.34262k       2.7694 +   3.0349i - 0.063055j -  0.2049
```

```
quatTransposed = quat.'
```

```
quatTransposed = 2x2 quaternion array
      0.53767 -   2.2588i +  0.31877j -  0.43359k       1.8339 +  0.86217i -   1.3077j +  0.3426
       3.5784 -   1.3499i +   0.7254j +  0.71474k       2.7694 +   3.0349i - 0.063055j -  0.2049
```

## Input Arguments

**`quat` — Quaternion array to transpose**
vector | matrix

Quaternion array to transpose, specified as a vector or matrix of quaternions. `transpose` is defined for 1-D and 2-D arrays. For higher-order arrays, use `permute`.

Data Types: `quaternion`

## Output Arguments

**`Y` — Transposed quaternion array**
vector | matrix

Transposed quaternion array, returned as an *N*-by-*M* array, where `quat` was specified as an *M*-by-*N* array.

# Version History

**Introduced in R2019b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Functions**
`ctranspose, '`

**Objects**
`quaternion`

**Topics**
"Rotations, Orientation, and Quaternions"

# uminus, -

Quaternion unary minus

## Syntax

```
mQuat = -quat
```

## Description

`mQuat = -quat` negates the elements of `quat` and stores the result in `mQuat`.

## Examples

### Negate Elements of Quaternion Matrix

Unary minus negates each part of a the quaternion. Create a 2-by-2 matrix, `Q`.

```
Q = quaternion(randn(2),randn(2),randn(2),randn(2))
```

```
Q = 2x2 quaternion array
      0.53767 +  0.31877i +   3.5784j +   0.7254k      -2.2588 -  0.43359i -   1.3499j +  0.7147
       1.8339 -   1.3077i +   2.7694j - 0.063055k      0.86217 +  0.34262i +   3.0349j -  0.2049
```

Negate the parts of each quaternion in `Q`.

```
R = -Q
```

```
R = 2x2 quaternion array
     -0.53767 -  0.31877i -   3.5784j -   0.7254k       2.2588 +  0.43359i +   1.3499j -  0.7147
      -1.8339 +   1.3077i -   2.7694j + 0.063055k     -0.86217 -  0.34262i -   3.0349j +  0.2049
```

## Input Arguments

**`quat` — Quaternion array**
scalar | vector | matrix | multidimensional array

Quaternion array, specified as a scalar, vector, matrix, or multidimensional array.

Data Types: `quaternion`

## Output Arguments

**`mQuat` — Negated quaternion array**
scalar | vector | matrix | multidimensional array

Negated quaternion array, returned as the same size as `quat`.

Data Types: `quaternion`

## Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Functions

`minus, -`

### Objects

`quaternion`

### Topics

"Rotations, Orientation, and Quaternions"

# zeros

Create quaternion array with all parts set to zero

## Syntax

```
quatZeros = zeros('quaternion')
quatZeros = zeros(n,'quaternion')
quatZeros = zeros(sz,'quaternion')
quatZeros = zeros(sz1,...,szN,'quaternion')

quatZeros = zeros( ___ ,'like',prototype,'quaternion')
```

## Description

`quatZeros = zeros('quaternion')` returns a scalar quaternion with all parts set to zero.

`quatZeros = zeros(n,'quaternion')` returns an `n`-by-`n` matrix of quaternions.

`quatZeros = zeros(sz,'quaternion')` returns an array of quaternions where the size vector, `sz`, defines `size(quatZeros)`.

`quatZeros = zeros(sz1,...,szN,'quaternion')` returns a `sz1`-by-...-by-`szN` array of quaternions where `sz1,…,szN` indicates the size of each dimension.

`quatZeros = zeros( ___ ,'like',prototype,'quaternion')` specifies the underlying class of the returned quaternion array to be the same as the underlying class of the quaternion prototype.

## Examples

### Quaternion Scalar Zero

Create a quaternion scalar zero.

```
quatZeros = zeros('quaternion')
```

```
quatZeros = quaternion
     0 + 0i + 0j + 0k
```

### Square Matrix of Quaternions

Create an n-by-n array of quaternion zeros.

```
n = 3;
quatZeros = zeros(n,'quaternion')
```

```
quatZeros = 3x3 quaternion array
     0 + 0i + 0j + 0k     0 + 0i + 0j + 0k     0 + 0i + 0j + 0k
```

```
     0 + 0i + 0j + 0k     0 + 0i + 0j + 0k     0 + 0i + 0j + 0k
     0 + 0i + 0j + 0k     0 + 0i + 0j + 0k     0 + 0i + 0j + 0k
```

#### Multidimensional Array of Quaternion Zeros

Create a multidimensional array of quaternion zeros by defining array dimensions in order. In this example, you create a 3-by-1-by-2 array. You can specify dimensions using a row vector or comma-separated integers.

Specify the dimensions using a row vector and display the results:

```
dims = [3,1,2];
quatZerosSyntax1 = zeros(dims,'quaternion')
```

```
quatZerosSyntax1 = 3x1x2 quaternion array
quatZerosSyntax1(:,:,1) =

     0 + 0i + 0j + 0k
     0 + 0i + 0j + 0k
     0 + 0i + 0j + 0k


quatZerosSyntax1(:,:,2) =

     0 + 0i + 0j + 0k
     0 + 0i + 0j + 0k
     0 + 0i + 0j + 0k
```

Specify the dimensions using comma-separated integers, and then verify the equivalence of the two syntaxes:

```
quatZerosSyntax2 = zeros(3,1,2,'quaternion');
isequal(quatZerosSyntax1,quatZerosSyntax2)
```

```
ans = logical
   1
```

#### Underlying Class of Quaternion Zeros

A quaternion is a four-part hyper-complex number used in three-dimensional representations. You can specify the underlying data type of the parts as `single` or `double`. The default is `double`.

Create a quaternion array of zeros with the underlying data type set to `single`.

```
quatZeros = zeros(2,'like',single(1),'quaternion')
```

```
quatZeros = 2x2 quaternion array
     0 + 0i + 0j + 0k     0 + 0i + 0j + 0k
     0 + 0i + 0j + 0k     0 + 0i + 0j + 0k
```

Verify the underlying class using the `classUnderlying` function.

```
classUnderlying(quatZeros)
```

```
ans =
'single'
```

## Input Arguments

**`n` — Size of square quaternion matrix**
integer value

Size of square quaternion matrix, specified as an integer value. If `n` is `0` or negative, then `quatZeros` is returned as an empty matrix.

Example: `zeros(4,'quaternion')` returns a 4-by-4 matrix of quaternion zeros.

Data Types: `single` | `double` | `int8` | `int16` | `int32` | `int64` | `uint8` | `uint16` | `uint32` | `uint64`

**`sz` — Output size**
row vector of integer values

Output size, specified as a row vector of integer values. Each element of `sz` indicates the size of the corresponding dimension in `quatZeros`. If the size of any dimension is `0` or negative, then `quatZeros` is returned as an empty array.

Example: `zeros([1,4,2],'quaternion')` returns a 1-by-4-by-2 array of quaternion zeros.

Data Types: `single` | `double` | `int8` | `int16` | `int32` | `int64` | `uint8` | `uint16` | `uint32` | `uint64`

**`prototype` — Quaternion prototype**
variable

Quaternion prototype, specified as a variable.

Example: `zeros(2,'like',quat,'quaternion')` returns a 2-by-2 matrix of quaternions with the same underlying class as the prototype quaternion, `quat`.

Data Types: `quaternion`

**`sz1,...,szN` — Size of each dimension**
two or more integer values

Size of each dimension, specified as two or more integers.

- If the size of any dimension is `0`, then `quatZeros` is returned as an empty array.
- If the size of any dimension is negative, then it is treated as `0`.

Example: `zeros(2,3,'quaternion')` returns a 2-by-3 matrix of quaternion zeros.

Data Types: `single` | `double` | `int8` | `int16` | `int32` | `int64` | `uint8` | `uint16` | `uint32` | `uint64`

## Output Arguments

**`quatZeros` — Quaternion zeros**
scalar | vector | matrix | multidimensional array

Quaternion zeros, returned as a quaternion or array of quaternions.

Given a quaternion of the form $Q = a + b\text{i} + c\text{j} + d\text{k}$, a quaternion zero is defined as $Q = 0 + 0\text{i} + 0\text{j} + 0\text{k}$.

Data Types: `quaternion`

## Version History

**Introduced in R2019b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Functions**
`ones`

**Objects**
`quaternion`

**Topics**
"Rotations, Orientation, and Quaternions"

# rateControl

Execute loop at fixed frequency

## Description

The `rateControl` object enables you to run a loop at a fixed frequency. It also collects statistics about the timing of the loop iterations. Use `waitfor` in the loop to pause code execution until the next time step. The loop operates every `DesiredPeriod` seconds, unless the enclosed code takes longer to operate. The object uses the `OverrunAction` property to determine how it handles longer loop operation times. The default setting, `'slip'`, immediately executes the loop if `LastPeriod` is greater than `DesiredPeriod`. Using `'drop'` causes the `waitfor` method to wait until the next multiple of `DesiredPeriod` is reached to execute the next loop.

---

**Tip** The scheduling resolution of your operating system and the level of other system activity can affect rate execution accuracy. As a result, accurate rate timing is limited to 100 Hz for execution of MATLAB code. To improve performance and execution speeds, use code generation.

---

## Creation

### Syntax

```
rateObj = rateControl(desiredRate)
```

#### Description

`rateObj = rateControl(desiredRate)` creates an object that operates loops at a fixed-rate based on your system time and directly sets the `DesireRate` property.

### Properties

**`DesiredRate` — Desired execution rate**
scalar

Desired execution rate of loop, specified as a scalar in Hz. When using `waitfor`, the loop operates every `DesiredRate` seconds, unless the loop takes longer. It then begins the next loop based on the specified `OverrunAction`.

**`DesiredPeriod` — Desired time period between executions**
scalar

Desired time period between executions, specified as a scalar in seconds. This property is equal to the inverse of `DesiredRate`.

**`TotalElapsedTime` — Elapsed time since construction or reset**
scalar

Elapsed time since construction or reset, specified as a scalar in seconds.

### `LastPeriod` — Elapsed time between last two calls to `waitfor`

NaN (default) | scalar

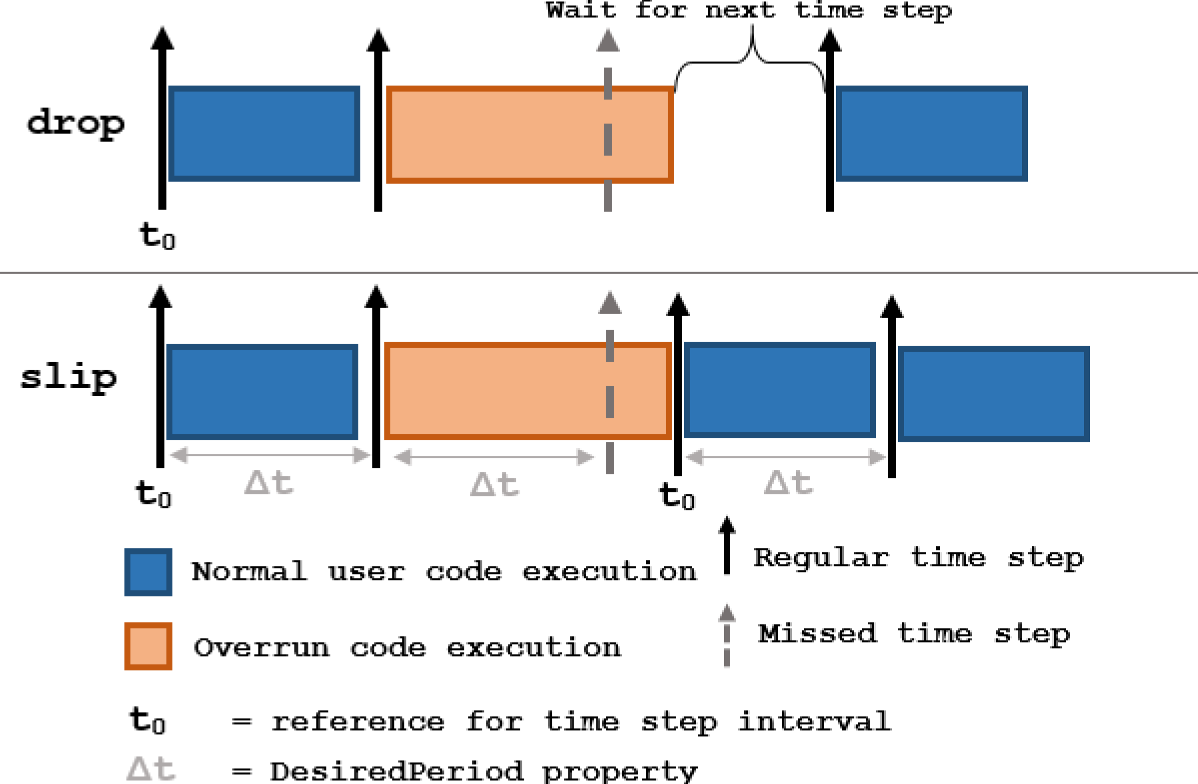
Elapsed time between last two calls to `waitfor`, specified as a scalar. By default, `LastPeriod` is set to `NaN` until `waitfor` is called for the first time. After the first call, `LastPeriod` equals `TotalElapsedTime`.

### `OverrunAction` — Method for handling overruns

'slip' (default) | 'drop'

Method for handling overruns, specified as one of these character vectors:

- `'drop'` — waits until the next time interval equal to a multiple of `DesiredPeriod`
- `'slip'` — immediately executes the loop again




Each code section calls `waitfor` at the end of execution.

## Object Functions

| | |
|---|---|
| waitfor | Pause code execution to achieve desired execution rate |
| statistics | Statistics of past execution periods |
| reset | Reset Rate object |

## Examples

### Run Loop at Fixed Rate

Create a rate object that runs at 1 Hz.

```
r = rateControl(1);
```

Start a loop using the `rateControl` object inside to control the loop execution. Reset the object prior to the loop execution to reset timer. Print the iteration and time elapsed.

```
reset(r)
for i = 1:10
    time = r.TotalElapsedTime;
    fprintf('Iteration: %d - Time Elapsed: %f\n',i,time)
    waitfor(r);
end
```

```
Iteration: 1 - Time Elapsed: 0.003114
Iteration: 2 - Time Elapsed: 1.003618
Iteration: 3 - Time Elapsed: 2.000382
Iteration: 4 - Time Elapsed: 3.000483
Iteration: 5 - Time Elapsed: 4.001145
Iteration: 6 - Time Elapsed: 5.011602
Iteration: 7 - Time Elapsed: 6.005804
Iteration: 8 - Time Elapsed: 7.000292
Iteration: 9 - Time Elapsed: 8.000162
Iteration: 10 - Time Elapsed: 9.006431
```

Each iteration executes at a 1-second interval.

### Get Statistics From Rate Object Execution

Create a `rateControl` object for running at 20 Hz.

```
r = rateControl(20);
```

Start a loop and control operation using the `rateControl` object.

```
for i = 1:30
    % Your code goes here
    waitfor(r);
end
```

Get `Rate` object statistics after loop operation.

```
stats = statistics(r)
```

```
stats = struct with fields:
              Periods: [0.0599 0.0418 0.0629 0.0449 0.0456 0.0591 0.0449 0.0461 0.0599 0.0449 0.0
           NumPeriods: 30
        AveragePeriod: 0.0501
    StandardDeviation: 0.0079
          NumOverruns: 0
```

### Run Loop At Fixed Rate and Reset Rate Object

Create a `rateControl` object for running at 20 Hz.

```
r = rateControl(2);
```

Start a loop and control operation using the `Rate` object.

```
for i = 1:30
    % Your code goes here
    waitfor(r);
end
```

Display the `rateControl` object properties after loop operation.

```
disp(r)
```

```
  rateControl with properties:

         DesiredRate: 2
       DesiredPeriod: 0.5000
       OverrunAction: 'slip'
    TotalElapsedTime: 15.0287
          LastPeriod: 0.5118
```

Reset the object to restart the time statistics.

```
reset(r);
disp(r)
```

```
  rateControl with properties:

         DesiredRate: 2
       DesiredPeriod: 0.5000
       OverrunAction: 'slip'
    TotalElapsedTime: 0.0026
          LastPeriod: NaN
```

## Version History

**Introduced in R2016a**

### R2019b: `rateControl` was renamed

*Behavior change in future release*

The `rateControl` object was renamed from `robotics.Rate`. Use `rateControl` for all object creation.

## See Also

`rosrate` | `waitfor` | `statistics` | `reset`

### Topics

"Execute Code at a Fixed-Rate"

# reset

Reset `Rate` object

## Syntax

```
reset(rate)
```

## Description

`reset(rate)` resets the state of the `Rate` object, including the elapsed time and all statistics about previous periods. `reset` is useful if you want to run multiple successive loops at the same rate, or if the object is created before the loop is executed.

## Input Arguments

**rate — Rate object**
handle

`Rate` object, specified as a handle. This object contains the information for the desired rate and other information about the execution. See `rateControl` for more information.

## Examples

### Run Loop At Fixed Rate and Reset Rate Object

Create a `rateControl` object for running at 20 Hz.

```
r = rateControl(2);
```

Start a loop and control operation using the `Rate` object.

```
for i = 1:30
    % Your code goes here
    waitfor(r);
end
```

Display the `rateControl` object properties after loop operation.

```
disp(r)
```

```
  rateControl with properties:

         DesiredRate: 2
       DesiredPeriod: 0.5000
       OverrunAction: 'slip'
    TotalElapsedTime: 15.0287
          LastPeriod: 0.5118
```

Reset the object to restart the time statistics.

```
reset(r);
disp(r)

  rateControl with properties:

         DesiredRate: 2
       DesiredPeriod: 0.5000
       OverrunAction: 'slip'
    TotalElapsedTime: 0.0026
          LastPeriod: NaN
```

# Version History

**Introduced in R2016a**

## See Also

`rateControl` | `waitfor`

### Topics

"Execute Code at a Fixed-Rate"

# statistics

Statistics of past execution periods

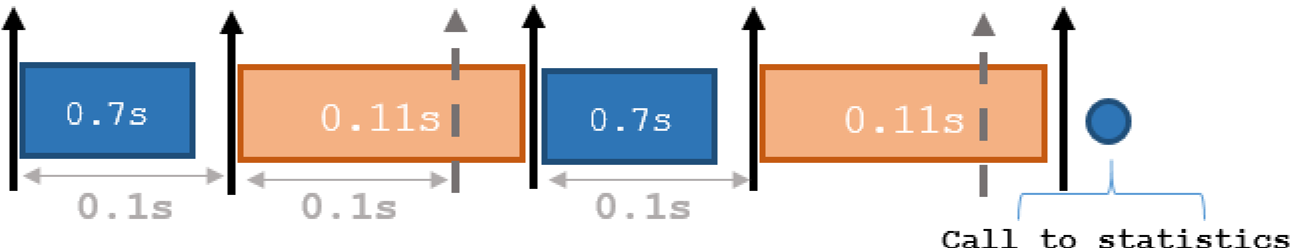
## Syntax

```
stats = statistics(rate)
```

## Description

`stats = statistics(rate)` returns statistics of previous periods of code execution. `stats` is a struct with these fields: `Periods`, `NumPeriods`, `AveragePeriod`, `StandardDeviation`, and `NumOverruns`.

Here is a sample execution graphic using the default setting, `'slip'`, for the `OverrunAction` property in the `Rate` object. See `OverrunAction` for more information on overrun code execution.




The output of `statistics` is:

```
stats = 

              Periods: [0.7 0.11 0.7 0.11]
           NumPeriods: 4
        AveragePeriod: 0.09
    StandardDeviation: 0.0231
          NumOverruns: 2
```

## Input Arguments

**rate — Rate object**
handle

`Rate` object, specified as an object handle. This object contains the information for the `DesiredRate` and other info about the execution. See `rateControl` for more information.

## Output Arguments

**stats — Time execution statistics**
structure

Time execution statistics, returned as a structure. This structure contains the following fields:

- `Period` — All time periods (returned in seconds) used to calculate statistics as an indexed array. `stats.Period(end)` is the most recent period.
- `NumPeriods` — Number of elements in `Periods`
- `AveragePeriod` — Average time in seconds
- `StandardDeviation` — Standard deviation of all periods in seconds, centered around the mean stored in `AveragePeriod`
- `NumOverruns` — Number of periods with overrun

## Examples

### Get Statistics From Rate Object Execution

Create a `rateControl` object for running at 20 Hz.

```
r = rateControl(20);
```

Start a loop and control operation using the `rateControl` object.

```
for i = 1:30
    % Your code goes here
    waitfor(r);
end
```

Get `Rate` object statistics after loop operation.

```
stats = statistics(r)
```

```
stats = struct with fields:
              Periods: [0.0599 0.0418 0.0629 0.0449 0.0456 0.0591 0.0449 0.0461 0.0599 0.0449 0.0
           NumPeriods: 30
        AveragePeriod: 0.0501
    StandardDeviation: 0.0079
          NumOverruns: 0
```

# Version History

**Introduced in R2016a**

## See Also

`rateControl` | `waitfor`

**Topics**

"Execute Code at a Fixed-Rate"

# waitfor

**Package:** `robotics`

Pause code execution to achieve desired execution rate

## Syntax

```
waitfor(rate)
numMisses = waitfor(rate)
```

## Description

`waitfor(rate)` pauses execution until the code reaches the desired execution rate. The function accounts for the time that is spent executing code between `waitfor` calls.

`numMisses = waitfor(rate)` returns the number of iterations missed while executing code between calls.

## Examples

### Run Loop at Fixed Rate

Create a rate object that runs at 1 Hz.

```
r = rateControl(1);
```

Start a loop using the `rateControl` object inside to control the loop execution. Reset the object prior to the loop execution to reset timer. Print the iteration and time elapsed.

```
reset(r)
for i = 1:10
    time = r.TotalElapsedTime;
    fprintf('Iteration: %d - Time Elapsed: %f\n',i,time)
    waitfor(r);
end
```

```
Iteration: 1 - Time Elapsed: 0.003114
Iteration: 2 - Time Elapsed: 1.003618
Iteration: 3 - Time Elapsed: 2.000382
Iteration: 4 - Time Elapsed: 3.000483
Iteration: 5 - Time Elapsed: 4.001145
Iteration: 6 - Time Elapsed: 5.011602
Iteration: 7 - Time Elapsed: 6.005804
Iteration: 8 - Time Elapsed: 7.000292
Iteration: 9 - Time Elapsed: 8.000162
Iteration: 10 - Time Elapsed: 9.006431
```

Each iteration executes at a 1-second interval.

## Input Arguments

**`rate` — `Rate` object**
handle

`Rate` object, specified as a handle. This object contains the information for the desired rate and other information about the execution. See `rateControl` for more information.

## Output Arguments

**`numMisses` — Number of missed task executions**
scalar

Number of missed task executions, returned as a scalar. `waitfor` returns the number of times the task was missed in the `Rate` object based on the `LastPeriod` time. For example, if the desired rate is 1 Hz and the last period was 3.2 seconds, `numMisses` returns 3.

# Version History

**Introduced in R2016a**

## See Also

`rateControl`

### Topics

"Execute Code at a Fixed-Rate"

# reedsSheppConnection

Reeds-Shepp path connection type

## Description

The `reedSheppConnection` object holds information for computing a `reedsSheppPathSegment` object to connect between poses. A Reeds-Shepp path segment connects two poses as a sequence of five motions. The motion options are:

- Straight
- Left turn at maximum steer
- Right turn at maximum steer
- No movement

A Reeds-Shepp path segment supports both forward and backward motion.

Use this connection object to define parameters for a vehicle motion model, including the minimum turning radius and options for path types. To generate a path segment between poses using this connection type, call the `connect` function.

## Creation

### Syntax

```
reedsConnObj = reedsSheppConnection
reedsConnObj = reedsSheppConnection(Name,Value)
```

#### Description

`reedsConnObj = reedsSheppConnection` creates an object using default property values.

`reedsConnObj = reedsSheppConnection(Name,Value)` specifies property values using name-value pairs. To set multiple properties, specify multiple name-value pairs.

## Properties

**`MinTurningRadius` — Minimum turning radius**
`1` (default) | positive scalar in meters

Minimum turning radius for the vehicle, specified as a positive scalar in meters. The minimum turning radius is for the smallest circle the vehicle can make with maximum steer in a single direction.

Data Types: `double`

**`DisabledPathTypes` — Path types to disable**
`{}` (default) | vector of string scalars | cell array of character vectors

Path types to disable, specified as a vector of string scalars or cell array of character vectors.

| Motion Type | Description |
|---|---|
| `"Sp","Sn"` | Straight (`p` = forward, `n` = reverse) |
| `"Lp","Ln"` | Left turn at the maximum steering angle of the vehicle (`p` = forward, `n` = reverse) |
| `"Rp","Rn"` | Right turn at the maximum steering angle of the vehicle (`p` = forward, `n` = reverse) |
| `"N"` | No motion |

If a path segment has fewer than five motion types, the remaining elements are `"N"` (no motion).

To see all available path types, see the `AllPathTypes` property.

Example: `["LpSnLp","LnSnRpSn","LnSnRpSnLp"]`

Data Types: `cell`

**`AllPathTypes` — All possible path types**
cell array of character vectors

This property is read-only.

All possible path types, specified as a cell array of character vectors. This property lists all types. To disable certain types, specify types from this list in `DisabledPathTypes`.

For Reeds-Shepp connections, there are 44 possible combinations of motion types.

Data Types: `cell`

**`ForwardCost` — Cost multiplier to travel forward**
`1` (default) | positive numeric scalar

Cost multiple to travel forward, specified as a positive numeric scalar. Increase this property to penalize forward motion.

Data Types: `double`

**`ReverseCost` — Cost multiplier to travel in reverse**
`1` (default) | positive numeric scalar

Cost multiple to travel in reverse, specified as a positive numeric scalar. Increase this property to penalize reverse motion.

Data Types: `double`

## Object Functions

connect Connect poses for given connection type

## Examples

### Connect Poses Using ReedsShepp Connection Path

Create a `reedsSheppConnection` object.

```
reedsConnObj = reedsSheppConnection;
```

Define start and goal poses as `[x y theta]` vectors.

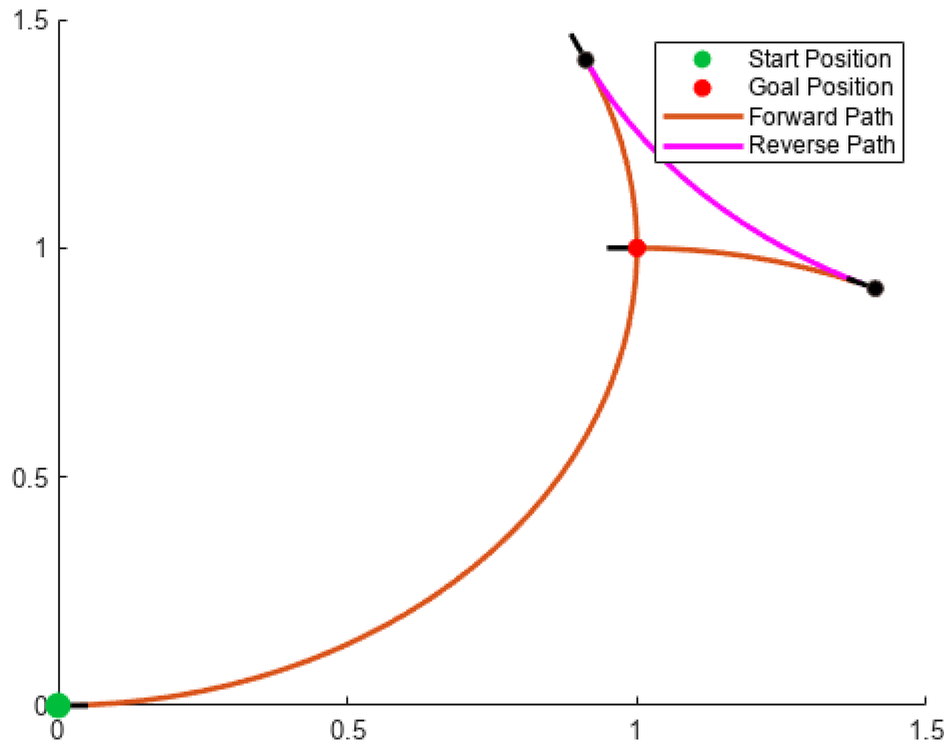
```
startPose = [0 0 0];
goalPose = [1 1 pi];
```

Calculate a valid path segment to connect the poses.

```
[pathSegObj,pathCosts] = connect(reedsConnObj,startPose,goalPose);
```

Show the generated path.

```
show(pathSegObj{1})
```




### Modify Connection Types for Reeds-Shepp Path

Create a `reedsSheppConnection` object.

```
reedsConnObj = reedsSheppConnection;
```

Define start and goal poses as `[x y theta]` vectors.

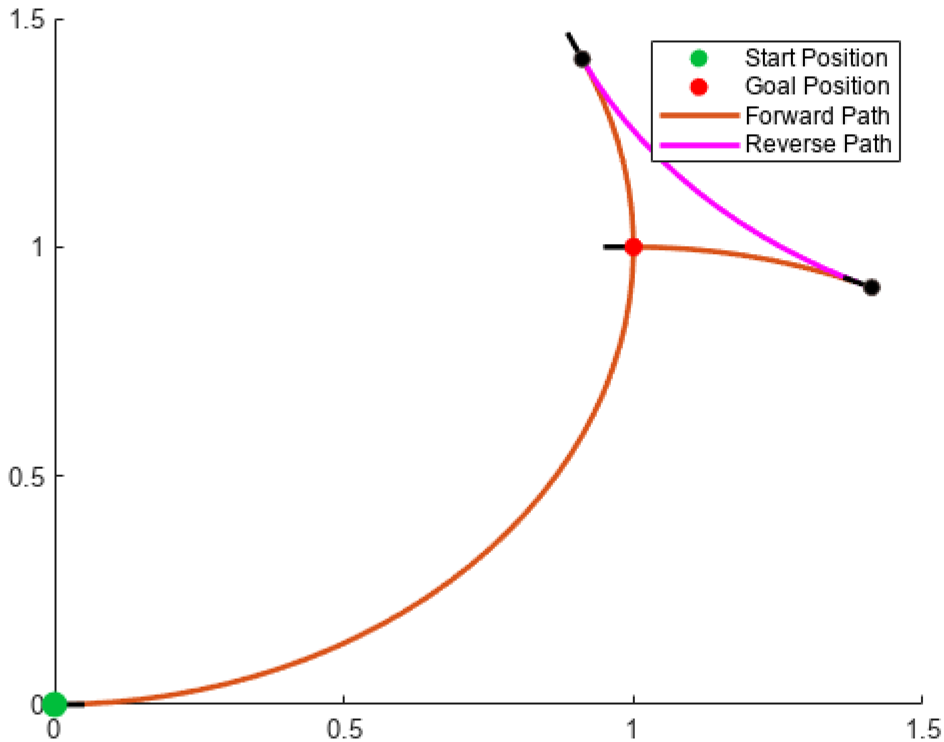
```
startPose = [0 0 0];
goalPose = [1 1 pi];
```

Calculate a valid path segment to connect the poses.

```
[pathSegObj,pathCosts] = connect(reedsConnObj,startPose,goalPose);
```

Show the generated path. Notice the direction of the turns.

```
show(pathSegObj{1})
```




```
pathSegObj{1}.MotionTypes
```

```
ans = 1x5 cell
    {'L'}    {'R'}    {'L'}    {'N'}    {'N'}
```

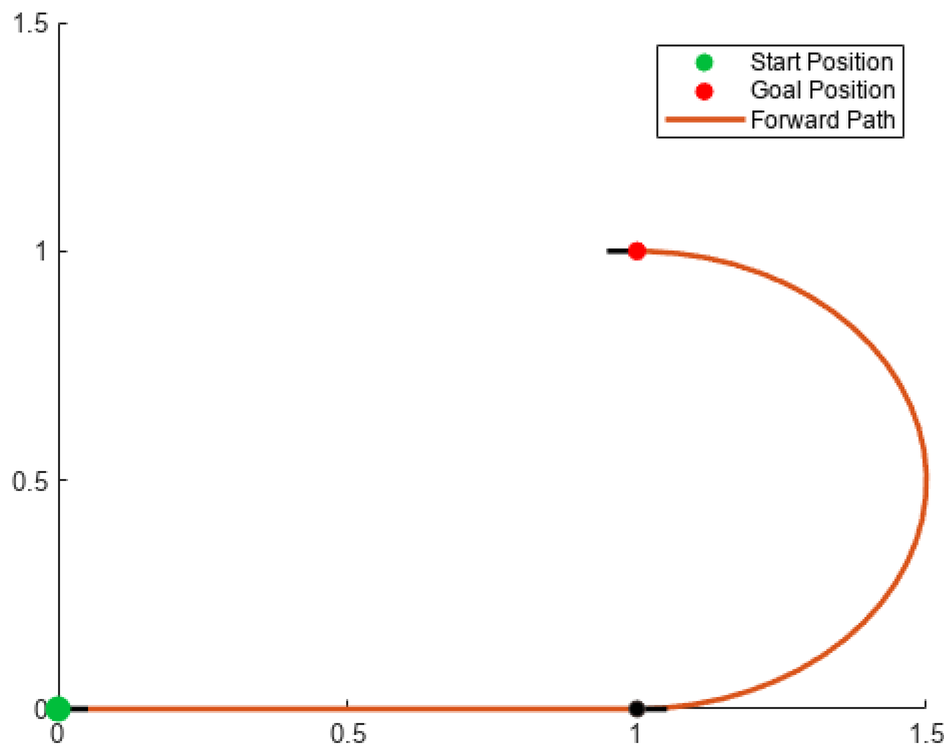
```
pathSegObj{1}.MotionDirections
```

```
ans = 1×5

     1    -1     1     1     1
```

Disable this specific motion sequence in a new connection object. Reduce the `MinTurningRadius` if the robot is more maneuverable. Increase the reverse cost to reduce the likelihood of reverse directions being used. Connect the poses again to get a different path.

```
reedsConnObj = reedsSheppConnection('DisabledPathTypes',{'LpRnLp'});
reedsConnObj.MinTurningRadius = 0.5;
reedsConnObj.ReverseCost = 5;

[pathSegObj,pathCosts] = connect(reedsConnObj,startPose,goalPose);
pathSegObj{1}.MotionTypes

ans = 1x5 cell
    {'L'}    {'S'}    {'L'}    {'N'}    {'N'}
```

```
show(pathSegObj{1})
xlim([0 1.5])
ylim([0 1.5])
```




# Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
`reedsSheppPathSegment` | `dubinsConnection` | `dubinsPathSegment`

**Functions**
`connect` | `interpolate` | `show`

# reedsSheppPathSegment

Reeds-Shepp path segment connecting two poses

## Description

The `reedSheppPathSegment` object holds information for a Reeds-Shepp path segment to connect between poses. A Reeds-Shepp path segment connects two poses as a sequence of five motion types. The motion options are:

- Straight
- Left turn at maximum steer
- Right turn at maximum steer
- No movement

## Creation

To generate a `reedSheppPathSegment` object, use the `connect` function with a `reedsSheppConnection` object:

`reedsPathSegObj = connect(connectionObj,start,goal)` connects the start and goal poses using the specified connection type object.

To specifically define a path segment:

`reedsPathSegObj = reedsSheppPathSegment(connectionObj,start,goal,motionLengths,motionTypes)` specifies the Reeds-Shepp connection type, the start and goal poses, and the corresponding motion lengths and types. These values are set to the corresponding properties in the object.

### Properties

**`MinTurningRadius` — Minimum turning radius of vehicle**
positive scalar

This property is read-only.

Minimum turning radius of the vehicle, specified as a positive scalar in meters. This value corresponds to the radius of the turning circle at the maximum steering angle of the vehicle.

Data Types: `double`

**`StartPose` — Initial pose of vehicle**
[$x$, $y$, $\Theta$] vector

This property is read-only.

Initial pose of the vehicle at the start of the path segment, specified as an [$x$, $y$, $\Theta$] vector. $x$ and $y$ are in meters. $\Theta$ is in radians.

Data Types: `double`

**`GoalPose` — Goal pose of vehicle**
[$x$, $y$, $\Theta$] vector

This property is read-only.

Goal pose of the vehicle at the end of the path segment, specified as an [$x$, $y$, $\Theta$] vector. $x$ and $y$ are in meters. $\Theta$ is in radians.

Data Types: `double`

**`MotionLengths` — Length of each motion**
five-element numeric vector

This property is read-only.

Length of each motion in the path segment, specified as a five-element numeric vector in meters. Each motion length corresponds to a motion type specified in `MotionTypes`.

Data Types: `double`

**`MotionTypes` — Type of each motion**
five-element string cell array

This property is read-only.

Type of each motion in the path segment, specified as a five-element string cell array.

| Motion Type | Description |
| --- | --- |
| `"S"` | Straight (forward, `p` or reverse, `n`) |
| `"L"` | Left turn at the maximum steering angle of the vehicle (forward, `p` or reverse, `n`) |
| `"R"` | Right turn at the maximum steering angle of the vehicle (forward, `p` or reverse, `n`) |
| `"N"` | No motion |

If a path segment has fewer than five motion types, the remaining elements are `"N"` (no motion).

Example: `{"L","S","R","L","R"}`

Data Types: `cell`

**`MotionDirections` — Direction of each motion**
five-element vector of 1s (forward motion) and –1s (reverse motion)

This property is read-only.

Direction of each motion in the path segment, specified as a five-element vector of 1s (forward motion) and –1s (reverse motion). Each motion direction corresponds to a motion length specified in `MotionLengths` and a motion type specified in `MotionTypes`.

When no motion occurs, that is, when a `MotionTypes` value is `"N"`, then the corresponding `MotionDirections` element is `1`.

Example: `[-1 1 -1 1 1]`

Data Types: `double`

**`Length` — Length of path segment**
positive scalar

This property is read-only.

Length of the path segment, specified as a positive scalar in meters. This length is just a sum of the elements in `MotionLengths`.

Data Types: `double`

## Object Functions

| | |
|---|---|
| interpolate | Interpolate poses along path segment |
| show | Visualize path segment |

## Examples

### Connect Poses Using ReedsShepp Connection Path

Create a `reedsSheppConnection` object.

```
reedsConnObj = reedsSheppConnection;
```

Define start and goal poses as `[x y theta]` vectors.

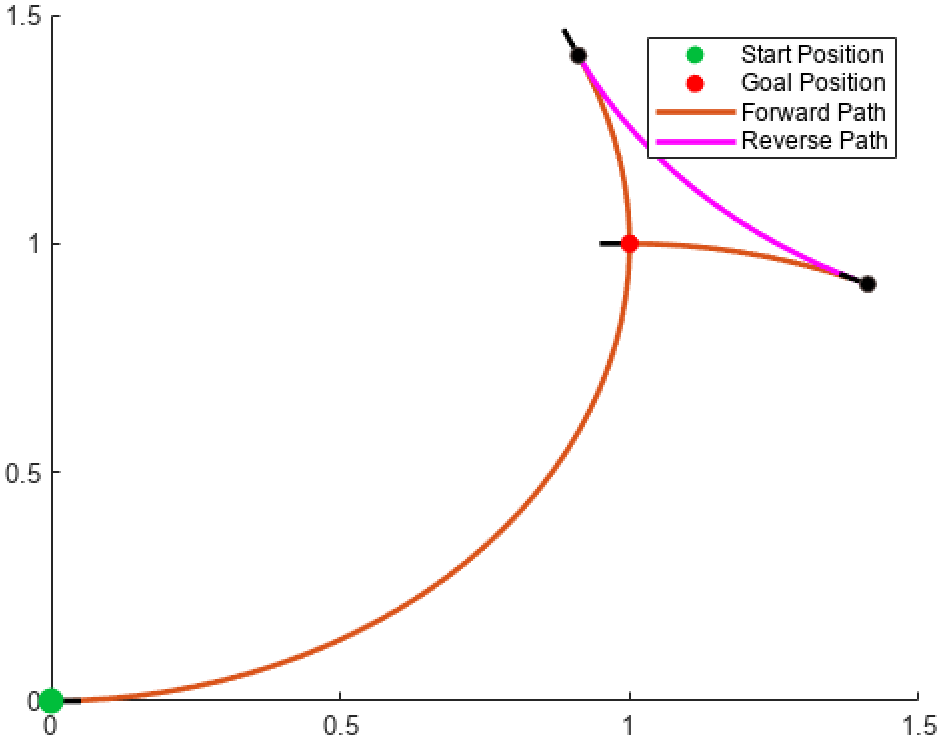
```
startPose = [0 0 0];
goalPose = [1 1 pi];
```

Calculate a valid path segment to connect the poses.

```
[pathSegObj,pathCosts] = connect(reedsConnObj,startPose,goalPose);
```

Show the generated path.

```
show(pathSegObj{1})
```




# Version History

**Introduced in R2019b**

## References

[1] Reeds, J. A., and L. A. Shepp. "Optimal Paths for a Car That Goes Both Forwards and Backwards." *Pacific Journal of Mathematics*. Vol. 145, Number 2, 1990, pp. 367–393.

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
`reedsSheppConnection` | `dubinsConnection` | `dubinsPathSegment`

**Functions**
`interpolate` | `show` | `connect`

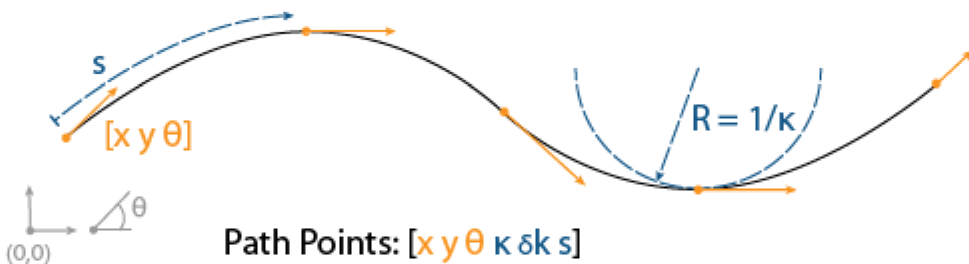
# referencePathFrenet

Smooth reference path fit to waypoints

## Description

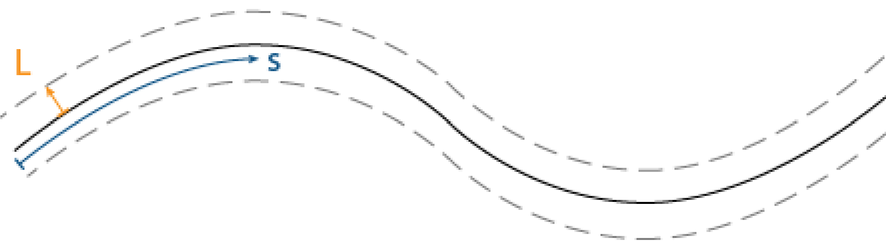
The `referencePathFrenet` object fits a smooth, piecewise, continuous curve to a set of waypoints given as `[x y]` or `[x y theta]`. After fitting, points along the curve, the path points are expressed as `[x y theta kappa dkappa s]`, where:

- *x y* and *theta*— SE(2) state expressed in global coordinates, with *x* and *y* in meters and *theta* in radians
- *kappa* — Curvature, or inverse of the radius, in $m^{-1}$
- *dkappa* — Derivative of curvature with respect to arc length in $m^{-2}$
- *s* — Arc length, or distance along path from path origin, in meters




Using this object, convert trajectories between global and Frenet coordinate systems, interpolate states along the path based on arc length, and query the closest point on a path from a global state.

The object expresses Frenet states as a vector of form `[S dS ddS L dL ddL]`, where *S* is the arc length and *L* is the perpendicular deviation from the direction of the reference path. Derivatives of *S* are relative to time. Derivatives of *L* are relative to the arc length, *S*.



# Creation

## Syntax

```
refPathObj = referencePathFrenet(waypoints)
refPathObj = referencePathFrenet( ___ ,Name,Value)
```

### Description

`refPathObj = referencePathFrenet(waypoints)` fits a piecewise, continuous set of curves to the specified waypoints. The `waypoints` argument sets the `Waypoints` property.

`refPathObj = referencePathFrenet( ___ ,Name,Value)` sets properties using one or more name-value pair arguments in addition to the input arguments in the previous syntax. You can specify the DiscretizationDistance and MaxNumWaypoints properties as name-value arguments.

## Properties

**`Waypoints` — Presampled points along path**
*P*-by-2 numeric matrix | *P*-by-3 numeric matrix

Presampled points along the path, specified as a *P*-by-2 matrix with rows of form `[x y]` or *P*-by-3 matrix with rows of form `[x y theta]`. Specify *x* and *y* in meters and *theta* in radians. *P* is the number of presampled points, and must be greater than or equal to two.

Data Types: `single` | `double`

**`PathLength` — Total arclength along the path**
nonnegative scalar

This property is read-only.

Total arclength along the path in meters.

Data Types: `single` | `double`

**`SegmentParameters` — Clothoid parameters at start of segments**
*N*-by-6 matrix

This property is read-only.

Clothoid parameters at start of segments, specified as an *N*-by-6 matrix where *N* is the total number of waypoints. Each row contains the parameters of the clothoidal segment to connect to the next consecutive waypoint and is in the form `[x y theta kappa dkappa s]` where:

- *x y* and *theta* — SE(2) state expressed in global coordinates, with *x* and *y* in meters and *theta* in radians
- *kappa* — Curvature, or inverse of the radius, in $m^{-1}$
- *dkappa* — Derivative of curvature with respect to arc length in $m^{-2}$
- *s* — Arc length, or distance along path from path origin, in meters

Data Types: `single` | `double`

**`DiscretizationDistance` — Arc length between interpolated path points**
`0.05` (default) | positive scalar

Arc length between interpolated path points, specified as a positive scalar in meters. The object uses interpolated path points to accelerate performance of the transformation functions `frenet2global` and `global2frenet`. A smaller discretization distance can improve accuracy at the expense of memory and computational efficiency.

Example: `refPath = referencePathFrenet(waypoints,'DiscretizationDistance',0.4)`

Data Types: `single` | `double`

**`MaxNumWaypoints` — Maximum waypoints allowed in path**
`Inf` (default) | positive integer

Maximum number of waypoints allowed in the path, specified as either `Inf` for resizeable path or a positive integer to enforce a static limit.

If `MaxNumWaypoints` is set to `Inf`, to generate code, `DynamicMemoryAllocation` must be set to `'on'`.

Example: `refPath = referencePathFrenet(waypoints,'MaxNumWaypoints',10)`

Data Types: `single` | `double`

## Object Functions

| | |
|---|---|
| closestPoint | Find closest point on reference path to global point |
| closestPointsToSequence | Projects sequence of points onto path |
| closestProjections | Find orthogonal projections between path tangent vector and query point |
| curvature | Return curvature at arclength |
| changeInCurvature | Return change-in-curvature at arclength |
| frenet2global | Convert Frenet states to global states |
| global2frenet | Convert global states to Frenet states |
| interpolate | Interpolate reference path at provided arc lengths |
| position | Return xy-position at arclength |
| tangentAngle | Return tangent angle at arclength |
| show | Display reference path in figure |

## Examples

### Generate Alternative Trajectories for Reference Path

Generate alternative trajectories for a reference path using Frenet coordinates. Specify different initial and terminal states for your trajectories. Tune your states based on the generated trajectories.

Generate a reference path from a set of waypoints. Create a `trajectoryGeneratorFrenet` object from the reference path.

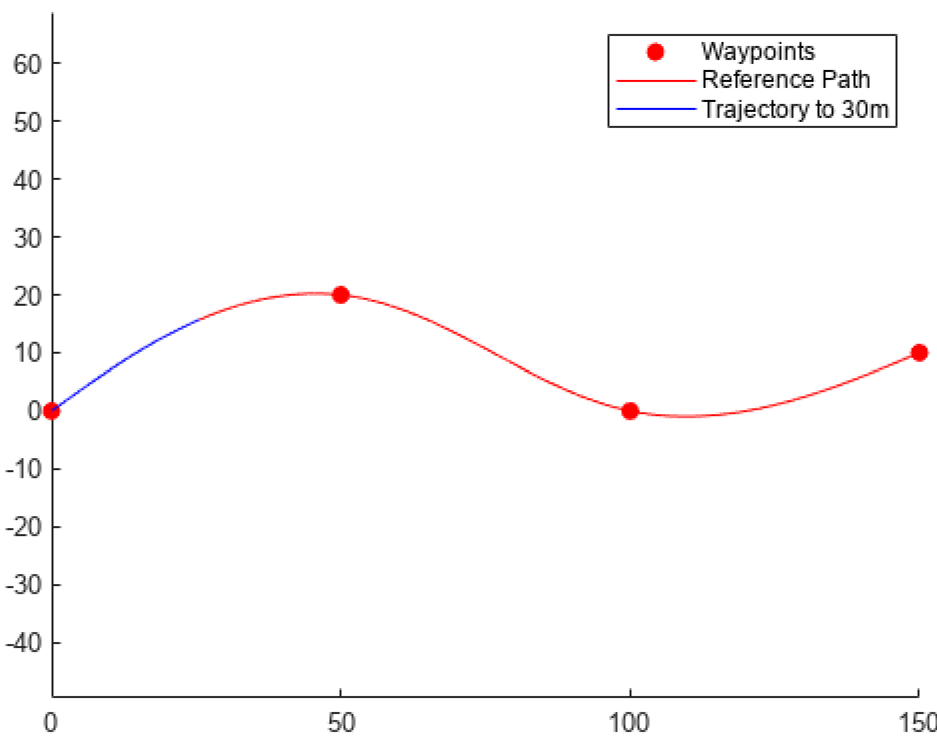
```
waypoints = [0 0; ...
    50 20; ...
    100 0; ...
    150 10];
refPath = referencePathFrenet(waypoints);
connector = trajectoryGeneratorFrenet(refPath);
```

Generate a five-second trajectory between the path origin and a point 30 m down the path as Frenet states.

```
initState = [0 0 0 0 0 0];  % [S ds ddS L dL ddL]
termState = [30 0 0 0 0 0]; % [S ds ddS L dL ddL]
[~,trajGlobal] = connect(connector,initState,termState,5);
```

Display the trajectory in global coordinates.

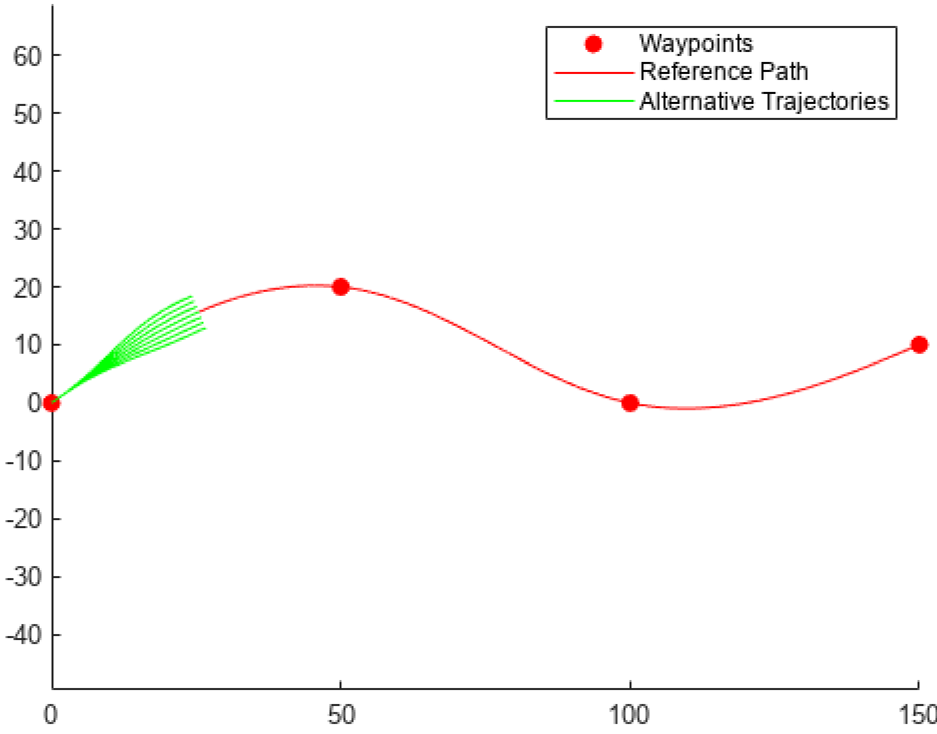
```
show(refPath);
hold on
axis equal
plot(trajGlobal.Trajectory(:,1),trajGlobal.Trajectory(:,2),'b')
legend(["Waypoints","Reference Path","Trajectory to 30m"])
```




Create a matrix of terminal states with lateral deviations between –3 m and 3 m. Generate trajectories that cover the same arc length in 10 seconds, but deviate laterally from the reference path. Display the new alternative paths.

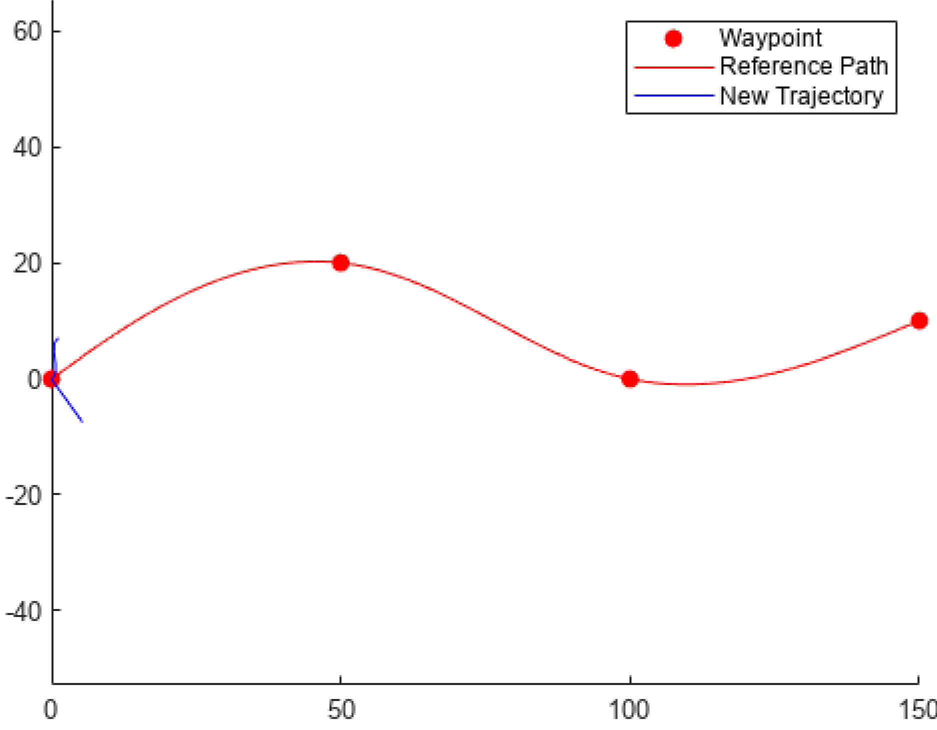
```
termStateDeviated = termState + ([-3:3]' * [0 0 0 1 0 0]);
[~,trajGlobal] = connect(connector,initState,termStateDeviated,10);

clf
show(refPath);
hold on
axis equal
for i = 1:length(trajGlobal)
    plot(trajGlobal(i).Trajectory(:,1),trajGlobal(i).Trajectory(:,2),'g')
```

```
end
legend(["Waypoints","Reference Path","Alternative Trajectories"])
hold off
```



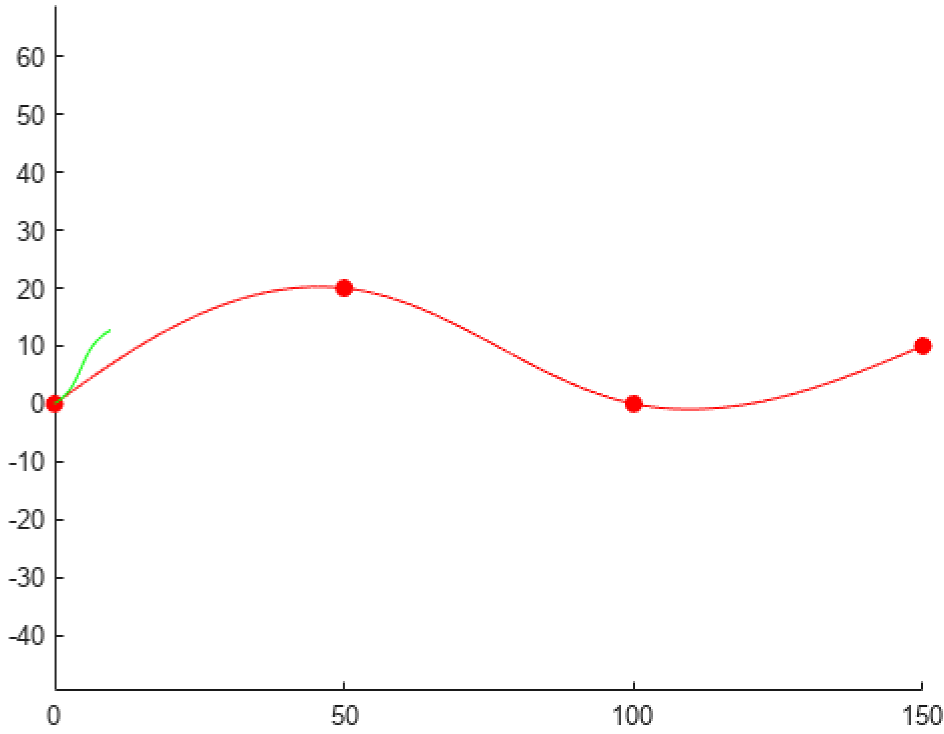

Specify a new terminal state to generate a new trajectory. This trajectory is not desirable because it requires reverse motion to achieve a lateral velocity of 10 m/s.

```
newTermState = [5 10 0 5 0 0];
[~,newTrajGlobal] = connect(connector,initState,newTermState,3);

clf
show(refPath);
hold on
axis equal
plot(newTrajGlobal.Trajectory(:,1),newTrajGlobal.Trajectory(:,2),'b');
legend(["Waypoint","Reference Path","New Trajectory"])
hold off
```




Relax the restriction on the longitudinal state by specifying an arc length of `NaN`. Generate and display the trajectory again. The new position shows a good alternative trajectory that deviates off the reference path.

```
relaxedTermState = [NaN 10 0 5 0 0];
[~,trajGlobalRelaxed] = connect(connector,initState,relaxedTermState,3);

clf
show(refPath);
hold on
axis equal
plot(trajGlobalRelaxed.Trajectory(:,1),trajGlobalRelaxed.Trajectory(:,2),'g');
hold off
```




# Version History

**Introduced in R2020b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

Starting in MATLAB **R**2022**a**, default behavior for `referencePathFrenet` has changed which may result in backwards compatibility issues. `referencePathFrenet` now supports fixed-size code generation (`DynamicMemoryAllocation="off"`). To restore previous behavior, the `MaxNumWaypoints` property and `DynamicMemoryAllocation` must be set to `Inf` and `'on'` respectively.

- If `MaxNumWaypoints` is specified, the returned path is variably-sized but the maximum size of the path is set is by the `MaxNumWaypoints` property, regardless of `DynamicMemoryAllocation`.
- If `DynamicMemoryAllocation` is set to `'on'` and:
  - If waypoints are compile-time constant, then the returned path is fixed-size.
  - If waypoints are variably-sized, then the returned path is variably-sized and unbounded.
- If `DynamicMemoryAllocation` is set to `'on'` and:

- If waypoints are fixed-sized, then the returned path is fixed-size.
- If waypoints are variably sized without specifying `MaxNumWaypoints`, then the path is invalid and causes an error.

## See Also

**Objects**
`trajectoryGeneratorFrenet` | `navPath`

**Functions**
`closestPoint` | `frenet2global` | `global2frenet` | `interpolate` | `show`

**Topics**
"Highway Trajectory Planning Using Frenet Reference Path"

# changeInCurvature

Return change-in-curvature at arclength

## Syntax

```
dkappa = changeInCurvature(refPath,S)
```

## Description

`dkappa = changeInCurvature(refPath,S)` calculates the change-in-curvature with respect to change-in-arclength, `dkappa`, of the reference path at a given arclength, `S`.

## Input Arguments

**`refPath` — Reference path**
`referencePathFrenet` object

Reference path, specified as a `referencePathFrenet` object.

**`S` — Path arclengths**
*N*-element column vector

Path arclengths, specified as an *N*-element column vector in meters, where *N* is the total number of desired arclengths to calculate.

## Output Arguments

**dkappa — Change-in-curvature angles**
*N*-element vector

Change-in-curvature angles, specified as an *N*-element vector in radians, where *N* is the total number of desired arclengths to calculate.

# Version History

**Introduced in R2022a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
`referencePathFrenet` | `trajectoryGeneratorFrenet` | `navPath`

**Functions**
`frenet2global` | `global2frenet` | `closestPoint` | `closestPointsToSequence` | `closestProjections` | `curvature` | `tangentAngle` | `interpolate` | `position` | `show`

**Topics**
"Highway Trajectory Planning Using Frenet Reference Path"

# closestPoint

Find closest point on reference path to global point

## Syntax

```
pathPoints = closestPoint(refPath,points)
[pathPoints,inWindow] = closestPoint(refPath,points)
[_] = closestPoint(refPath,points,searchWindow)
```

## Description

`pathPoints = closestPoint(refPath,points)` finds the closest point on the reference path to each of the specified (*x*,*y*)-positions `points`.

`[pathPoints,inWindow] = closestPoint(refPath,points)` optionally returns a logical vector `inWindow`, specifying whether each point for the corresponding *xy* coordinate in `points` is projected within the search window..

`[_] = closestPoint(refPath,points,searchWindow)` optionally accepts a nondecreasing row vector `searchWindow`, which defines the interval of the path to use to find the closest points.

## Examples

### Generate Trajectory from Reference Path

Generate a reference path from a set of waypoints.

```
waypoints = [0 0; 50 20; 100 0; 150 10];
refPath = referencePathFrenet(waypoints);
```

Create a `trajectoryGeneratorFrenet` object from the reference path.

```
connector = trajectoryGeneratorFrenet(refPath);
```

Generate a five-second trajectory between the path origin and a point 30 meters down the path as Frenet states.

```
initCartState = refPath.SegmentParameters(1,:);
initFrenetState = global2frenet(refPath,initCartState);
termFrenetState = initFrenetState + [30 zeros(1,5)];
frenetTraj = connect(connector,initFrenetState,termFrenetState,5);
```

Convert the trajectory to the global states.

```
globalTraj = frenet2global(refPath,frenetTraj.Trajectory);
```

Display the reference path and the trajectory.

```
show(refPath);
axis equal
```

```
hold on
plot(globalTraj(:,1),globalTraj(:,2),'b')
```

Specify global points and find the closest points on reference path.

```
globalPoints = waypoints(2:end,:) + [20 -50];
nearestPathPoint = closestPoint(refPath,globalPoints);
```

Display the global points and the closest points on reference path.

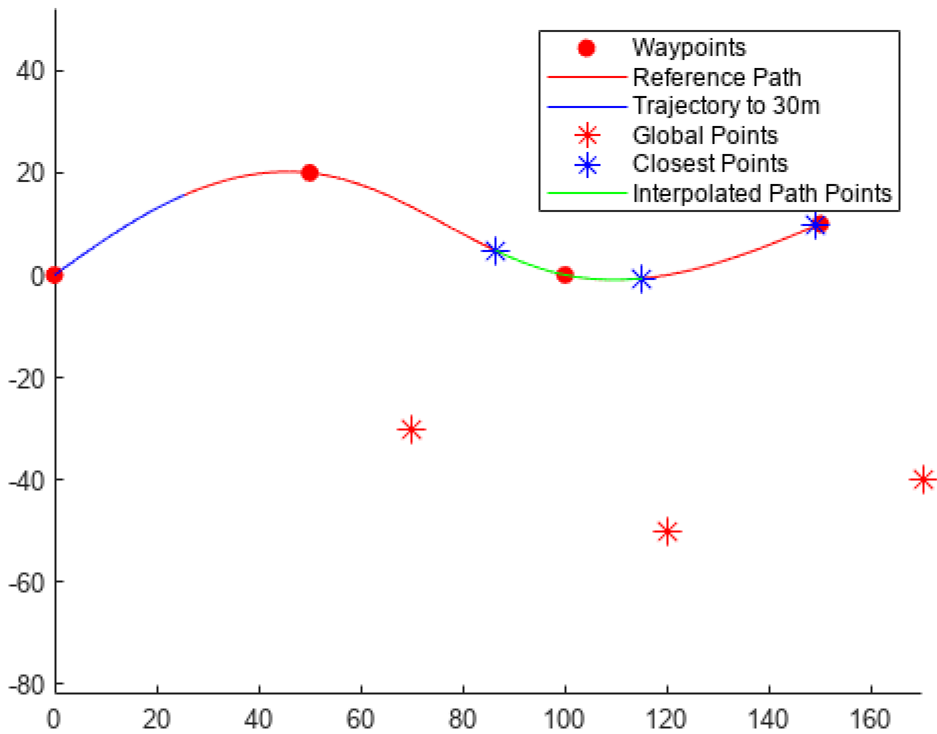
```
plot(globalPoints(:,1),globalPoints(:,2),'r*','MarkerSize',10)
plot(nearestPathPoint(:,1),nearestPathPoint(:,2),'b*','MarkerSize',10)
```

Interpolate between the arc lengths of the first two closest points along the reference path.

```
arclengths = linspace(nearestPathPoint(1,6),nearestPathPoint(2,6),10);
pathStates = interpolate(refPath,arclengths);
```

Display the interpolated path points.

```
plot(pathStates(:,1),pathStates(:,2),'g')
legend(["Waypoints","Reference Path","Trajectory to 30m",...
        "Global Points","Closest Points","Interpolated Path Points"])
```



## Input Arguments

**`refPath` — Reference path**
`referencePathFrenet` object

Reference path, specified as a `referencePathFrenet` object.

**`points` — Global points**
*P*-by-2 numeric matrix

Global points, specified as a *P*-by-2 numeric matrix with rows of the form `[x y]`. *P* is the number of points. Positions are in meters.

**`searchWindow` — Search window**
two-element row vector

Search window on path to determine closest points, specified as an two-element row vector.

## Output Arguments

**`pathPoints` — Closest points on reference path**
*N*-by-6 numeric matrix

Closest points on the reference path , returned as an *N*-by-6 numeric matrix with rows of form `[x y theta kappa dkappa s]`, where:

- *x y* and *theta* — SE(2) state expressed in global coordinates, with *x* and *y* in meters and *theta* in radians
- *kappa* — Curvature, or inverse of the radius, in $m^{-1}$
- *dkappa* — Derivative of curvature with respect to arc length in $m^{-2}$
- *s* — Arc length, or distance along path from path origin, in meters

*N* is the number of points sampled along the reference path.

**`inWindow` — Indicator of points being in search window**
*N*-element logical column vector

Indication whether each point nearest to the corresponding *xy* coordinate in `points`, is projected within the search window, returned as an *N*-element logical column vector, where *N* is the number of points in `points`. Points being projected within the search window are `true`, or `false` if they lie at the end of a window.

# Version History

**Introduced in R2020b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
referencePathFrenet | trajectoryGeneratorFrenet | navPath

**Functions**
frenet2global | global2frenet | closestPointsToSequence | closestProjections | curvature | changeInCurvature | tangentAngle | interpolate | position | show

**Topics**
"Highway Trajectory Planning Using Frenet Reference Path"

# closestPointsToSequence

Projects sequence of points onto path

## Syntax

```
pathPoints = closestPointsToSequence(refPath,points,initWindow)
[pathPoints,inWindow] = closestPointsToSequence(refPath,points,initWindow)
```

## Description

`pathPoints = closestPointsToSequence(refPath,points,initWindow)` uses the closest point within a sequence of points, `points`, to be within the valid search window, `initWindow`. For each point in `Points`, the search window is centered at the previous point.

`[pathPoints,inWindow] = closestPointsToSequence(refPath,points,initWindow)` optionally returns a logical vector `inWindow`, specifying whether each point for the corresponding *xy* coordinate in `points` is projected within the search window.

## Input Arguments

**`refPath` — Reference path**
`referencePathFrenet` object

Reference path, specified as a `referencePathFrenet` object.

**`points` — Global points**
*P*-by-2 numeric matrix

Global points, specified as a *P*-by-2 numeric matrix with rows of the form `[x y]`. *P* is the number of points. Positions are in meters.

**`initWindow` — Initial search window**
two-element row vector

Initial search window, specified as a two-element row vector in the form `[minimum_bound maximum_bound]` .

## Output Arguments

**`pathPoints` — Closest points on reference path**
*N*-by-6 numeric matrix

Closest points on the reference path , returned as an *N*-by-6 numeric matrix with rows of form `[x y theta kappa dkappa s]`, where:

- *x y* and *theta* — SE(2) state expressed in global coordinates, with *x* and *y* in meters and *theta* in radians
- *kappa* — Curvature, or inverse of the radius, in $m^{-1}$

- *dkappa* — Derivative of curvature with respect to arc length in $m^{-2}$
- *s* — Arc length, or distance along path from path origin, in meters

*N* is the number of points sampled along the reference path.

**`inWindow` — Indicator of points being in search window**
*N*-element logical column vector

Indication whether each point nearest to the corresponding *xy* coordinate in `points`, is projected within the search window, returned as an *N*-element logical column vector, where *N* is the number of points in `points`. Points being projected within the search window are `true`, or `false` if they lie at the end of a window.

# Version History

**Introduced in R2022a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Objects

`referencePathFrenet` | `trajectoryGeneratorFrenet` | `navPath`

### Functions

`frenet2global` | `global2frenet` | `closestPoint` | `closestProjections` | `curvature` | `changeInCurvature` | `tangentAngle` | `interpolate` | `position` | `show`

### Topics

"Highway Trajectory Planning Using Frenet Reference Path"

# closestProjections

Find orthogonal projections between path tangent vector and query point

## Syntax

```
[arclengths,distances] = closestProjections(refPath,points)
[ ___ ,projPoints] = closestProjections(refPath,points)
[ ___ ] = closestProjections(refPath,points,bestN)
[ ___ ] = closestProjections(refPath,points,intervals)
[ ___ ] = closestProjections(refPath,points,intervals,bestN)
```

## Description

`[arclengths,distances] = closestProjections(refPath,points)` attempts to project each *xy* point in the *points* matrix, onto each clothoid segment contained in the reference path, `refPath`, such that the projection vector is orthogonal to the path tangent-angle. Returns closest orthogonal projection between the curve and query point in each segment as a pair of two cell arrays, `arclengths` and `distances` containing the arclengths and distances respectively.

`[ ___ ,projPoints] = closestProjections(refPath,points)` optionally returns the projected points, `projPoints` as a cell array containing path data evaluated at the corresponding arclengths element.

`[ ___ ] = closestProjections(refPath,points,bestN)` returns the nearest projections, `bestN`for each *xy* point in `points`.

`[ ___ ] = closestProjections(refPath,points,intervals)` accepts an optional matrix of arclengths intervals, `intervals`, where each row contains a lower and upper arclength bounds.

`[ ___ ] = closestProjections(refPath,points,intervals,bestN)` returns up to the nearest projections `bestN` for each *xy* point in `points`.

## Input Arguments

**`refPath` — Reference path**
`referencePathFrenet` object

Reference path, specified as a `referencePathFrenet` object.

**`points` — Global points**
*P*-by-2 numeric matrix

Global points, specified as a *P*-by-2 numeric matrix with rows of the form `[x y]`. *P* is the number of points. Positions are in meters.

**`bestN` — Best *N* projections**
scalar in the range [1,*N*]

Best *N* projections, specified as a scalar in the range [1,*N*], where *N* is the number of segments in the path.

### `intervals` — Arclength intervals

*N*-by-2 matrix

Arclength intervals, specified as a *N*-by-2 matrix, where each row is of the form [*minimum_arclength*, *maximum_arclength*] in meters, and *N* is the number of segments in the path.

## Output Arguments

### `arclengths` — Arclengths between curve and query points

*M*-element cell array

Arclengths between curve and query points, returned as an *M*-element cell array, where *M* is the number of query points in the `points` input. Each cell contains a *P*-element column vector, where *P* is in the range [0,*N*] and *N* is the number of segments in the path.

### `distances` — Distances between curve and query points

*M*-element cell array

Distances between curve and query points, returned as an *M*-element cell array, where *M* is the number of query points in the `points` input. Each cell contains a *P*-element column vector, where *P* is in the range [0,*N*] and *N* is the number of segments in the path.

### `projPoints` — Projected points

*M*-element cell array

Projected points, returned as an *M*-element cell array, where *M* is the number of query points in the `points` input. Each cell contains a *P*-by-6 matrix, where *P* is in the range [0,*N*] and each row is in the form [*x y theta k dk s*]. *x*, *y*, *theta*, *k*, *dk*, *s*, are the x and y positions, tangent angle, curvature, change in curvature, at the arclength, *s*, respectively.

# Version History

**Introduced in R2022a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Objects

`referencePathFrenet` | `trajectoryGeneratorFrenet` | `navPath`

### Functions

`frenet2global` | `global2frenet` | `closestPoint` | `closestPointsToSequence` | `curvature` | `changeInCurvature` | `tangentAngle` | `interpolate` | `position` | `show`

### Topics

"Highway Trajectory Planning Using Frenet Reference Path"

# curvature

Return curvature at arclength

## Syntax

```
kappa = curvature(refPath,S)
```

## Description

`kappa = curvature(refPath,S)` calculates the curvature angle, `kappa` of the reference path at a given arclength, `S`.

## Input Arguments

### `refPath` — Reference path

`referencePathFrenet` object

Reference path, specified as a `referencePathFrenet` object.

### S — Path arclengths

*N*-element column vector

Path arclengths, specified as an *N*-element column vector in meters, where *N* is the total number of desired arclengths to calculate.

## Output Arguments

### kappa — Curvature angles

*N*-element vector

Change-in-curvature angles, specified as an *N*-element vector in radians, where *N* is the total number of desired arclengths to calculate.

# Version History

**Introduced in R2022a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Objects

`referencePathFrenet` | `trajectoryGeneratorFrenet` | `navPath`

**Functions**
`frenet2global` | `global2frenet` | `closestPoint` | `closestPointsToSequence` | `closestProjections` | `changeInCurvature` | `tangentAngle` | `interpolate` | `position` | `show`

**Topics**
"Highway Trajectory Planning Using Frenet Reference Path"

# frenet2global

Convert Frenet states to global states

## Syntax

```
globalState = frenet2global(refPath,frenetState)
globalState = frenet2global(refPath,frenetState,latTimeDerivatives)
```

## Description

`globalState = frenet2global(refPath,frenetState)` converts Frenet trajectory states to global states.

`globalState = frenet2global(refPath,frenetState,latTimeDerivatives)` accepts `latTimeDerivatives` containing 1st and 2nd order derivatives of lateral deviation with respect to time and a flag indicating if the heading should flip during the conversion to global coordinates.

## Examples

### Generate Trajectory from Reference Path

Generate a reference path from a set of waypoints.

```
waypoints = [0 0; 50 20; 100 0; 150 10];
refPath = referencePathFrenet(waypoints);
```

Create a `trajectoryGeneratorFrenet` object from the reference path.

```
connector = trajectoryGeneratorFrenet(refPath);
```

Generate a five-second trajectory between the path origin and a point 30 meters down the path as Frenet states.

```
initCartState = refPath.SegmentParameters(1,:);
initFrenetState = global2frenet(refPath,initCartState);
termFrenetState = initFrenetState + [30 zeros(1,5)];
frenetTraj = connect(connector,initFrenetState,termFrenetState,5);
```

Convert the trajectory to the global states.

```
globalTraj = frenet2global(refPath,frenetTraj.Trajectory);
```

Display the reference path and the trajectory.

```
show(refPath);
axis equal
hold on
plot(globalTraj(:,1),globalTraj(:,2),'b')
```

Specify global points and find the closest points on reference path.

```
globalPoints = waypoints(2:end,:) + [20 -50];
nearestPathPoint = closestPoint(refPath,globalPoints);
```

Display the global points and the closest points on reference path.

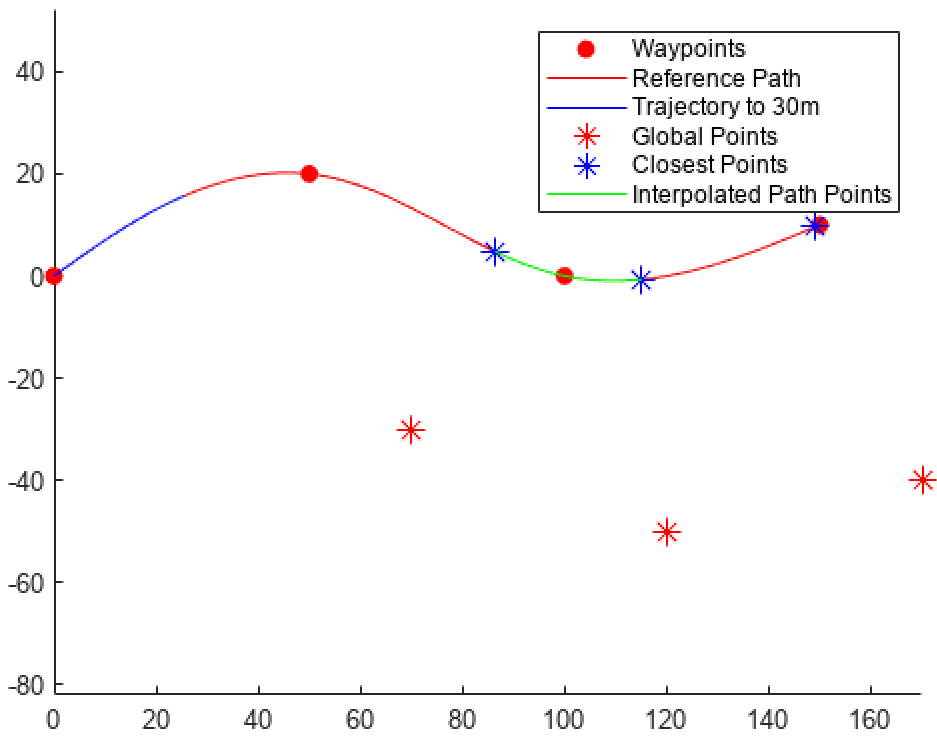
```
plot(globalPoints(:,1),globalPoints(:,2),'r*','MarkerSize',10)
plot(nearestPathPoint(:,1),nearestPathPoint(:,2),'b*','MarkerSize',10)
```

Interpolate between the arc lengths of the first two closest points along the reference path.

```
arclengths = linspace(nearestPathPoint(1,6),nearestPathPoint(2,6),10);
pathStates = interpolate(refPath,arclengths);
```

Display the interpolated path points.

```
plot(pathStates(:,1),pathStates(:,2),'g')
legend(["Waypoints","Reference Path","Trajectory to 30m",...
        "Global Points","Closest Points","Interpolated Path Points"])
```




## Input Arguments

**refPath — Reference path**
referencePathFrenet object

Reference path, specified as a `referencePathFrenet` object.

**`frenetState` — States in Frenet coordinate frame**
*P*-by-6 numeric matrix

States in the Frenet coordinate frame, returned as a *P*-by-6 numeric matrix with rows of form `[S dS ddS L dL ddL]`, where `S` is the arc length and `L` is the perpendicular deviation from the direction of the reference path. Derivatives of `S` are relative to time. Derivatives of `L` are relative to the arc length, `S`. *P* is the total number of Frenet states.

**`latTimeDerivatives` — Lateral time derivatives**
*N*-by-3 matrix

Lateral time derivatives, specified as an *N*-by-3 matrix where each row is of the form [*dL/dt ddL/dt^2 invertHeading*] and *N* is the total number of points in `points`. Each row contains the 1st and 2nd order time derivatives of lateral deviation and a flag, *invertHeading*, which indicates whether the heading should be flipped when converting to global coordinates (`true`) or not (`false`).

---

**Note** If defining `latTimeDerivatives` without the use of `global2frenet`, the following rules should be followed:

1. The *invertHeading* flag should be true when:
   a. The vehicle is moving in reverse (speed is less than 0)
   b. The vehicle is stationary (speed is equal to 0), and the vehicle is facing away from the path's tangent vector. i.e. cos(|tangentAngle(obj,S)-thetaExpected|) < 0
2. If 1b is true, then *dL/dS* must be negated.

---

## Output Arguments

**`globalState` — States in global coordinate frame**
*P*-by-6 numeric matrix

States in the global coordinate frame, specified as a *P*-by-6 numeric matrix with rows of form `[x y theta kappa speed accel]`, where:

- *x y* and *theta* –– SE(2) state expressed in global coordinates, with *x* and *y* in meters and *theta* in radians.
- *kappa* –– Curvature, or inverse of the radius, in $m^{-1}$.
- *speed* –– Speed in the `theta` direction in `m/s`.
- *accel* –– Acceleration in the `theta` direction in $m/s^2$.

*P* is the total number of Global states.

# Version History

**Introduced in R2020b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Objects

`referencePathFrenet` | `trajectoryGeneratorFrenet` | `navPath`

### Functions

`global2frenet` | `closestPoint` | `closestPointsToSequence` | `closestProjections` | `curvature` | `changeInCurvature` | `tangentAngle` | `interpolate` | `position` | `show`

### Topics

"Highway Trajectory Planning Using Frenet Reference Path"

# global2frenet

Convert global states to Frenet states

## Syntax

```
frenetState = global2frenet(refPath,globalState)
[ ___ ,latTimeDerivatives] = global2frenet(refPath,globalState)
[ ___ ] = global2frenet(refPath,globalState,sFrame)
```

## Description

`frenetState = global2frenet(refPath,globalState)` converts global states to Frenet trajectory states.

`[ ___ ,latTimeDerivatives] = global2frenet(refPath,globalState)` returns `latTimeDerivatives` containing 1st and 2nd order derivatives of lateral deviation with respect to time and a flag indicating if the heading should flip when converting to global coordinates.

`[ ___ ] = global2frenet(refPath,globalState,sFrame)` accepts a vector of arclengths, `sFrame` at which the Frenet frame should be centered at.

## Examples

### Generate Trajectory from Reference Path

Generate a reference path from a set of waypoints.

```
waypoints = [0 0; 50 20; 100 0; 150 10];
refPath = referencePathFrenet(waypoints);
```

Create a `trajectoryGeneratorFrenet` object from the reference path.

```
connector = trajectoryGeneratorFrenet(refPath);
```

Generate a five-second trajectory between the path origin and a point 30 meters down the path as Frenet states.

```
initCartState = refPath.SegmentParameters(1,:);
initFrenetState = global2frenet(refPath,initCartState);
termFrenetState = initFrenetState + [30 zeros(1,5)];
frenetTraj = connect(connector,initFrenetState,termFrenetState,5);
```

Convert the trajectory to the global states.

```
globalTraj = frenet2global(refPath,frenetTraj.Trajectory);
```

Display the reference path and the trajectory.

```
show(refPath);
axis equal
```

```
hold on
plot(globalTraj(:,1),globalTraj(:,2),'b')
```

Specify global points and find the closest points on reference path.

```
globalPoints = waypoints(2:end,:) + [20 -50];
nearestPathPoint = closestPoint(refPath,globalPoints);
```

Display the global points and the closest points on reference path.

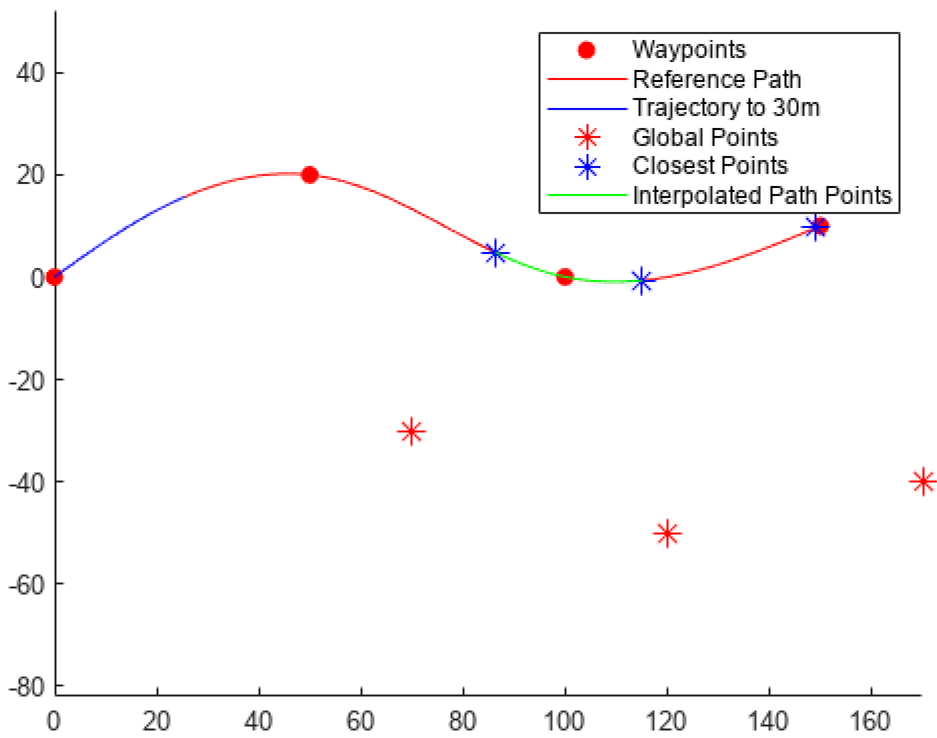
```
plot(globalPoints(:,1),globalPoints(:,2),'r*','MarkerSize',10)
plot(nearestPathPoint(:,1),nearestPathPoint(:,2),'b*','MarkerSize',10)
```

Interpolate between the arc lengths of the first two closest points along the reference path.

```
arclengths = linspace(nearestPathPoint(1,6),nearestPathPoint(2,6),10);
pathStates = interpolate(refPath,arclengths);
```

Display the interpolated path points.

```
plot(pathStates(:,1),pathStates(:,2),'g')
legend(["Waypoints","Reference Path","Trajectory to 30m",...
        "Global Points","Closest Points","Interpolated Path Points"])
```



## Input Arguments

**`refPath` — Reference path**
`referencePathFrenet` object

Reference path, specified as a `referencePathFrenet` object.

**`globalState` — States in global coordinate frame**
*P*-by-6 numeric matrix

States in the global coordinate frame, specified as a *P*-by-6 numeric matrix with rows of form `[x y theta kappa speed accel]`, where:

- *x y* and *theta* –– SE(2) state expressed in global coordinates, with *x* and *y* in meters and *theta* in radians.
- *kappa* –– Curvature, or inverse of the radius, in $m^{-1}$.
- *speed* –– Speed in the `theta` direction in `m/s`.
- *accel* –– Acceleration in the `theta` direction in $m/s^2$.

*P* is the total number of Global states.

**`sFrame` — Arclength frame locations**
*N*-element vector

Arclength center locations for the Frenet frames, specified as an *N*-element vector in meters. For correct results, the vector between the frame and the *xy* location of the `globalState` must be orthogonal to the tangent angle.

## Output Arguments

**`frenetState` — States in Frenet coordinate frame**
*P*-by-6 numeric matrix

States in the Frenet coordinate frame, returned as a *P*-by-6 numeric matrix with rows of form `[S dS ddS L dL ddL]`, where `S` is the arc length and `L` is the perpendicular deviation from the direction of the reference path. Derivatives of `S` are relative to time. Derivatives of `L` are relative to the arc length, `S`. *P* is the total number of Frenet states.

**`latTimeDerivatives` — Lateral time derivatives**
*N*-by-3 matrix

Lateral time derivatives, specified as an *N*-by-3 matrix where each row is of the form [*dL/dt ddL/dt^2 invertHeading*] and *N* is the total number of points in `points`. Each row contains the 1st and 2nd order time derivatives of lateral deviation and a flag, *invertHeading*, which indicates whether the heading should be flipped when converting to global coordinates (`true`) or not (`false`).

---

**Note** If defining `latTimeDerivatives` without the use of `global2frenet`, the following rules should be followed:

1. The *invertHeading* flag should be true when:
   a. The vehicle is moving in reverse (speed is less than 0)

   b. The vehicle is stationary (speed is equal to 0), and the vehicle is facing away from the path's tangent vector. i.e. cos(|tangentAngle(obj,S)-thetaExpected|) < 0
2. If 1b is true, then *dL/dS* must be negated.

---

# Version History

**Introduced in R2020b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Objects

`referencePathFrenet` | `trajectoryGeneratorFrenet` | `navPath`

### Functions

`frenet2global` | `closestPoint` | `closestPointsToSequence` | `closestProjections` | `curvature` | `changeInCurvature` | `tangentAngle` | `interpolate` | `position` | `show`

### Topics

"Highway Trajectory Planning Using Frenet Reference Path"

# interpolate

Interpolate reference path at provided arc lengths

## Syntax

```
pathPoints = interpolate(refPath,arclengths)
```

## Description

`pathPoints = interpolate(refPath,arclengths)` interpolates the reference path at the provided arc lengths and returns the interpolated points on the path in global coordinates.

## Examples

### Generate Trajectory from Reference Path

Generate a reference path from a set of waypoints.

```
waypoints = [0 0; 50 20; 100 0; 150 10];
refPath = referencePathFrenet(waypoints);
```

Create a `trajectoryGeneratorFrenet` object from the reference path.

```
connector = trajectoryGeneratorFrenet(refPath);
```

Generate a five-second trajectory between the path origin and a point 30 meters down the path as Frenet states.

```
initCartState = refPath.SegmentParameters(1,:);
initFrenetState = global2frenet(refPath,initCartState);
termFrenetState = initFrenetState + [30 zeros(1,5)];
frenetTraj = connect(connector,initFrenetState,termFrenetState,5);
```

Convert the trajectory to the global states.

```
globalTraj = frenet2global(refPath,frenetTraj.Trajectory);
```

Display the reference path and the trajectory.

```
show(refPath);
axis equal
hold on
plot(globalTraj(:,1),globalTraj(:,2),'b')
```

Specify global points and find the closest points on reference path.

```
globalPoints = waypoints(2:end,:) + [20 -50];
nearestPathPoint = closestPoint(refPath,globalPoints);
```

Display the global points and the closest points on reference path.

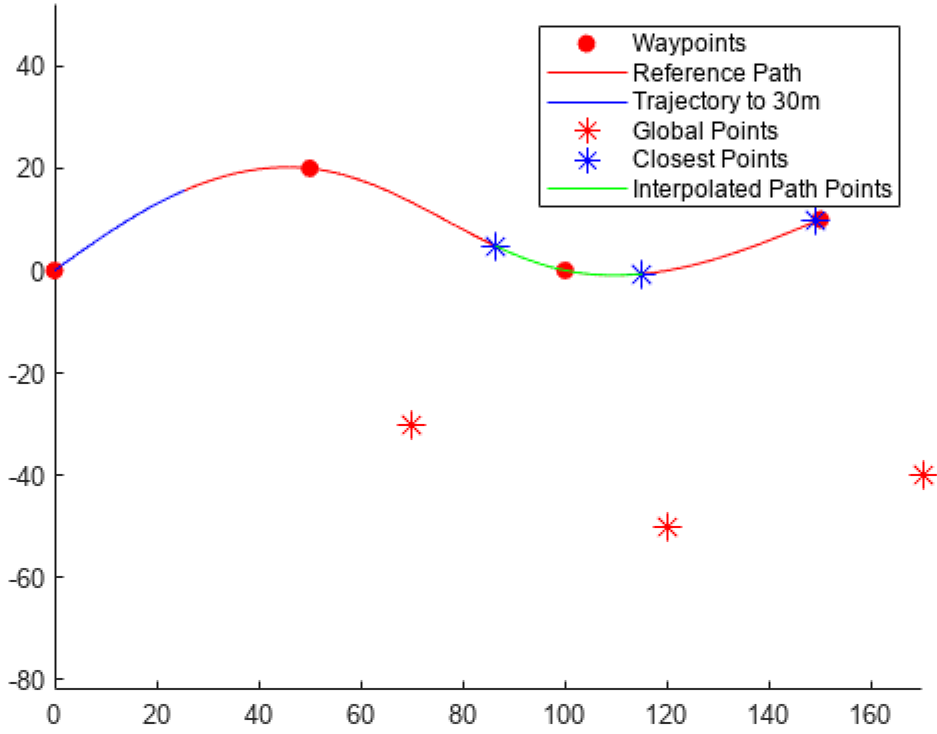
```
plot(globalPoints(:,1),globalPoints(:,2),'r*','MarkerSize',10)
plot(nearestPathPoint(:,1),nearestPathPoint(:,2),'b*','MarkerSize',10)
```

Interpolate between the arc lengths of the first two closest points along the reference path.

```
arclengths = linspace(nearestPathPoint(1,6),nearestPathPoint(2,6),10);
pathStates = interpolate(refPath,arclengths);
```

Display the interpolated path points.

```
plot(pathStates(:,1),pathStates(:,2),'g')
legend(["Waypoints","Reference Path","Trajectory to 30m",...
        "Global Points","Closest Points","Interpolated Path Points"])
```




## Input Arguments

**`refPath` — Reference path**
`referencePathFrenet` object

Reference path, specified as a `referencePathFrenet` object.

**`arclengths` — Distances along reference path**
*N*-element vector

Distances along the reference path, specified as an *N*-element vector. *N* is the number of arc lengths at which to sample points. Each distance is in meters.

## Output Arguments

**`pathPoints` — Points on reference path**
*N*-by-6 numeric matrix

Points on the reference path , returned as an *N*-by-6 numeric matrix with rows of form `[x y theta kappa dkappa s]`, where:

- *x y* and *theta* — SE(2) state expressed in global coordinates, with *x* and *y* in meters and *theta* in radians
- *kappa* — Curvature, or inverse of the radius, in $m^{-1}$
- *dkappa* — Derivative of curvature with respect to arc length in $m^{-2}$
- *s* — Arc length, or distance along path from path origin, in meters

*N* is the number of points sampled along the reference path.

# Version History

**Introduced in R2020b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
`referencePathFrenet` | `trajectoryGeneratorFrenet` | `navPath`

**Functions**
`closestPoint` | `closestPointsToSequence` | `closestProjections` | `curvature` | `changeInCurvature` | `tangentAngle` | `frenet2global` | `global2frenet` | `position` | `show`

**Topics**
"Highway Trajectory Planning Using Frenet Reference Path"

# show

Display reference path in figure

## Syntax

```
show(refPath)
show(refPath,'Parent',parentAx)
ax = show( ___ )
```

## Description

`show(refPath)` displays the reference path and its lateral states in the current figure.

`show(refPath,'Parent',parentAx)` displays the reference path on the specified axes. `parentAx` is specified as an `Axes` handle.

`ax = show( ___ )` displays the reference path using any of the previous input combinations and returns the axes handle on which the reference path is plotted.

## Examples

### Generate Alternative Trajectories for Reference Path

Generate alternative trajectories for a reference path using Frenet coordinates. Specify different initial and terminal states for your trajectories. Tune your states based on the generated trajectories.

Generate a reference path from a set of waypoints. Create a `trajectoryGeneratorFrenet` object from the reference path.

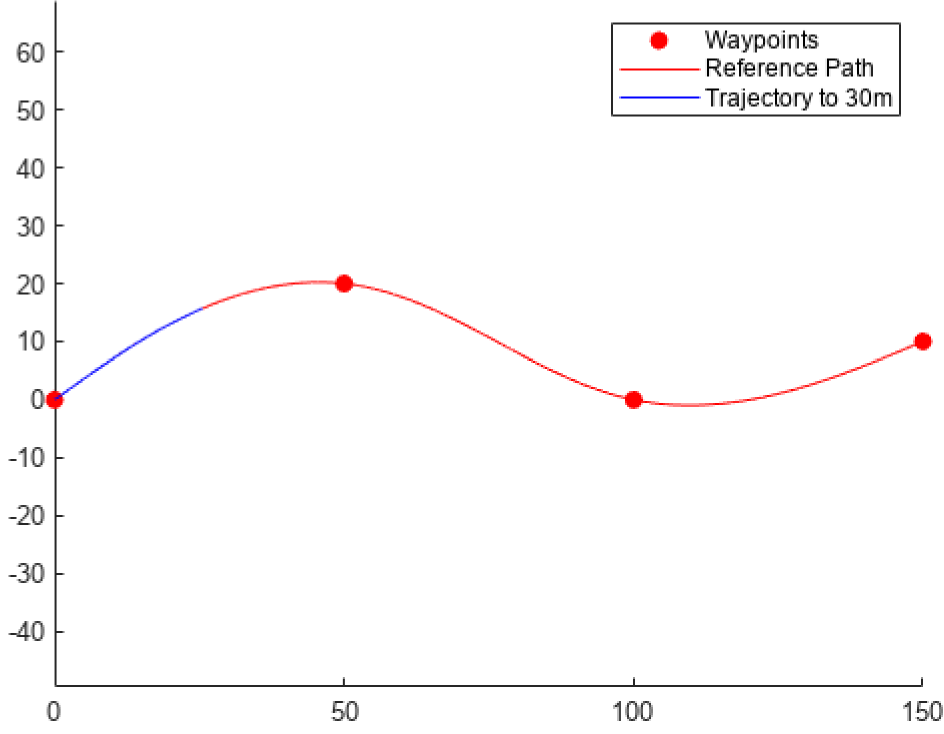
```
waypoints = [0 0; ...
    50 20; ...
    100 0; ...
    150 10];
refPath = referencePathFrenet(waypoints);
connector = trajectoryGeneratorFrenet(refPath);
```

Generate a five-second trajectory between the path origin and a point 30 m down the path as Frenet states.

```
initState = [0 0 0 0 0 0];  % [S ds ddS L dL ddL]
termState = [30 0 0 0 0 0]; % [S ds ddS L dL ddL]
[~,trajGlobal] = connect(connector,initState,termState,5);
```

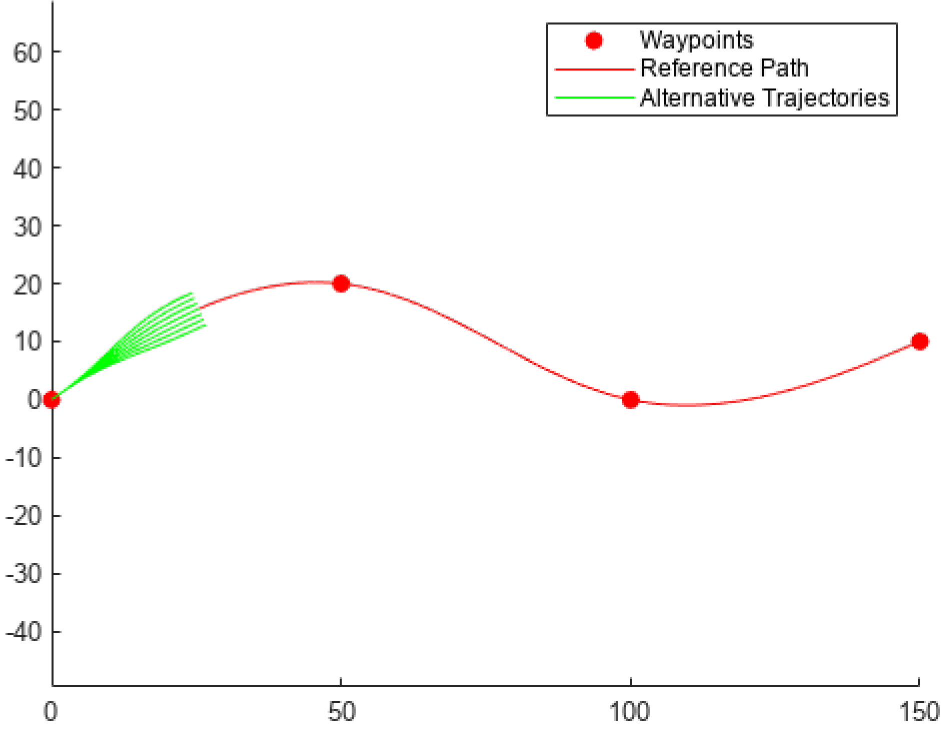
Display the trajectory in global coordinates.

```
show(refPath);
hold on
axis equal
plot(trajGlobal.Trajectory(:,1),trajGlobal.Trajectory(:,2),'b')
legend(["Waypoints","Reference Path","Trajectory to 30m"])
```



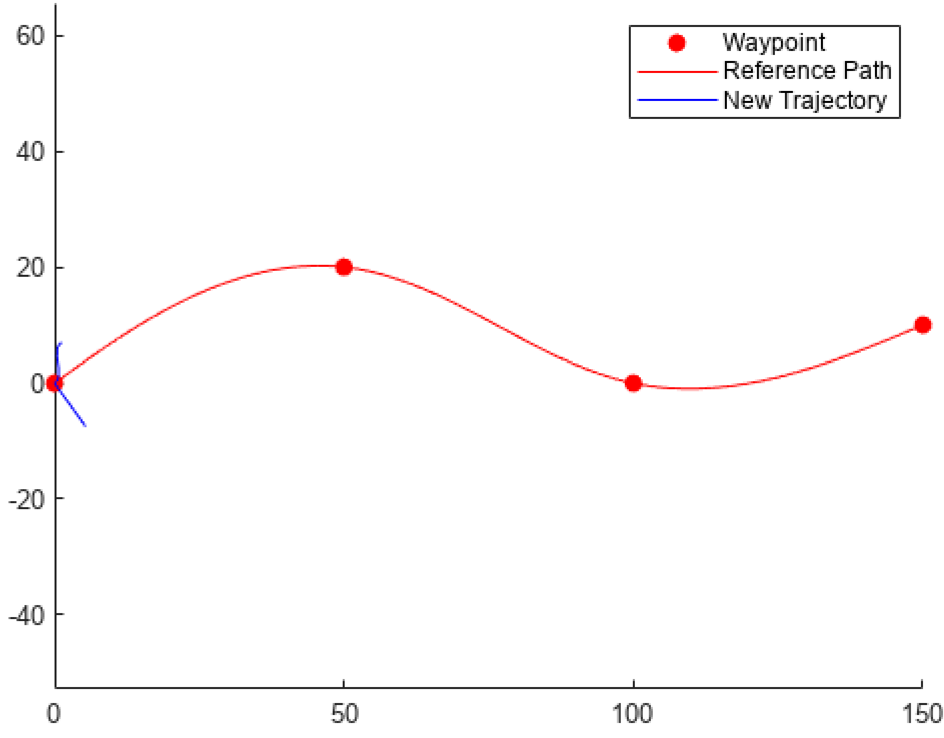

Create a matrix of terminal states with lateral deviations between –3 m and 3 m. Generate trajectories that cover the same arc length in 10 seconds, but deviate laterally from the reference path. Display the new alternative paths.

```
termStateDeviated = termState + ([-3:3]' * [0 0 0 1 0 0]);
[~,trajGlobal] = connect(connector,initState,termStateDeviated,10);

clf
show(refPath);
hold on
axis equal
for i = 1:length(trajGlobal)
    plot(trajGlobal(i).Trajectory(:,1),trajGlobal(i).Trajectory(:,2),'g')
end
legend(["Waypoints","Reference Path","Alternative Trajectories"])
hold off
```



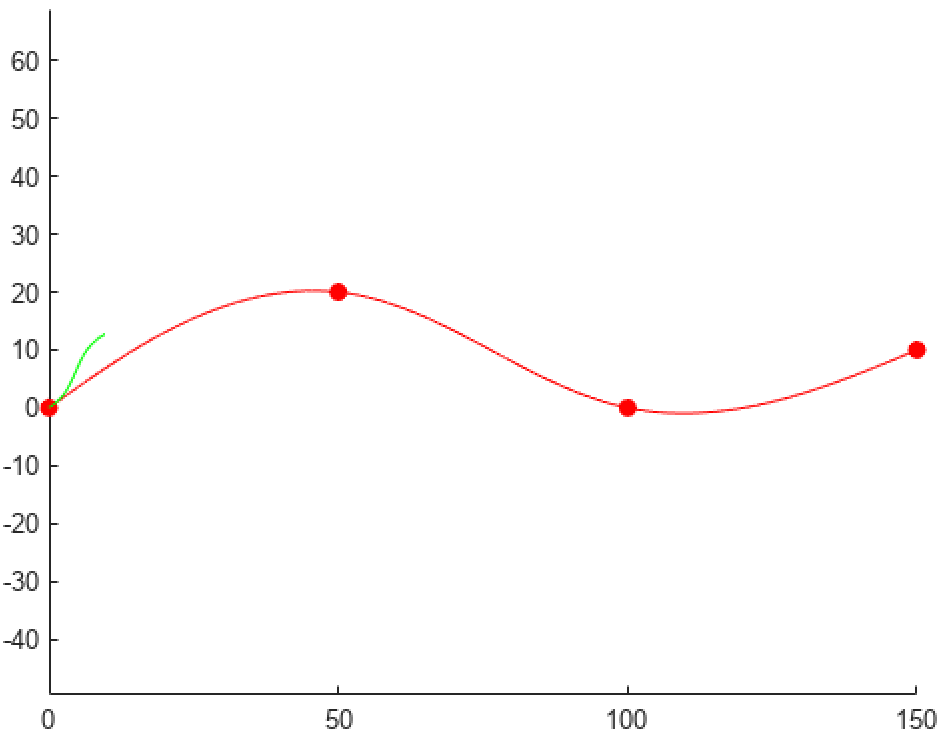

Specify a new terminal state to generate a new trajectory. This trajectory is not desirable because it requires reverse motion to achieve a lateral velocity of 10 m/s.

```
newTermState = [5 10 0 5 0 0];
[~,newTrajGlobal] = connect(connector,initState,newTermState,3);

clf
show(refPath);
hold on
axis equal
plot(newTrajGlobal.Trajectory(:,1),newTrajGlobal.Trajectory(:,2),'b');
legend(["Waypoint","Reference Path","New Trajectory"])
hold off
```




Relax the restriction on the longitudinal state by specifying an arc length of `NaN`. Generate and display the trajectory again. The new position shows a good alternative trajectory that deviates off the reference path.

```
relaxedTermState = [NaN 10 0 5 0 0];
[~,trajGlobalRelaxed] = connect(connector,initState,relaxedTermState,3);

clf
show(refPath);
hold on
axis equal
plot(trajGlobalRelaxed.Trajectory(:,1),trajGlobalRelaxed.Trajectory(:,2),'g');
hold off
```




## Input Arguments

**refPath — Reference path**
referencePathFrenet object

Reference path, specified as a referencePathFrenet object.

## Output Arguments

**ax — Axes on which the reference path is plotted**
Axes handle

Axes on which the reference path is plotted, returned as an Axes handle.

# Version History

**Introduced in R2020b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
referencePathFrenet | trajectoryGeneratorFrenet | navPath

**Functions**
closestPoint | closestPoint | closestPointsToSequence | closestProjections | curvature | changeInCurvature | tangentAngle | frenet2global | global2frenet | interpolate | position

**Topics**
"Highway Trajectory Planning Using Frenet Reference Path"

# position

Return *xy*-position at arclength

## Syntax

```
pos = position(refPath,S)
```

## Description

`pos = position(refPath,S)` calculates the *xy*-position `pos` of the reference path `refPath` at the specified arclength, `S`.

## Input Arguments

### `refPath` — Reference path

`referencePathFrenet` object

Reference path, specified as a `referencePathFrenet` object.

### `S` — Path arclengths

*N*-element column vector

Path arclengths, specified as an *N*-element column vector in meters, where *N* is the total number of desired arclengths to calculate.

## Output Arguments

### pos — *xy*-position

*N*-by-2 matrix

*xy*-position, returned as *N*-by-2 matrix, where *N* is the total number of specified arclengths. Each row is of the form [*x y*], containing the *xy*-positions for an arclength.

# Version History

**Introduced in R2022b**

## See Also

**Objects**

`referencePathFrenet`

**Functions**

`closestPoint` | `closestPointsToSequence` | `closestProjections` | `curvature` | `changeInCurvature` | `frenet2global` | `global2frenet` | `interpolate` | `tangentAngle` | `show`

# tangentAngle

Return tangent angle at arclength

## Syntax

```
theta = tangentAngle(refPath,S)
```

## Description

`theta = tangentAngle(refPath,S)` calculates the tangent angle, `theta`, of the reference path at specified arclength, `S`.

## Input Arguments

**`refPath` — Reference path**
`referencePathFrenet` object

Reference path, specified as a `referencePathFrenet` object.

**`S` — Path arclengths**
*N*-element column vector

Path arclengths, specified as an *N*-element column vector in meters, where *N* is the total number of desired arclengths to calculate.

## Output Arguments

**`theta` — Path tangent angles**
*N*-element vector

Path tangent angles, specified as an *N*-element vector in radians, where *N* is the total number of desired arclengths to calculate.

# Version History

**Introduced in R2022a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
`referencePathFrenet` | `trajectoryGeneratorFrenet` | `navPath`

**Functions**
`frenet2global` | `global2frenet` | `closestPoint` | `closestPointsToSequence` | `closestProjections` | `curvature` | `changeInCurvature` | `interpolate` | `position` | `show`

**Topics**
"Highway Trajectory Planning Using Frenet Reference Path"

# resamplingPolicyPF

Create resampling policy object with resampling settings

## Description

The `resamplingPolicyPF` object stores settings for when resampling should occur when using a particle filter for state estimation. The object contains the method that triggers resampling and the relevant threshold for this resampling. Use this object as the `ResamplingPolicy` property of the `stateEstimatorPF` object.

## Creation

### Syntax

`policy = resamplingPolicyPF`

#### Description

`policy = resamplingPolicyPF` creates a `resamplingPolicyPF` object `policy`, which contains properties to be modified to control when resampling should be triggered. Use this object as the `ResamplingPolicy` property of the `stateEstimatorPF` object.

### Properties

**`TriggerMethod` — Method for determining if resampling should occur**
`'ratio'` (default) | character vector

Method for determining if resampling should occur, specified as a character vector. Possible choices are `'ratio'` and `'interval'`. The `'interval'` method triggers resampling at regular intervals of operating the particle filter. The `'ratio'` method triggers resampling based on the ratio of effective total particles.

**`SamplingInterval` — Fixed interval between resampling**
1 (default) | scalar

Fixed interval between resampling, specified as a scalar. This interval determines during which correction steps the resampling is executed. For example, a value of 2 means the resampling is executed every second correction step. A value of `inf` means that resampling is never executed.

This property only applies with the `TriggerMethod` is set to `'interval'`.

**`MinEffectiveParticleRatio` — Minimum desired ratio of effective to total particles**
0.5 (default) | scalar

Minimum desired ratio of effective to total particles, specified as a scalar. The effective number of particles is a measure of how well the current set of particles approximates the posterior distribution. A lower effective particle ratio means less particles are contributing to the estimation and resampling

might be required. If the ratio of effective particles to total particles falls below the `MinEffectiveParticleRatio`, a resampling step is triggered.

## Version History

**Introduced in R2019b**

### See Also

`stateEstimatorPF` | `correct`

# se3

SE(3) homogeneous transformation

## Description

The `se3` object represents an SE(3) transformation as a 3-D homogeneous transformation matrix consisting of a translation and rotation:

For more information, see the “3-D Homogeneous Transformation Matrix” on page 2-1495 section.

This object acts like a numerical matrix enabling you to compose poses using multiplication and division.

## Creation

### Syntax

```
transformation = se3
transformation = se3(rotation)
transformation = se3(rotation,translation)
transformation = se3(transformation)

transformation = se3(euler,"eul")
transformation = se3(euler,"eul",sequence)
transformation = se3(quat,"quat")
transformation = se3(quaternion)
transformation = se3(axang,"axang")
transformation = se3(angle,axis)
transformation = se3( ___ ,translation,"trvec")

transformation = se3(translation,"trvec")
transformation = se3(pose,"xyzquat")
```

#### Description

**Rotation Matrices, Translation Vectors, and Transformation Matrices**

`transformation = se3` creates an SE(3) transformation representing an identity rotation with no translation.

$$transformation = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

`transformation = se3(rotation)` creates an SE(3) transformation representing a pure rotation defined by the orthonormal rotation `rotation` with no translation. The rotation matrix is represented by the elements in the top left of the `transformation` matrix.

$$rotation = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{11} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix}$$

$$transformation = \begin{bmatrix} r_{11} & r_{12} & r_{13} & 0 \\ r_{21} & r_{22} & r_{23} & 0 \\ r_{31} & r_{32} & r_{33} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

`transformation = se3(rotation,translation)` creates an SE(3) transformation representing a rotation defined by the orthonormal rotation `rotation` and the translation `translation`. The function applies the rotation matrix first, then translation vector to create the transformation.

$$rotation = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{11} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix}, translation = \begin{bmatrix} t_1 \\ t_2 \\ t_3 \end{bmatrix}$$

$$transformation = \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_1 \\ r_{21} & r_{22} & r_{23} & t_2 \\ r_{31} & r_{32} & r_{33} & t_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & t_1 \\ 0 & 1 & 0 & t_2 \\ 0 & 0 & 1 & t_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} r_{11} & r_{12} & r_{13} & 0 \\ r_{21} & r_{22} & r_{23} & 0 \\ r_{31} & r_{32} & r_{33} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

`transformation = se3(transformation)` creates an SE(3) transformation representing a translation and rotation as defined by the homogeneous transformation `transformation`.

**Other 3-D Rotation Representations**

`transformation = se3(euler,"eul")` creates an SE(3) transformation from the rotations defined by the Euler angles `euler`.

`transformation = se3(euler,"eul",sequence)` specifies the sequence of the Euler angle rotations `sequence`. For example, the sequence `"ZYX"` rotates the *z*-axis, then the *y*-axis and *x*-axis.

`transformation = se3(quat,"quat")` creates an SE(3) transformation from the rotations defined by the numeric quaternions `quat`.

`transformation = se3(quaternion)` creates an SE(3) transformation from the rotations defined by the quaternion `quaternion`.

`transformation = se3(axang,"axang")` creates an SE(3) transformation from the rotations defined by the axis-angle rotation `axang`.

`transformation = se3(angle,axis)` creates an SE(3) transformation from the rotations `angles` about the rotation axis `axis`.

`transformation = se3( ___ ,translation,"trvec")` creates an SE(3) transformation from the translation vector `translation` along with any other type of rotation input arguments.

**Other Translations and Transformation Representations**

`transformation = se3(translation,"trvec")` creates an SE(3) transformation from the translation vector `translation`.

`transformation = se3(pose,"xyzquat")` creates an SE(3) transformation from the 3-D compact pose `pose`.

---

**Note** If any inputs contain more than one rotation, translation, or transformation, then the output `transformation` is an *N*-element array of `se3` objects corresponding to each of the *N* input rotations, translations, or transformations.

---

#### Input Arguments

**`rotation` — Orthonormal rotation**
3-by-3 matrix | 3-by-3-by-*N* matrix | `so3` object | *N*-element array of `so3` objects

Orthonormal rotation, specified as a 3-by-3 matrix, a 3-by-3-by-*N* array, a scalar `so3` object, or an *N*-element array of `so3` objects. *N* is the total number of rotations.

If `rotation` contains more than one rotation and you also specify `translation` at construction, the number of translations in `translation` must be one or equal to the number of rotations in `rotation`. The resulting number of transformation objects is equal to the value of the `translation` or `rotation` argument, whichever is larger.

Example: `eye(3)`

Data Types: `single` | `double`

**`translation` — Translation**
three-element row vector | *N*-by-3 matrix

Translation, specified as a three-element row vector or an *N*-by-3 array. *N* is the total number of translations and each translation is of the form [*x y z*].

If `translation` contains more than one translation, the number of rotations in `rotation` must be one or equal to the number of translations in `translation`. The resulting number of created transformation objects is equal to the value of the `translation` or `rotation` argument, whichever is larger.

Example: `[1 4 3]`

Data Types: `single` | `double`

**`transformation` — Homogeneous transformation**
4-by-4 matrix | 4-by-4-*N* array | `se3` object | *N*-element array of `se3` objects

Homogeneous transformation, specified as a 4-by-4 matrix, a 4-by-4-*N* array, a scalar `se3` object, or an *N*-element array of `se3` objects. *N* is the total number of transformations specified.

If `transformation` is an array, the resulting number of created `se3` objects is equal to *N*.

Example: `eye(4)`

Data Types: `single` | `double`

**`quaternion` — Quaternion**
`quaternion` object | *N*-element array of `quaternion` objects

Quaternion, specified as a scalar `quaternion` object or as an *N*-element array of `quaternion` objects. *N* is the total number of specified quaternions.

If `quaternion` is an $N$-element array, the resulting number of created `se3` objects is equal to $N$.

Example: `quaternion(1,0.2,0.4,0.2)`

**`euler` — Euler angles**
$N$-by-3 matrix

Euler angles, specified as an $N$-by-3 matrix, in radians. Each row represents one set of Euler angles with the axis-rotation sequence defined by the `sequence` argument. The default axis-rotation sequence is *ZYX*.

If `euler` is an $N$-by-3 matrix, the resulting number of created `se3` objects is equal to $N$.

Example: `[pi/2 pi pi/4]`

Data Types: `single` | `double`

**`sequence` — Axis-rotation sequence**
`"ZYX"` (default) | `"ZYZ"` | `"ZXY"` | `"ZXZ"` | `"YXY"` | `"YZX"` | `"YXZ"` | `"YZY"` | `"XYX"` | `"XYZ"` | `"XZX"` | `"XZY"`

Axis-rotation sequence for the Euler angles, specified as one of these string scalars:

- `"ZYX"` (default)
- `"ZYZ"`
- `"ZXY"`
- `"ZXZ"`
- `"YXY"`
- `"YZX"`
- `"YXZ"`
- `"YZY"`
- `"XYX"`
- `"XYZ"`
- `"XZX"`
- `"XZY"`

These are orthonormal rotation matrices for rotations of $\phi$, $\psi$, and $\theta$ about the *x*-, *y*-, and *z*-axis, respectively:

$$R_x(\phi) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & \sin\phi \\ 0 & -\sin\phi & \cos\phi \end{bmatrix}, R_y(\psi) = \begin{bmatrix} \cos\psi & 0 & \sin\psi \\ 0 & 1 & 0 \\ -\sin\psi & 0 & \cos\psi \end{bmatrix}, R_z(\theta) = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

When constructing the rotation matrix from this sequence, each character indicates the corresponding axis. For example, if the sequence is `"XYZ"`, then the `se3` object constructs the rotation matrix $R$ by multiplying the rotation about *x*-axis with the rotation about the *y*-axis, and then multiplying that product with the rotation about the *z*-axis:

$$R = R_x(\phi) \cdot R_y(\psi) \cdot R_z(\theta)$$

Example: `se3([pi/2 pi/3 pi/4],"eul","ZYZ")` rotates a point by `pi/4` radians about the *z*-axis, then rotates the point by `pi/3` radians about the *y*-axis, and then rotates the point by `pi/2`

radians about the *z*-axis. This is equivalent to `se3(pi/2,"rotz") * se3(pi/3,"roty") * se3(pi/4,"rotz")`

Data Types: `string` | `char`

**`quat` — Quaternion**
*N*-by-4 matrix

Quaternion, specified as an *N*-by-4 matrix. *N* is the number of specified quaternions. Each row represents one quaternion of the form [*qw qx qy qz*], where *qw* is a scalar number.

If `quat` is an *N*-by-4 matrix, the resulting number of created `se3` objects is equal to *N*.

**Note** The `se3` object normalizes the input quaternions before converting the quaternions to a rotation matrix.

Example: `[0.7071 0.7071 0 0]`

Data Types: `single` | `double`

**`axang` — Axis-angle rotation**
*N*-by-4 matrix

Axis-angle rotation, specified as an *N*-by-4 matrix in the form [*x y z theta*]. *N* is the total number of axis-angle rotations. *x*, *y*, and *z* are vector components from the *x*-, *y*-, and *z*-axis, respectively. The vector defines the axis to rotate by the angle *theta*, in radians.

If `axang` is an *N*-by-4 matrix, the resulting number of created `se3` objects is equal to *N*.

Example: `[.2 .15 .25 pi/4]` rotates the axis, defined as `0.2` in the *x*-axis, `0.15` along the *y*-axis, and `0.25` along the *z*-axis, by `pi/4` radians.

Data Types: `single` | `double`

**`angle` — Single-axis-angle rotation**
*N*-by-*M* matrix

Single-axis-angle rotation, specified as an *N*-by-*M* matrix. Each element of the matrix is an angle, in radians, about the axis specified using the `axis` argument, and the `se3` object creates an `se3` object for each angle.

If `angle` is an *N*-by-*M* matrix, the resulting number of created `se3` objects is equal to *N*.

The rotation angle is counterclockwise positive when you look along the specified axis toward the origin.

Data Types: `single` | `double`

**`axis` — Axis to rotate**
`"rotx"` | `"roty"` | `"rotz"`

Axis to rotate, specified as one of these options:

- `"rotx"` — Rotate about the *x*-axis:

$$R_x(\phi) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & \sin\phi \\ 0 & -\sin\phi & \cos\phi \end{bmatrix}$$

- `"roty"` — Rotate about the *y*-axis:

$$R_y(\psi) = \begin{bmatrix} \cos\psi & 0 & \sin\psi \\ 0 & 1 & 0 \\ -\sin\psi & 0 & \cos\psi \end{bmatrix}$$

- `"rotz"` — Rotate about the *z*-axis:

$$R_z(\theta) = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Use the `angle` argument to specify how much to rotate about the specified axis.

Example: `Rx = se3(phi,"rotx");`

Example: `Ry = se3(psi,"roty");`

Example: `Rz = se3(theta,"rotz");`

Data Types: `string` | `char`

**pose — 3-D compact pose**
*N*-by-7 matrix

3-D compact pose, specified as an *N*-by-7 matrix, where *N* is the total number of compact poses. Each row is a pose, comprised of a xyz position and quaternion, in the form [*x y z qw qx qy qz*]. *x*, *y*, and *z* are the positions in the *x*-, *y*-, and *z*-axes, respectively. *qw*, *qx*, *qy*, and *qz* together are the quaternion rotation in *w*, *x*, *y*, and *z*, respectively.

If `pose` is an *N*-by-7 matrix, the resulting number of created `se3` objects is equal to *N*.

Data Types: `single` | `double`

## Object Functions

### Mathematical Operations

| | |
|---|---|
| mtimes, * | Transformation or rotation multiplication |
| mrdivide, / | Transformation or rotation right division |
| rdivide, ./ | Element-wise transformation or rotation right division |
| times, .* | Element-wise transformation or rotation multiplication |

### Utilities

| | |
|---|---|
| interp | Interpolate between transformations |
| dist | Calculate distance between transformations |
| normalize | Normalize transformation or rotation matrix |
| transform | Apply rigid body transformation to points |

## Numerical Conversions

| | |
|---|---|
| axang | Convert transformation or rotation into axis-angle rotations |
| eul | Convert transformation or rotation into Euler angles |
| rotm | Extract rotation matrix |
| quat | Convert transformation or rotation to numeric quaternion |
| quaternion | Create a quaternion array |
| trvec | Extract translation vector |
| tform | Extract homogeneous transformation |
| xyzquat | Convert transformation or rotation to compact 3-D pose representation |

## Object Conversions

| | |
|---|---|
| so3 | SO(3) rotation |

## Examples

### Create SE(3) Transformation Using Euler Angles and Translation

Define an Euler-angle rotation of `[pi/2 0 pi/7]` with a `"XYZ"` rotation sequence, and a *xyz* translation of `[6 4 1]`.

```
angles = [pi/2 0 pi/7];
trvec = [6 4 1];
```

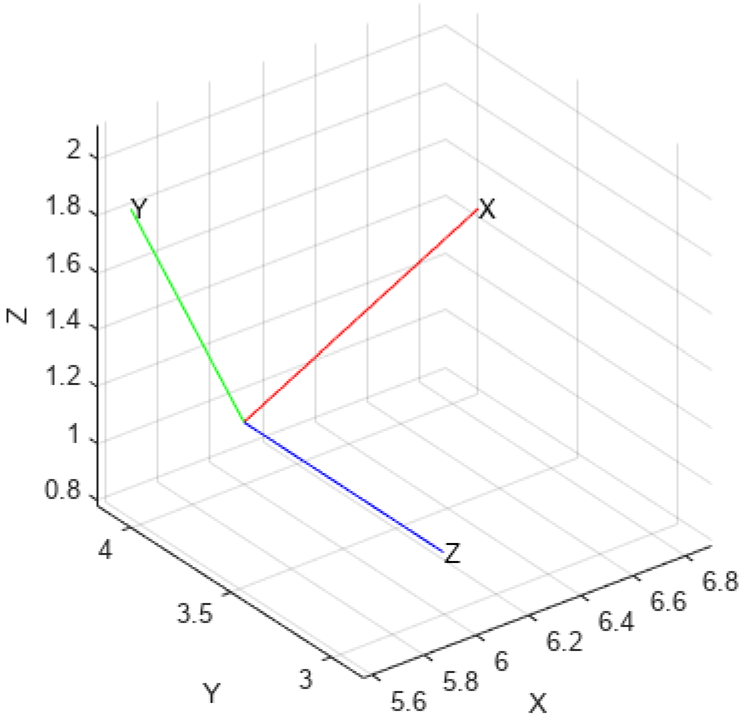
Create an SE(3) transformation using the Euler angles and the translation.

```
TF = se3(angles,"eul","XYZ",trvec)
```

```
TF = se3
    0.9010   -0.4339         0    6.0000
    0.0000    0.0000   -1.0000    4.0000
    0.4339    0.9010    0.0000    1.0000
         0         0         0    1.0000
```

Plot the transformation.

```
plotTransforms(TF,AxisLabels="on",FrameAxisLabels="on");
```




## Algorithms

### 3-D Homogeneous Transformation Matrix

3-D homogeneous transformation matrices consist of both an SO(3) rotation and an *xyz*-translation.

To read more about SO(3) rotations, see the "3-D Orthonormal Rotation Matrix" on page 2-1508 section of the `so3` object.

The translation is along the *x*-, *y*-, and *z*-axes as a three-element column vector:

$$t = \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

The SO(3) rotation matrix $R$ is applied to the translation vector $t$ to create the homogeneous translation matrix $T$. The rotation matrix is present in the upper-left of the transformation matrix as 3-by-3 submatrix, and the translation vector is present as a three-element vector in the last column.

$$T = \begin{bmatrix} R & t \\ 0_{1x3} & 1 \end{bmatrix} = \begin{bmatrix} I_3 & t \\ 0_{1x3} & 1 \end{bmatrix} \cdot \begin{bmatrix} R & 0 \\ 0_{1x3} & 1 \end{bmatrix}$$

## Version History

**Introduced in R2022b**

### R2023a: New methods and syntaxes

`se3` supports new methods and syntaxes for converting to and from other transformations and rotations.

The new methods are:

- `axang`
- `eul`
- `so3`
- `quat`
- `quaternion`
- `xyzquat`

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Functions

`axang2tform` | `eul2tform` | `quat2tform` | `rotm2tform` | `trvec2tform` | `plotTransforms`

### Objects

`se2` | `so2` | `so3` | `quaternion`

# se2

SE(2) homogeneous transformation

## Description

The `se2` object represents an SE(2) transformation as a 2-D homogeneous transformation matrix consisting of a translation and rotation.

For more information, see the “2-D Homogeneous Transformation Matrix” on page 2-1501 section.

This object acts like a numerical matrix, enabling you to compose poses using multiplication and division.

## Creation

### Syntax

```
transformation = se2
transformation = se2(rotation)
transformation = se2(rotation,translation)
transformation = se2(transformation)
```

```
transformation = se2(angle,"theta")
transformation = se2(angle,"theta",translation)
transformation = se2(translation,"trvec")
transformation = se2(pose,"xytheta")
```

#### Description

**Rotation Matrices, Translation Vectors, and Transformation Matrices**

`transformation = se2` creates an SE(2) transformation representing an identity rotation with no translation.

$$transformation = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

`transformation = se2(rotation)` creates an SE(2) transformation representing a pure rotation defined by the orthonormal rotation `rotation` with no translation. The rotation matrix is represented by the elements in the top left of the `transformation` matrix.

$$rotation = \begin{bmatrix} r_{11} & r_{12} \\ r_{21} & r_{22} \end{bmatrix}$$

$$transformation = \begin{bmatrix} r_{11} & r_{12} & 0 \\ r_{21} & r_{22} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

`transformation = se2(rotation,translation)` creates an SE(2) transformation representing a rotation defined by the orthonormal rotation `rotation` and the translation `translation`. The function applies the rotation matrix first, then the translation vector, to create the transformation.

$$rotation = \begin{bmatrix} r_{11} & r_{12} \\ r_{21} & r_{22} \end{bmatrix}, translation = \begin{bmatrix} t_1 \\ t_2 \end{bmatrix}$$

$$transformation = \begin{bmatrix} r_{11} & r_{12} & t_1 \\ r_{21} & r_{22} & t_2 \\ 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & t_1 \\ 0 & 1 & t_2 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} r_{11} & r_{12} & 0 \\ r_{21} & r_{22} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

`transformation = se2(transformation)` creates an SE(2) transformation representing a translation and rotation as defined by the homogeneous transformation `transformation`.

**Other 2-D Rotations and Transformation Representations**

`transformation = se2(angle,"theta")` creates SE(2) transformations `transformation` from rotations around the *z*-axis, in radians. The transformation contains zero translation.

`transformation = se2(angle,"theta",translation)` creates SE(2) transformations from rotations around the *z*-axis, in radians, with translations `translation`.

`transformation = se2(translation,"trvec")` creates an SE(2) transformation from the translation vector `translation`.

`transformation = se2(pose,"xytheta")` creates an SE(2) transformation from the 2-D compact pose `pose`.

### Input Arguments

#### `rotation` — Orthonormal rotation

2-by-2 matrix | 2-by-2-by-*N* matrix | `so2` object | *N*-element array of `so2` objects

Orthonormal rotation, specified as a 2-by-2 matrix, a 2-by-2-by-*N* array, a scalar `so2` object, or an *N*-element array of `so2` objects. *N* is the total number of rotations.

If `rotation` contains more than one rotation and you also specify `translation` at construction, the number of translations in `translation` must be one or equal to the number of rotations in `rotation`. The resulting number of transformation objects is equal to the value of the `translation` or `rotation` argument, whichever is larger.

If `rotation` contains one rotation and you also specify `translation` as an *N*-by-2 matrix, then the resulting transformations contain the same rotation specified by `rotation` and the corresponding translation vector in `translation`. The resulting number of transformation objects is equal to the number of translations in `translation`.

Example: `eye(2)`

Data Types: `single` | `double`

#### `translation` — Translation

two-element row vector | *N*-by-2 matrix

Translation, specified as an *N*-by-2 matrix. *N* is the total number of translations and each translation is of the form [*x y*].

If `translation` contains more than one translation, the number of rotations in `rotation` must be one or equal to the number of translations in `translation`. The resulting number of created transformation objects is equal to the value of the `translation` or `rotation` argument, whichever is larger.

If you specify more than one translation but only one rotation, the resulting transformations contain the same rotation specified in `rotation` and the corresponding translation in `translation`. The resulting number of created `se2` objects is equal to the value of the `translation`.

Example: `[1 4]`

Data Types: `single` | `double`

**`transformation` — Homogeneous transformation**
3-by-3 matrix | 3-by-3-*N* array | `se2` object | *N*-element array of `se2` objects

Homogeneous transformation, specified as a 3-by-3 matrix, a 3-by-3-*N* array, a scalar `se3` object, or an *N*-element array of `se2` objects. *N* is the total number of transformations specified.

If `transformation` is an array, the resulting number of created `se2` objects is equal to *N*.

Example: `eye(3)`

Data Types: `single` | `double`

**`angle` — *z*-axis rotation angle**
*N*-by-*M* matrix

*z*-axis rotation angle, specified as an *N*-by-*M* matrix. Each element of the matrix is an angle, in radians, about the *z*-axis. The `se2` object creates an `se2` object for each angle.

If `angle` is an *N*-by-*M* matrix, the resulting number of created `se2` objects is equal to *N*.

The rotation angle is counterclockwise positive when you look along the specified axis toward the origin.

Data Types: `single` | `double`

**`pose` — 2-D compact pose**
*N*-by-3 matrix

3-D compact pose, specified as an *N*-by-3 matrix, where *N* is the total number of compact poses. Each row is a pose, comprised of an xy position and a rotation about the *z*-axis, in the form [*x y theta*]. *x*, *y* are the xy-positions and *theta* is the rotation about the *z*-axis.

If `pose` is an *N*-by-3 matrix, the resulting number of created `se2` objects is equal to *N*.

Data Types: `single` | `double`

## Object Functions

## Mathematical Operations

| | |
|---|---|
| mtimes, * | Transformation or rotation multiplication |
| mrdivide, / | Transformation or rotation right division |
| rdivide, ./ | Element-wise transformation or rotation right division |

times, .* Element-wise transformation or rotation multiplication

## Utilities

interp Interpolate between transformations
dist Calculate distance between transformations
normalize Normalize transformation or rotation matrix
transform Apply rigid body transformation to points

## Numerical Conversions

rotm Extract rotation matrix
trvec Extract translation vector
tform Extract homogeneous transformation
theta Convert transformation or rotation to 2-D rotation angle
xytheta Convert transformation or rotation to compact 2-D pose representation

## Object Conversions

so2 SO(2) rotation

## Examples

### Create SE(2) Transformation Using Angle and Translation

Define an angle rotation of `pi/4` and a *xyz* translation of `[6 4]`.

```
angle = pi/6;
trvec = [2 1];
```

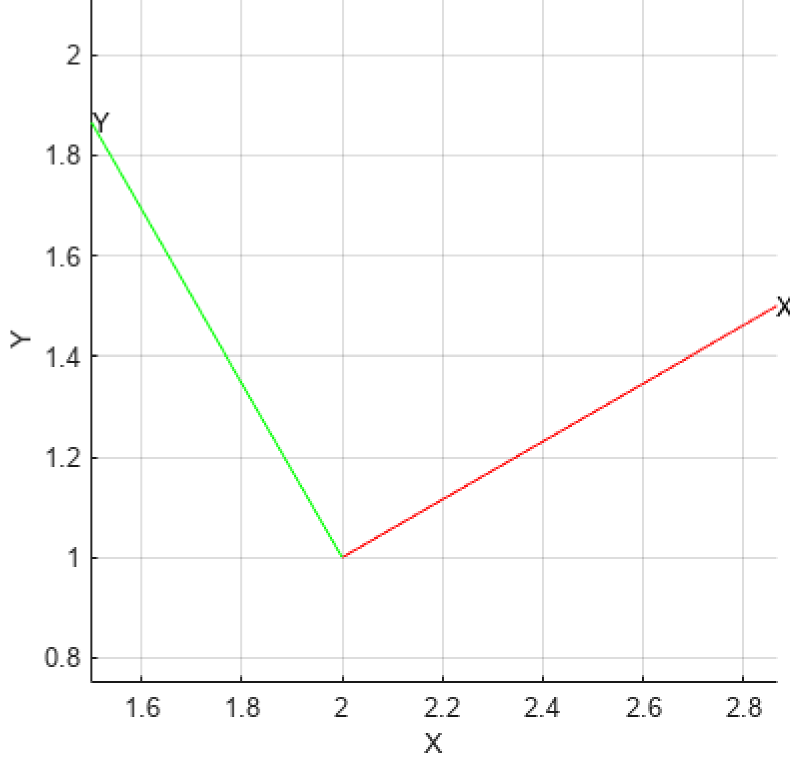
Create an SE(2) transformation using the angle and translation.

```
TF = se2(angle,"theta",trvec)
```

```
TF = se2
    0.8660   -0.5000    2.0000
    0.5000    0.8660    1.0000
         0         0    1.0000
```

Plot the transformation.

```
plotTransforms(TF,AxisLabels="on",FrameAxisLabels="on");
```




## Algorithms

### 2-D Homogeneous Transformation Matrix

2-D homogeneous transformation matrices consist of both an SO(2) rotation and an *xy*-translation.

To read more about SO(2) rotations, see the “2-D Orthonormal Rotation Matrix” on page 2-1512 section of the `so2` object.

The translation is along the *x*-, *y*-, and *z*-axes as a three-element column vector:

$$t = \begin{bmatrix} x \\ y \end{bmatrix}$$

The SO(2) rotation matrix *R* is applied to the translation vector *t* to create the homogeneous translation matrix *T*. The rotation matrix is present in the upper-left of the transformation matrix as 2-by-2 submatrix, and the translation vector is present as a two-element vector in the last column.

$$T = \begin{bmatrix} R & t \\ 0_{1 \times 2} & 1 \end{bmatrix} = \begin{bmatrix} I_2 & t \\ 0_{1 \times 2} & 1 \end{bmatrix} \cdot \begin{bmatrix} R & 0 \\ 0_{1 \times 2} & 1 \end{bmatrix}$$

# Version History

**Introduced in R2022b**

#### R2023a: New methods and syntaxes

`se2` supports new methods and syntaxes for converting to and from other transformations and rotations.

The new methods are:

- `se3`
- `so2`
- `theta`
- `xytheta`

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Functions**
`axang2tform` | `eul2tform` | `quat2tform` | `rotm2tform` | `trvec2tform` | `plotTransforms`

**Objects**
`se3` | `so2` | `so3` | `quaternion`

# so3

SO(3) rotation

## Description

The `so3` object represents an SO(3) rotation in 3-D in a right-handed Cartesian coordinate system.

The SO(3) rotation is a 3-by-3 orthonormal rotation matrix. For example, these are orthonormal rotation matrices for rotations of $\phi$, $\psi$, and $\theta$ about the *x*-, *y*-, and *z*-axis, respectively:

$$R_x(\phi) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & \sin\phi \\ 0 & -\sin\phi & \cos\phi \end{bmatrix}, R_y(\psi) = \begin{bmatrix} \cos\psi & 0 & \sin\psi \\ 0 & 1 & 0 \\ -\sin\psi & 0 & \cos\psi \end{bmatrix}, R_z(\theta) = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

For more information, see the 3-D Orthonormal Rotation Matrix section.

This object acts like a numerical matrix, enabling you to compose rotations using multiplication and division.

## Creation

### Syntax

```
rotation = so3
rotation = so3(rotation)
rotation = so3(quaternion)
rotation = so3(transformation)

rotation = so3(euler,"eul")
rotation = so3(euler,"eul",sequence)
rotation = so3(quat,"quat")
rotation = so3(axang,"axang")
rotation = so3(angle,axis)
```

#### Description

##### 3-D Rotation Representations

`rotation = so3` creates an SO(3) rotation representing an identity rotation with no translation.

$$rotation = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

`rotation = so3(rotation)` creates an SO(3) rotation representing a pure rotation defined by the orthonormal rotation `rotation`.

$$rotation = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{11} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix}$$

`rotation = so3(quaternion)` creates an SO(3) rotation from the rotations defined by the quaternion `quaternion`.

`rotation = so3(transformation)` creates an SO(3) rotation from the SE(3) transformation `transformation`.

#### Other Numeric 3-D Rotation Representations

`rotation = so3(euler,"eul")` creates an SO(3) rotation from the rotations defined by the Euler angles `euler`.

`rotation = so3(euler,"eul",sequence)` specifies the sequence of the Euler angle rotations `sequence`. For example, the sequence `"ZYX"` rotates the *z*-axis, then the *y*-axis and *x*-axis.

`rotation = so3(quat,"quat")` creates an SO(3) rotation from the rotations defined by the numeric quaternions `quat`.

`rotation = so3(axang,"axang")` creates an SO(3) rotation from the rotations defined by the axis-angle rotation `axang`.

`rotation = so3(angle,axis)` creates an SO(3) rotation from the rotations `angles` about the rotation axis `axis`.

---

**Note** If any inputs contain more than one rotation, then the output `rotation` is an *N*-element array of `so3` objects corresponding to each of the *N* input rotations.

---

### Input Arguments

#### `rotation` — Orthonormal rotation

3-by-3 matrix | 3-by-3-by-*N* matrix | `so3` object | *N*-element array of `so3` objects

Orthonormal rotation, specified as a 3-by-3 matrix, a 3-by-3-by*N* array, a scalar `so3` object, or an *N*-element array of `so3` objects. *N* is the total number of rotations.

If `rotation` is an array, the resulting number of created `so3` objects in the output array is equal to *N*.

Example: `eye(3)`

#### `transformation` — Homogeneous transformation

`se3` object | *N*-element array of `se3` objects

Homogeneous transformation, specified as an `se3` object or a *N*-element array of `se3` objects. *N* is the total number of transformations specified.

The output `so3` object contains only the rotational submatrix of the `se3` object.

If `transformation` is an array, the resulting number of created `so3` objects in the output array is equal to *N*.

Example: `se3(pi/4,"rotx")`

**quaternion — Quaternion**
`quaternion` object | *N*-element array of `quaternion` objects

Quaternion, specified as a scalar `quaternion` object or as an *N*-element array of `quaternion` objects. *N* is the total number of specified quaternions.

If `quaternion` is an *N*-element array, the resulting number of created `so3` objects is equal to *N*.

Example: `quaternion(1,0.2,0.4,0.2)`

**euler — Euler angles**
*N*-by-3 matrix

Euler angles, specified as an *N*-by-3 matrix, in radians. Each row represents one set of Euler angles with the axis-rotation sequence defined by the `sequence` argument. The default axis-rotation sequence is *ZYX*.

If `euler` is an *N*-by-3 matrix, the resulting number of created `so3` objects is equal to *N*.

Example: `[pi/2 pi pi/4]`

Data Types: `single` | `double`

**sequence — Axis-rotation sequence**
`"ZYX"` (default) | `"ZYZ"` | `"ZXY"` | `"ZXZ"` | `"YXY"` | `"YZX"` | `"YXZ"` | `"YZY"` | `"XYX"` | `"XYZ"` | `"XZX"` | `"XZY"`

Axis-rotation sequence for the Euler angles, specified as one of these string scalars:

- `"ZYX"` (default)
- `"ZYZ"`
- `"ZXY"`
- `"ZXZ"`
- `"YXY"`
- `"YZX"`
- `"YXZ"`
- `"YZY"`
- `"XYX"`
- `"XYZ"`
- `"XZX"`
- `"XZY"`

These are orthonormal rotation matrices for rotations of $\phi$, $\psi$, and $\theta$ about the *x*-, *y*-, and *z*-axis, respectively:

$$R_x(\phi) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & \sin\phi \\ 0 & -\sin\phi & \cos\phi \end{bmatrix}, R_y(\psi) = \begin{bmatrix} \cos\psi & 0 & \sin\psi \\ 0 & 1 & 0 \\ -\sin\psi & 0 & \cos\psi \end{bmatrix}, R_z(\theta) = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

When constructing the rotation matrix from this sequence, each character indicates the corresponding axis. For example, if the sequence is `"XYZ"`, then the `so3` object constructs the

rotation matrix *R* by multiplying the rotation about *x*-axis with the rotation about the *y*-axis, and then multiplying that product with the rotation about the *z*-axis:

$$R = R_x(\phi) \cdot R_y(\psi) \cdot R_z(\theta)$$

Example: `so3([pi/2 pi/3 pi/4],"eul","ZYZ")` rotates a point by `pi/4` radians about the *z*-axis, then rotates the point by `pi/3` radians about the *y*-axis, and then rotates the point by `pi/2` radians about the *z*-axis. This is equivalent to `so3(pi/2,"rotz") * so3(pi/3,"roty") * so3(pi/4,"rotz")`

Data Types: `string` | `char`

**quat — Quaternion**
*N*-by-4

Quaternion, specified as an *N*-by-4 matrix. *N* is the number of specified quaternions. Each row represents one quaternion of the form [*qw qx qy qz*], where *qw* is a scalar number.

If `quat` is an *N*-by-4 matrix, the resulting number of created `so3` objects is equal to *N*.

---

**Note** The `so3` object normalizes the input quaternions before converting the quaternions to a rotation matrix.

---

Example: `[0.7071 0.7071 0 0]`

Data Types: `single` | `double`

**axang — Axis-angle rotation**
*N*-by-4 matrix

Axis-angle rotation, specified as an *N*-by-4 matrix in the form [*x y z theta*]. *N* is the total number of axis-angle rotations. *x*, *y*, and *z* are vector components from the *x*-, *y*-, and *z*-axis, respectively. The vector defines the axis to rotate by the angle *theta*, in radians.

If `axang` is an *N*-by-4 matrix, the resulting number of created `so3` objects is equal to *N*.

Example: `[.2 .15 .25 pi/4]` rotates the axis, defined as `0.2` in the *x*-axis, `0.15` along the *y*-axis, and `0.25` along the *z*-axis, by `pi/4` radians.

Data Types: `single` | `double`

**angle — Single-axis-angle rotation**
*N*-by-*M* matrix

Single-axis-angle rotation, specified as an *N*-by-*M* matrix. Each element of the matrix is an angle, in radians, about the axis specified using the `axis` argument, and the `so3` object creates an `so3` object for each angle.

If `angle` is an *N*-by-*M* matrix, the resulting number of created `so3` objects is equal to *N*.

The rotation angle is counterclockwise positive when you look along the specified axis toward the origin.

Data Types: `single` | `double`

**`axis` — Axis to rotate**
`"rotx"` | `"roty"` | `"rotz"`

Axis to rotate, specified as one of these options:

- `"rotx"` — Rotate about the $x$-axis:

$$R_x(\phi) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & \sin\phi \\ 0 & -\sin\phi & \cos\phi \end{bmatrix}$$

- `"roty"` — Rotate about the $y$-axis:

$$R_y(\psi) = \begin{bmatrix} \cos\psi & 0 & \sin\psi \\ 0 & 1 & 0 \\ -\sin\psi & 0 & \cos\psi \end{bmatrix}$$

- `"rotz"` — Rotate about the $z$-axis:

$$R_z(\theta) = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Use the `angle` argument to specify how much to rotate about the specified axis.

Example: `Rx = so3(phi,"rotx");`

Example: `Ry = so3(psi,"roty");`

Example: `Rz = so3(theta,"rotz");`

Data Types: `string` | `char`

## Object Functions

### Mathematical Operations

| | |
|---|---|
| mtimes, * | Transformation or rotation multiplication |
| mrdivide, / | Transformation or rotation right division |
| rdivide, ./ | Element-wise transformation or rotation right division |
| times, .* | Element-wise transformation or rotation multiplication |

### Utilities

| | |
|---|---|
| interp | Interpolate between transformations |
| dist | Calculate distance between transformations |
| normalize | Normalize transformation or rotation matrix |
| transform | Apply rigid body transformation to points |

### Numerical Conversions

| | |
|---|---|
| axang | Convert transformation or rotation into axis-angle rotations |
| eul | Convert transformation or rotation into Euler angles |
| rotm | Extract rotation matrix |
| quat | Convert transformation or rotation to numeric quaternion |
| trvec | Extract translation vector |

| | |
|---|---|
| tform | Extract homogeneous transformation |
| xyzquat | Convert transformation or rotation to compact 3-D pose representation |

## Object Conversions

| | |
|---|---|
| se3 | SE(3) homogeneous transformation |
| quaternion | Create a quaternion array |

## Examples

### Convert SO(3) Rotation to Euler Angles

Create SO(3) rotation defined by a Euler angles.

```
eul1 = [pi/4 pi/3 pi/8]
```

```
eul1 = 1×3

    0.7854    1.0472    0.3927
```

```
R = so3(eul1,"eul")
```

```
R = so3
    0.3536   -0.4189    0.8364
    0.3536    0.8876    0.2952
   -0.8660    0.1913    0.4619
```

Get the Euler angles from the transformation.

```
eul2 = eul(R)
```

```
eul2 = 1×3

    0.7854    1.0472    0.3927
```

## Algorithms

### 3-D Orthonormal Rotation Matrix

SO(3) rotation matrices are 3-by-3 orthonormal matrices that represent any rotation in 3-D Euclidean space. SO(3) rotations have many special properties. For example, SO(3) rotation matrices are in the 3-D special orthogonal group, so the product of two SO(3) rotation matrices is an SO(3) rotation matrix. This enables you to compose rotations from multiple rotations. For example, these are orthonormal rotation matrices for rotations of $\phi$, $\psi$, and $\theta$ about the *x*-, *y*-, and *z*-axis, respectively:

$$R_x(\phi) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & \sin\phi \\ 0 & -\sin\phi & \cos\phi \end{bmatrix}, R_y(\psi) = \begin{bmatrix} \cos\psi & 0 & \sin\psi \\ 0 & 1 & 0 \\ -\sin\psi & 0 & \cos\psi \end{bmatrix}, R_z(\theta) = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Depending on the order in which you multiply these *x*-, *y*-, and *z*-axis rotations, you can construct compound matrices that represent any rotation in 3-D Euclidean space.

These are other properties of SO(3) rotations:

- Each column is both orthogonal and a unit vector, meaning that none of the columns are multiples of each other.
- The determinant of the matrix is positive 1.
- The inverse of the matrix is the same as the transpose of the matrix: $R^{-1} = R^T$.

## Version History

**Introduced in R2022b**

### R2023a: New methods and syntaxes

`so3` supports new methods and syntaxes for converting to and from other transformations and rotations.

The new methods are:

- `axang`
- `eul`
- `quat`
- `quaternion`
- `tform`
- `trvec`
- `xyzquat`

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Functions**
`axang2rotm` | `eul2rotm` | `quat2rotm` | `tform2rotm`

**Objects**
`se2` | `se3` | `so2` | `quaternion`

# so2

SO(2) rotation

## Description

The `so2` object represents an SO(2) rotation in 2-D.

For more information, see the “2-D Orthonormal Rotation Matrix” on page 2-1512 section.

This object acts like a numerical matrix, enabling you to compose rotations using multiplication and division.

## Creation

### Syntax

```
rotation = so2
rotation = so2(rotation)
rotation = so2(transformation)
rotation = so2(angle,"theta")
```

#### Description

`rotation = so2` creates an SO(2) rotation representing an identity rotation with no translation.

$$rotation = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

`rotation = so2(rotation)` creates an SO(2) rotation `rotation` representing a pure rotation defined by the orthonormal rotation `rotation`.

$$rotation = \begin{bmatrix} r_{11} & r_{12} \\ r_{21} & r_{22} \end{bmatrix}$$

`rotation = so2(transformation)` creates an SO(2) rotation from the SE(2) transformation `transformation`.

`rotation = so2(angle,"theta")` creates an SO(2) rotation `rotation` from a rotation angle about the *z*-axis `angle`.

---

**Note** If any inputs contain more than one rotation, the output `rotation` is an *N*-element array of `so2` objects corresponding to each of the *N* input rotations.

---

### Input Arguments

**`rotation` — Orthonormal rotation**
2-by-2 matrix | 2-by-2-by-*N* matrix | `so2` object | *N*-element array of `so2` objects

Orthonormal rotation, specified as a 2-by-2 matrix, a 3-by-3-by-*N* array, a scalar `so2` object, or an *N*-element array of `so2` objects. *N* is the total number of rotations.

If `rotation` is an array, the resulting number of created `so2` objects in the output array is equal to *N*.

Example: `eye(3)`

Data Types: `single` | `double`

**`transformation` — Homogeneous transformation**
`se2` object | *N*-element array of `se2` objects

Homogeneous transformation, specified as an `se2` object or an *N*-element array of `se2` objects. *N* is the total number of transformations specified.

The output `so2` object contains only the rotational submatrix of the `se2` object.

If `transformation` is an array, the resulting number of created `so2` objects in the output array is equal to *N*.

Example: `se2([1 2],"trvec")`

**`angle` — *z*-axis rotation angle**
*N*-by-*M* matrix

*z*-axis rotation angle, specified as an *N*-by-*M* matrix. Each element of the matrix is an angle, in radians, about the *z*-axis. The `so2` object creates an `so2` object for each angle.

If `angle` is an *N*-by-*M* matrix, the resulting number of created `so2` objects is equal to *N*.

The rotation angle is counterclockwise positive when you look along the specified axis toward the origin.

Data Types: `single` | `double`

## Object Functions

## Mathematical Operations

| | |
|---|---|
| mtimes, * | Transformation or rotation multiplication |
| mrdivide, / | Transformation or rotation right division |
| rdivide, ./ | Element-wise transformation or rotation right division |
| times, .* | Element-wise transformation or rotation multiplication |

## Utilities

| | |
|---|---|
| interp | Interpolate between transformations |
| dist | Calculate distance between transformations |
| normalize | Normalize transformation or rotation matrix |
| transform | Apply rigid body transformation to points |

## Numerical Conversions

| | |
|---|---|
| rotm | Extract rotation matrix |
| trvec | Extract translation vector |
| tform | Extract homogeneous transformation |
| theta | Convert transformation or rotation to 2-D rotation angle |
| xytheta | Convert transformation or rotation to compact 2-D pose representation |

## Object Conversions

| | |
|---|---|
| so3 | SO(3) rotation |

## Examples

### Create SO(2) Rotation Using Angle

Define an angle rotation of `pi/4` and a *xy* translation of `[6 4]`.

```
angle = pi/4;
```

Create an SO(2) rotation using the angle.

```
R = so2(angle,"theta")
```

```
R = so2
    0.7071   -0.7071
    0.7071    0.7071
```

## Algorithms

### 2-D Orthonormal Rotation Matrix

SO(2) rotation matrices are 2-by-2 orthonormal matrices that represent a rotation about a single axis 2-D Euclidean space. SO(2) rotations have many special properties. For example, SO(2) rotation matrices are in the 2-D special orthogonal group, so the product of two SO(2) rotation matrices is an SO(2) rotation matrix. This enables you to compose rotations from multiple rotations.

This is a 2-D orthonormal rotation matrix that describes describe a rotation $\theta$ about the $z$-axis:

$$R_z(\theta) = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}$$

These are other properties of SO(2) rotations:

- Each column is both orthogonal and a unit vector, meaning that none of the columns are multiples of each other.
- The determinant of the matrix is positive 1.
- The inverse of the matrix is the same as the transpose of the matrix: $R^{-1} = R^T$.

## Version History

**Introduced in R2022b**

### R2023a: New methods and syntaxes

`so2` supports new methods and syntaxes for converting to and from other transformations and rotations.

The new methods are:

- `so3`
- `theta`
- `tform`
- `trvec`
- `xytheta`

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Functions

`axang2rotm` | `eul2rotm` | `quat2rotm` | `tform2rotm`

### Objects

`se2` | `se3` | `so3` | `quaternion`

# SkyPlotChart Properties

Sky plot chart appearance and behavior

## Description

The `SkyPlotChart` properties control the appearance of a sky plot chart generated using the `skyplot` function. To modify the chart appearance, use dot notation on the `SkyPlotChart` object:

```
h = skyplot;
h.AzimuthData = [45 120 295];
h.ElevationData = [10 45 60];
h.Labels = ["G1" "G4" "G11"];
```

### Properties

#### Sky Plot Properties

**`AzimuthData` — Azimuth angles for visible satellite positions**
*n*-element vector of angles | *t*-by-*n* matrix of angles

Azimuth angles for visible satellite positions, specified as an *n*-element vector of angles or *t*-by-*n* matrix of angles. *n* is the number of visible satellite positions in the plot, and *t* is the number of time steps of the satellites. Azimuth angles are measured in degrees, clockwise-positive from the north direction.

If you specify `AzimuthData` as a matrix, the last row indicates the current azimuth angles of the satellites.

Example: `[25 45 182 356]` specifies azimuth angles for four satellites at one time step

Data Types: `double`

**`ElevationData` — Elevation angles for visible satellite positions**
*n*-element vector of angles | *t*-by-*n* matrix of angles

Elevation angles for visible satellite positions, specified as an *n*-element vector of angles or *t*-by-*n* matrix of angles. *n* is the number of visible satellite positions in the plot, and *t* is the number of time steps of the satellites. Elevation angles are measured from the horizon line with 90 degrees being directly up.

If you specify `ElevationData` as a matrix, the last row indicates the current elevation angles of the satellites.

Example: `[45 90 27 74]` specifies elevation angles for four satellites at one time step

Data Types: `double`

**`LabelData` — Labels for visible satellite positions**
*n*-element string array

Labels for visible satellite positions, specified as an *n*-element string array. *n* is the number of visible satellite positions in the plot.

Example: `["G1" "G11" "G7" "G3"]`

Data Types: `string`

**`GroupData` — Group for each satellite position**
`categorical` array

Group for each satellite position, specified as a `categorical` array. Each group has a different color label defined by the ColorOrder property.

Example: `[GPS GPS Galileo Galileo]`

Data Types: `double`

**`ColorOrder` — Color order**
seven predefined colors (default) | three-column matrix of RGB triplets

Color order, specified as a three-column matrix of RGB triplets. This property defines the palette of colors MATLAB uses to create plot objects such as `Line`, `Scatter`, and `Bar` objects. Each row of the array is an RGB triplet. An RGB triplet is a three-element vector whose elements specify the intensities of the red, green, and blue components of a color. The intensities must be in the range [0, 1]. This table lists the default colors.

| Colors | `ColorOrder` Matrix |
| --- | --- |
| | `[ 0 0.4470 0.7410`<br>`0.8500 0.3250 0.0980`<br>`0.9290 0.6940 0.1250`<br>`0.4940 0.1840 0.5560`<br>`0.4660 0.6740 0.1880`<br>`0.3010 0.7450 0.9330`<br>`0.6350 0.0780 0.1840]` |

MATLAB assigns colors to objects according to their order of creation. For example, when plotting lines, the first line uses the first color, the second line uses the second color, and so on. If there are more lines than colors, then the cycle repeats.

You can also set the color order using the `colororder` function.

#### Label Properties

**`LabelFontSize` — Font size of labels**
scalar numeric value

Font size of labels, specified as a scalar numeric value. The default font depends on the specific operating system and locale.

Example: `h = skyplot(__,'LabelFontSize',12)`

Example: `h.LabelFontSize = 12`

**`LabelFontSizeMode` — Selection mode for font size of labels**
`'auto'` (default) | `'manual'`

Selection mode for the font size of labels, specified as one of these values:

- `'auto'` — Font size specified by MATLAB. If you resize the axes to be smaller than the default size, the font size can scale down to improve readability and layout.
- `'manual'` — Font size specified manually. MATLAB does not scale the font size as the axes size changes. To specify the font size, set the `LabelFontSize` property.

**Mask Properties**

### `MaskElevation` — Mask elevation angle

`0` (default) | nonnegative scalar | *N*-element vector

Elevation angle of mask, specified as a nonnegative scalar or *N*-element vector of nonnegative values, in degrees. $N$ is $m + 1$, where $m$ is the number of elements in `MaskAzimuthEdges`..

Example: `h = skyplot(__,MaskElevation=25)`

Data Types: `double`

### `MaskAlpha` — Mask transparency

`0.3` (default) | scalar in range [0, 1]

Mask transparency, specified as a scalar in the range [0, 1]. A transparency value of `1` is opaque, `0` is completely transparent, and values between `0` and `1` are semitransparent.

Example: `h = skyplot(__,MaskAlpha=0.1)`

Data Types: `double`

### `MaskColor` — Mask color

`[0.4902 0.4902 0.4902]` (default) | RGB triplet | hexadecimal color code | color name | short color name

Mask color, specified as an RGB triplet, a hexadecimal color code, a color name, or a short color name.

For a custom color, specify an RGB triplet or a hexadecimal color code.

- An RGB triplet is a three-element row vector whose elements specify the intensities of the red, green, and blue components of the color. The intensities must be in the range `[0,1]`. For example, `[0.4 0.6 0.7]`.
- A hexadecimal color code is a character vector or a string scalar that starts with a hash symbol (`#`) followed by three or six hexadecimal digits, which can range from `0` to `F`. The values are not case sensitive. Thus, the color codes `'#FF8800'`, `'#ff8800'`, `'#F80'`, and `'#f80'` are equivalent.

Alternatively, you can specify some common colors by name. This table lists the named color options, the equivalent RGB triplets, and the hexadecimal color codes.

| Color Name | Short Name | RGB Triplet | Hexadecimal Color Code | Appearance |
|---|---|---|---|---|
| `'red'` | `'r'` | `[1 0 0]` | `'#FF0000'` | |
| `'green'` | `'g'` | `[0 1 0]` | `'#00FF00'` | |
| `'blue'` | `'b'` | `[0 0 1]` | `'#0000FF'` | |
| `'cyan'` | `'c'` | `[0 1 1]` | `'#00FFFF'` | |
| `'magenta'` | `'m'` | `[1 0 1]` | `'#FF00FF'` | |

| Color Name | Short Name | RGB Triplet | Hexadecimal Color Code | Appearance |
|---|---|---|---|---|
| 'yellow' | 'y' | [1 1 0] | '#FFFF00' | |
| 'black' | 'k' | [0 0 0] | '#000000' | |
| 'white' | 'w' | [1 1 1] | '#FFFFFF' | |
| 'none' | Not applicable | Not applicable | Not applicable | No color |

This table shows the RGB triplets and hexadecimal color codes for the default colors MATLAB uses in many types of plots.

| RGB Triplet | Hexadecimal Color Code | Appearance |
|---|---|---|
| [0 0.4470 0.7410] | '#0072BD' | |
| [0.8500 0.3250 0.0980] | '#D95319' | |
| [0.9290 0.6940 0.1250] | '#EDB120' | |
| [0.4940 0.1840 0.5560] | '#7E2F8E' | |
| [0.4660 0.6740 0.1880] | '#77AC30' | |
| [0.3010 0.7450 0.9330] | '#4DBEEE' | |
| [0.6350 0.0780 0.1840] | '#A2142F' | |

Example: `h = skyplot(__,MaskColor="r")`

Data Types: `double` | `string` | `char`

### `MaskAzimuthEdges` — Mask angle azimuth edges

`[0 360]` (default) | *m*-element row vector

Mask angle azimuth edges, specified as an *m*-element row vector, where *m* is the total number of azimuth edges.

Example: `h = skyplot(__,MaskAzimuthEdges=0:45:360)`

Data Types: `double`

### `MaskAzimuthEdgesMode` — Mask angle azimuth edges mode

`"auto"` (default) | `"manual"`

Mask angle azimuth edges mode, specified as `"auto"` or `"manual"`.

- `"auto"` — Automatically divide mask angle azimuth edges evenly between `0` and `360` degrees.
- `"manual"` — Specify mask angle azimuth edges manually using the `MaskAzimuthEdges` property.

Example: `h = skyplot(__,MaskAzimuthEdgesMode="manual")`

Data Types: `string` | `char`

**Chart Properties**

### `HandleVisibility` — Visibility of object handle

`'on'` (default) | `'off'` | `'callback'`

Visibility of the `SkyPlotChart` object handle in the `Children` property of the parent, specified as one of these values:

- `'on'` — Object handle is always visible.
- `'off'` — Object handle is invisible at all times. This option is useful for preventing unintended changes to the UI by another function. To temporarily hide the handle during the execution of that function, set the `HandleVisibility` to `'off'`.
- `'callback'` — Object handle is visible from within callbacks or functions invoked by callbacks, but not from within functions invoked from the command line. This option blocks access to the object at the command line, but allows callback functions to access it.

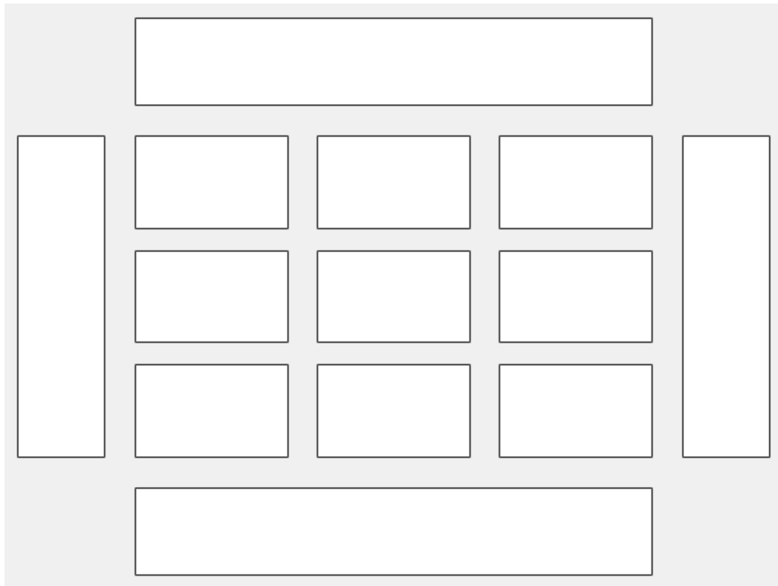
If the object is not listed in the `Children` property of the parent, then functions that obtain object handles by searching the object hierarchy or querying handle properties cannot return it. This includes `get`, `findobj`, `gca`, `gcf`, `gco`, `newplot`, `cla`, `clf`, and `close`.

Hidden object handles are still valid. Set the root `ShowHiddenHandles` property to `'on'` to list all object handles, regardless of their `HandleVisibility` property setting.

**`Layout` — Layout options**
empty `LayoutOptions` array (default) | `TiledChartLayoutOptions` object | `GridLayoutOptions` object

Layout options, specified as a `TiledChartLayoutOptions` or `GridLayoutOptions` object. This property is useful when the chart is either in a tiled chart layout or a grid layout.

To position the chart within the grid of a tiled chart layout, set the `Tile` and `TileSpan` properties on the `TiledChartLayoutOptions` object. For example, consider a 3-by-3 tiled chart layout. The layout has a grid of tiles in the center, and four tiles along the outer edges. In practice, the grid is invisible and the outer tiles do not take up space until you populate them with axes or charts.



This code places the chart `c` in the third tile of the grid.

```
c.Layout.Tile = 3;
```

To make the chart span multiple tiles, specify the `TileSpan` property as a two-element vector. For example, this chart spans 2 rows and 3 columns of tiles.

```
c.Layout.TileSpan = [2 3];
```

To place the chart in one of the surrounding tiles, specify the `Tile` property as `"north"`, `"south"`, `"east"`, or `"west"`. For example, setting the value to `"east"` places the chart in the tile to the right of the grid.

```
c.Layout.Tile = "east";
```

To place the chart into a layout within an app, specify this property as a `GridLayoutOptions` object. For more information about working with grid layouts in apps, see `uigridlayout`.

If the chart is not a child of either a tiled chart layout or a grid layout (for example, if it is a child of a figure or panel) then this property is empty and has no effect.

### Parent — Parent container

`Figure` object | `Panel` object | `Tab` object | `TiledChartLayout` object | `GridLayout` object

Parent container, specified as a `Figure`, `Panel`, `Tab`, `TiledChartLayout`, or `GridLayout` object.

#### Marker Properties

### MarkerEdgeAlpha — Marker edge transparency

`1` (default) | scalar in range `[0,1]` | `'flat'`

Marker edge transparency, specified as a scalar in the range `[0,1]` or `'flat'`. A value of 1 is opaque and 0 is completely transparent. Values between 0 and 1 are semitransparent.

To set the edge transparency to a different value for each point in the plot, set the `AlphaData` property to a vector the same size as the `XData` property, and set the `MarkerEdgeAlpha` property to `'flat'`.

### MarkerEdgeColor — Marker outline color

`'flat'` (default) | `'auto'` | RGB triplet | hexadecimal color code | `'r'` | `'g'` | `'b'` | ...

Marker outline color, specified as `'auto'`, an RGB triplet, a hexadecimal color code, a color name, or a short name. The value of `'auto'` uses the same color as the `Color` property.

For a custom color, specify an RGB triplet or a hexadecimal color code.

- An RGB triplet is a three-element row vector whose elements specify the intensities of the red, green, and blue components of the color. The intensities must be in the range `[0,1]`. For example, `[0.4 0.6 0.7]`.
- A hexadecimal color code is a character vector or a string scalar that starts with a hash symbol (`#`) followed by three or six hexadecimal digits, which can range from `0` to `F`. The values are not case sensitive. Thus, the color codes `'#FF8800'`, `'#ff8800'`, `'#F80'`, and `'#f80'` are equivalent.

Alternatively, you can specify some common colors by name. This table lists the named color options, the equivalent RGB triplets, and the hexadecimal color codes.

| Color Name | Short Name | RGB Triplet | Hexadecimal Color Code | Appearance |
|---|---|---|---|---|
| 'red' | 'r' | [1 0 0] | '#FF0000' | |
| 'green' | 'g' | [0 1 0] | '#00FF00' | |
| 'blue' | 'b' | [0 0 1] | '#0000FF' | |
| 'cyan' | 'c' | [0 1 1] | '#00FFFF' | |
| 'magenta' | 'm' | [1 0 1] | '#FF00FF' | |
| 'yellow' | 'y' | [1 1 0] | '#FFFF00' | |
| 'black' | 'k' | [0 0 0] | '#000000' | |
| 'white' | 'w' | [1 1 1] | '#FFFFFF' | |
| 'none' | Not applicable | Not applicable | Not applicable | No color |

This table shows the RGB triplets and hexadecimal color codes for the default colors MATLAB uses in many types of plots.

| RGB Triplet | Hexadecimal Color Code | Appearance |
|---|---|---|
| [0 0.4470 0.7410] | '#0072BD' | |
| [0.8500 0.3250 0.0980] | '#D95319' | |
| [0.9290 0.6940 0.1250] | '#EDB120' | |
| [0.4940 0.1840 0.5560] | '#7E2F8E' | |
| [0.4660 0.6740 0.1880] | '#77AC30' | |
| [0.3010 0.7450 0.9330] | '#4DBEEE' | |
| [0.6350 0.0780 0.1840] | '#A2142F' | |

**MarkerFaceAlpha — Marker face transparency**
0.6 (default) | scalar in range [0,1] | 'flat'

Marker face transparency, specified as a scalar in the range [0,1] or 'flat'. A value of 1 is opaque and 0 is completely transparent. Values between 0 and 1 are partially transparent.

To set the marker face transparency to a different value for each point, set the AlphaData property to a vector the same size as the XData property, and set the MarkerFaceAlpha property to 'flat'.

**MarkerFaceColor — Marker fill color**
'flat' (default) | 'auto' | 'none' | RGB triplet | hexadecimal color code | 'r' | 'g' | 'b' | ...

Marker fill color, specified as 'flat', 'auto', an RGB triplet, a hexadecimal color code, a color name, or a short name. The 'flat' option uses the CData values. The 'auto' option uses the same color as the Color property for the axes.

For a custom color, specify an RGB triplet or a hexadecimal color code.

- An RGB triplet is a three-element row vector whose elements specify the intensities of the red, green, and blue components of the color. The intensities must be in the range [0,1]; for example, [0.4 0.6 0.7].

- A hexadecimal color code is a character vector or a string scalar that starts with a hash symbol (#) followed by three or six hexadecimal digits, which can range from `0` to `F`. The values are not case sensitive. Thus, the color codes `'#FF8800'`, `'#ff8800'`, `'#F80'`, and `'#f80'` are equivalent.

Alternatively, you can specify some common colors by name. This table lists the named color options, the equivalent RGB triplets, and hexadecimal color codes.

| Color Name | Short Name | RGB Triplet | Hexadecimal Color Code | Appearance |
|---|---|---|---|---|
| 'red' | 'r' | [1 0 0] | '#FF0000' | |
| 'green' | 'g' | [0 1 0] | '#00FF00' | |
| 'blue' | 'b' | [0 0 1] | '#0000FF' | |
| 'cyan' | 'c' | [0 1 1] | '#00FFFF' | |
| 'magenta' | 'm' | [1 0 1] | '#FF00FF' | |
| 'yellow' | 'y' | [1 1 0] | '#FFFF00' | |
| 'black' | 'k' | [0 0 0] | '#000000' | |
| 'white' | 'w' | [1 1 1] | '#FFFFFF' | |
| 'none' | Not applicable | Not applicable | Not applicable | No color |

Here are the RGB triplets and hexadecimal color codes for the default colors MATLAB uses in many types of plots.

| RGB Triplet | Hexadecimal Color Code | Appearance |
|---|---|---|
| [0 0.4470 0.7410] | '#0072BD' | |
| [0.8500 0.3250 0.0980] | '#D95319' | |
| [0.9290 0.6940 0.1250] | '#EDB120' | |
| [0.4940 0.1840 0.5560] | '#7E2F8E' | |
| [0.4660 0.6740 0.1880] | '#77AC30' | |
| [0.3010 0.7450 0.9330] | '#4DBEEE' | |
| [0.6350 0.0780 0.1840] | '#A2142F' | |

Example: `[0.3 0.2 0.1]`

Example: `'green'`

Example: `'#D2F9A7'`

### `MarkerSizeData` — Marker size

`100` (default) | positive scalar | vector of positive values

Marker size, specified as a positive scalar or vector of positive values in points, where one point = 1/72 of an inch. If specified as a vector, the vector must be of the same length as `AzimuthData`.

**Position**

### `PositionConstraint` — Position to hold constant

`"outerposition"` | `"innerposition"`

Position property to hold constant when adding, removing, or changing decorations, specified as one of the following values:

- `"outerposition"` — The `OuterPosition` property remains constant when you add, remove, or change decorations such as a title or an axis label. If any positional adjustments are needed, MATLAB adjusts the `InnerPosition` property.
- `"innerposition"` — The `InnerPosition` property remains constant when you add, remove, or change decorations such as a title or an axis label. If any positional adjustments are needed, MATLAB adjusts the `OuterPosition` property.

**Note** Setting this property has no effect when the parent container is a `TiledChartLayout`.

**`OuterPosition` — Outer size and location**
`[0 0 1 1]` (default) | four-element vector

Outer size and location of the skyplot within the parent container (typically a figure, panel, or tab), specified as a four-element vector of the form `[left bottom width height]`. The outer position includes the colorbar, title, and axis labels.

- The `left` and `bottom` elements define the distance from the lower-left corner of the container to the lower-left corner of the skyplot.
- The `width` and `height` elements are the skyplot dimensions, which include the skyplot cells, plus a margin for the surrounding text and colorbar.

The default value of `[0 0 1 1]` covers the whole interior of the container. The units are normalized relative to the size of the container. To change the units, set the `Units` property.

**Note** Setting this property has no effect when the parent container is a `TiledChartLayout`.

**`InnerPosition` — Inner size and location**
`[0.1300 0.1100 0.7750 0.8114]` (default) | four-element vector

Inner size and location of the skyplot within the parent container (typically a figure, panel, or tab), specified as a four-element vector of the form `[left bottom width height]`. The inner position does not include the colorbar, title, or axis labels.

- The `left` and `bottom` elements define the distance from the lower-left corner of the container to the lower-left corner of the skyplot.
- The `width` and `height` elements are the skyplot dimensions, which include only the skyplot cells.

**Note** Setting this property has no effect when the parent container is a `TiledChartLayout`.

**`Position` — Inner size and location**
four-element vector

Inner size and location of the skyplot within the parent container (typically a figure, panel, or tab), specified as a four-element vector of the form `[left bottom width height]`. This property is equivalent to the `InnerPosition` property.

**Note** Setting this property has no effect when the parent container is a `TiledChartLayout`.

### Units — Position units

'normalized' (default) | 'inches' | 'centimeters' | 'points' | 'pixels' | 'characters'

Position units, specified as one of these values.

| Units | Description |
| --- | --- |
| 'normalized' (default) | Normalized with respect to the container, which is typically the figure or a panel. The lower left corner of the container maps to (0,0), and the upper right corner maps to (1,1). |
| 'inches' | Inches. |
| 'centimeters' | Centimeters. |
| 'characters' | Based on the default uicontrol font of the graphics root object:<br>• Character width = width of letter x.<br>• Character height = distance between the baselines of two lines of text. |
| 'points' | Typography points. One point equals 1/72 inch. |
| 'pixels' | Pixels.<br>Starting in R2015b, distances in pixels are independent of your system resolution on Windows® and Macintosh systems:<br>• On Windows systems, a pixel is 1/96th of an inch.<br>• On Macintosh systems, a pixel is 1/72nd of an inch.<br>On Linux® systems, the size of a pixel is determined by your system resolution. |

When specifying the units as a name-value argument during object creation, you must set the `Units` property before specifying the properties that you want to use these units, such as `OuterPosition`.

### Visible — State of visibility

'on' (default) | on/off logical value

State of visibility, specified as `'on'` or `'off'`, or as numeric or logical `1` (`true`) or `0` (`false`). A value of `'on'` is equivalent to `true`, and `'off'` is equivalent to `false`. Thus, you can use the value of this property as a logical value. The value is stored as an on/off logical value of type `matlab.lang.OnOffSwitchState`.

- `'on'` — Display the skyplot.
- `'off'` — Hide the skyplot without deleting it. You can still access the properties of an invisible `SkyPlotChart` object.

## Version History

**Introduced in R2021a**

### R2022b: `SkyPlotChart` supports azimuth and elevation trajectories and elevation masks

- The `AzimuthData` and `ElevationData` properties now accept matrices, enabling you to represent trajectories by adding azimuth and elevation data for satellites at multiple time steps.
- Elevation angle masks are now supported using these new properties:
  - `MaskElevation`
  - `MaskAlpha`
  - `MaskColor`
  - `MaskAzimuthEdges`
  - `MaskAzimuthEdgesMode`

## See Also

**Functions**
`skyplot` | `polarscatter`

**Objects**
`gnssSensor` | `nmeaParser`

# stateEstimatorPF

Create particle filter state estimator

## Description

The `stateEstimatorPF` object is a recursive, Bayesian state estimator that uses discrete particles to approximate the posterior distribution of the estimated state.

The particle filter algorithm computes the state estimate recursively and involves two steps: prediction and correction. The prediction step uses the previous state to predict the current state based on a given system model. The correction step uses the current sensor measurement to correct the state estimate. The algorithm periodically redistributes, or resamples, the particles in the state space to match the posterior distribution of the estimated state.

The estimated state consists of state variables. Each particle represents a discrete state hypothesis of these state variables. The set of all particles is used to help determine the final state estimate.

You can apply the particle filter to arbitrary nonlinear system models. Process and measurement noise can follow arbitrary non-Gaussian distributions.

For more information on the particle filter workflow and setting specific parameters, see:

- "Particle Filter Workflow"
- "Particle Filter Parameters"

## Creation

### Syntax

```
pf = stateEstimatorPF
```

#### Description

`pf = stateEstimatorPF` creates an object that enables the state estimation for a simple system with three state variables. Use the `initialize` method to initialize the particles with a known mean and covariance or uniformly distributed particles within defined bounds. To customize the particle filter's system and measurement models, modify the `StateTransitionFcn` and `MeasurementLikelihoodFcn` properties.

After you create the object, use `initialize` to initialize the `NumStateVariables` and `NumParticles` properties. The `initialize` function sets these two properties based on your inputs.

### Properties

**`NumStateVariables` — Number of state variables**
3 (default) | scalar

This property is read-only.

Number of state variables, specified as a scalar. This property is set based on the inputs to the `initialize` method. The number of states is implicit based on the specified matrices for initial state and covariance.

**`NumParticles` — Number of particles used in the filter**
1000 (default) | scalar

This property is read-only.

Number of particles using in the filter, specified as a scalar. You can specify this property only by calling the `initialize` method.

**`StateTransitionFcn` — Callback function for determining the state transition between particle filter steps**
function handle

Callback function for determining the state transition between particle filter steps, specified as a function handle. The state transition function evolves the system state for each particle. The function signature is:

```
function predictParticles = stateTransitionFcn(pf,prevParticles,varargin)
```

The callback function accepts at least two input arguments: the `stateEstimatorPF` object, `pf`, and the particles at the previous time step, `prevParticles`. These specified particles are the `predictParticles` returned from the previous call of the object. `predictParticles` and `prevParticles` are the same size: `NumParticles`-by-`NumStateVariables`.

You can also use `varargin` to pass in a variable number of arguments from the `predict` function. When you call:

```
predict(pf,arg1,arg2)
```

MATLAB essentially calls `stateTranstionFcn` as:

```
stateTransitionFcn(pf,prevParticles,arg1,arg2)
```

**`MeasurementLikelihoodFcn` — Callback function calculating the likelihood of sensor measurements**
function handle

Callback function calculating the likelihood of sensor measurements, specified as a function handle. Once a sensor measurement is available, this callback function calculates the likelihood that the measurement is consistent with the state hypothesis of each particle. You must implement this function based on your measurement model. The function signature is:

```
function likelihood = measurementLikelihoodFcn(PF,predictParticles,measurement,varargin)
```

The callback function accepts at least three input arguments:

1. `pf` – The associated `stateEstimatorPF` object
2. `predictParticles` – The particles that represent the predicted system state at the current time step as an array of size `NumParticles`-by-`NumStateVariables`
3. `measurement` – The state measurement at the current time step

You can also use `varargin` to pass in a variable number of arguments. These arguments are passed by the `correct` function. When you call:

```
correct(pf,measurement,arg1,arg2)
```

MATLAB essentially calls `measurementLikelihoodFcn` as:

```
measurementLikelihoodFcn(pf,predictParticles,measurement,arg1,arg2)
```

The callback needs to return exactly one output, `likelihood`, which is the likelihood of the given `measurement` for each particle state hypothesis.

#### `IsStateVariableCircular` — Indicator if state variables have a circular distribution

[0 0 0] (default) | logical array

Indicator if state variables have a circular distribution, specified as a logical array. Circular (or angular) distributions use a probability density function with a range of `[-pi,pi]`. If the object has multiple state variables, then `IsStateVariableCircular` is a row vector. Each vector element indicates if the associated state variable is circular. If the object has only one state variable, then `IsStateVariableCircular` is a scalar.

#### `ResamplingPolicy` — Policy settings that determine when to trigger resampling

object

Policy settings that determine when to trigger resampling, specified as an object. You can trigger resampling either at fixed intervals, or you can trigger it dynamically, based on the number of effective particles. See `resamplingPolicyPF` for more information.

#### `ResamplingMethod` — Method used for particle resampling

`'multinomial'` (default) | `'residual'` | `'stratified'` | `'systematic'`

Method used for particle resampling, specified as `'multinomial'`, `'residual'`, `'stratified'`, and `'systematic'`.

#### `StateEstimationMethod` — Method used for state estimation

`'mean'` (default) | `'maxweight'`

Method used for state estimation, specified as `'mean'` and `'maxweight'`.

#### `Particles` — Array of particle values

`NumParticles`-by-`NumStateVariables` matrix

Array of particle values, specified as a `NumParticles`-by-`NumStateVariables` matrix. Each row corresponds to the state hypothesis of a single particle.

#### `Weights` — Particle weights

`NumParticles`-by-1 vector

Particle weights, specified as a `NumParticles`-by-1 vector. Each weight is associated with the particle in the same row in the `Particles` property.

#### `State` — Best state estimate

vector

This property is read-only.

Best state estimate, returned as a vector with length `NumStateVariables`. The estimate is extracted based on the `StateEstimationMethod` property.

**`StateCovariance` — Corrected system covariance**
*N*-by-*N* matrix | `[]`

This property is read-only.

Corrected system variance, returned as an *N*-by-*N* matrix, where *N* is equal to the `NumStateVariables` property. The corrected state is calculated based on the `StateEstimationMethod` property and the `MeasurementLikelihoodFcn`. If you specify a state estimate method that does not support covariance, then the property is set to `[]`.

## Object Functions

| | |
|---|---|
| initialize | Initialize the state of the particle filter |
| getStateEstimate | Extract best state estimate and covariance from particles |
| predict | Predict state of robot in next time step |
| correct | Adjust state estimate based on sensor measurement |

## Examples

### Particle Filter Prediction and Correction

Create a `stateEstimatorPF` object, and execute a prediction and correction step for state estimation. The particle filter gives a predicted state estimate based on the return value of `StateTransitionFcn`. It then corrects the state based on a given measurement and the return value of `MeasurementLikelihoodFcn`.

Create a particle filter with the default three states.

```
pf = stateEstimatorPF
```

```
pf = 
  stateEstimatorPF with properties:

           NumStateVariables: 3
                NumParticles: 1000
          StateTransitionFcn: @nav.algs.gaussianMotion
    MeasurementLikelihoodFcn: @nav.algs.fullStateMeasurement
     IsStateVariableCircular: [0 0 0]
            ResamplingPolicy: [1x1 resamplingPolicyPF]
            ResamplingMethod: 'multinomial'
       StateEstimationMethod: 'mean'
            StateOrientation: 'row'
                   Particles: [1000x3 double]
                     Weights: [1000x1 double]
                       State: 'Use the getStateEstimate function to see the value.'
             StateCovariance: 'Use the getStateEstimate function to see the value.'
```

Specify the mean state estimation method and systematic resampling method.

```
pf.StateEstimationMethod = 'mean';
pf.ResamplingMethod = 'systematic';
```

Initialize the particle filter at state [4 1 9] with unit covariance (`eye(3)`). Use 5000 particles.

```
initialize(pf,5000,[4 1 9],eye(3));
```

Assuming a measurement [4.2 0.9 9], run one predict and one correct step.

```
[statePredicted,stateCov] = predict(pf);
[stateCorrected,stateCov] = correct(pf,[4.2 0.9 9]);
```

Get the best state estimate based on the `StateEstimationMethod` algorithm.

```
stateEst = getStateEstimate(pf)
```

```
stateEst = 1×3

    4.1562    0.9185    9.0202
```

### Estimate Robot Position in a Loop Using Particle Filter

Use the `stateEstimatorPF` object to track a robot as it moves in a 2-D space. The measured position has random noise added. Using `predict` and `correct`, track the robot based on the measurement and on an assumed motion model.

Initialize the particle filter and specify the default state transition function, the measurement likelihood function, and the resampling policy.

```
pf = stateEstimatorPF;
pf.StateEstimationMethod = 'mean';
pf.ResamplingMethod = 'systematic';
```

Sample 1000 particles with an initial position of [0 0] and unit covariance.

```
initialize(pf,1000,[0 0],eye(2));
```

Prior to estimation, define a sine wave path for the dot to follow. Create an array to store the predicted and estimated position. Define the amplitude of noise.

```
t = 0:0.1:4*pi;
dot = [t; sin(t)]';
robotPred = zeros(length(t),2);
robotCorrected = zeros(length(t),2);
noise = 0.1;
```

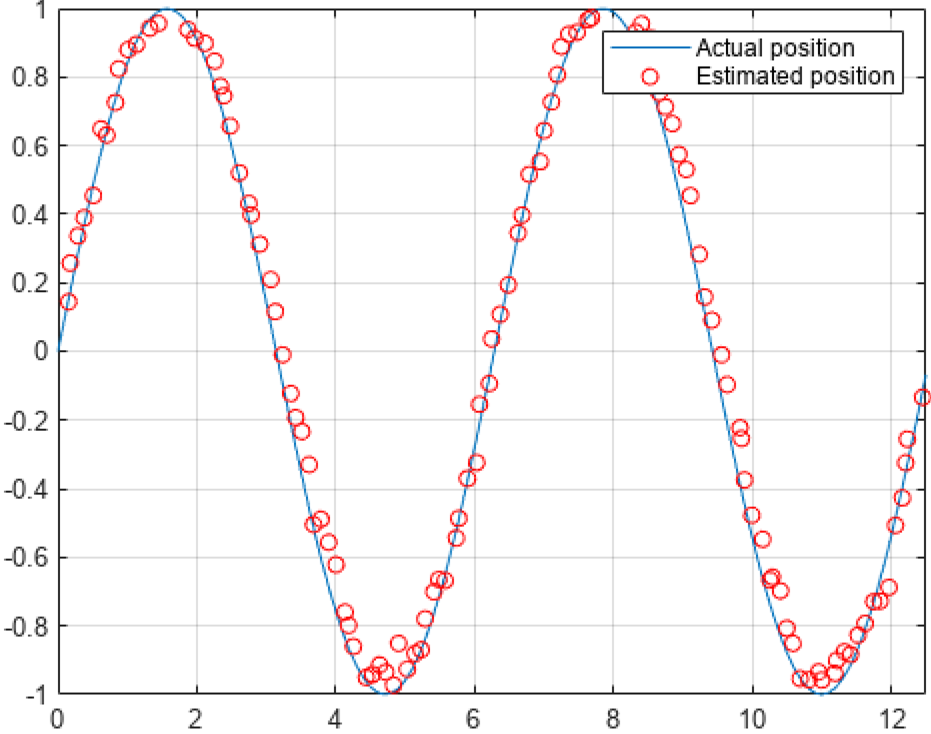
Begin the loop for predicting and correcting the estimated position based on measurements. The resampling of particles occurs based on the`ResamplingPolicy` property. The robot moves based on a sine wave function with random noise added to the measurement.

```
for i = 1:length(t)
    % Predict next position. Resample particles if necessary.
    [robotPred(i,:),robotCov] = predict(pf);
    % Generate dot measurement with random noise. This is
    % equivalent to the observation step.
    measurement(i,:) = dot(i,:) + noise*(rand([1 2])-noise/2);
    % Correct position based on the given measurement to get best estimation.
```

```
    % Actual dot position is not used. Store corrected position in data array.
    [robotCorrected(i,:),robotCov] = correct(pf,measurement(i,:));
end
```

Plot the actual path versus the estimated position. Actual results may vary due to the randomness of particle distributions.

```
plot(dot(:,1),dot(:,2),robotCorrected(:,1),robotCorrected(:,2),'or')
xlim([0 t(end)])
ylim([-1 1])
legend('Actual position','Estimated position')
grid on
```




The figure shows how close the estimate state matches the actual position of the robot. Try tuning the number of particles or specifying a different initial position and covariance to see how it affects tracking over time.

# Version History

**Introduced in R2016a**

### R2019b: `stateEstimatorPF` was renamed

*Behavior change in future release*

The `stateEstimatorPF` object was renamed from `robotics.ParticleFilter`. Use `stateEstimatorPF` for all object creation.

## References

[1] Arulampalam, M.S., S. Maskell, N. Gordon, and T. Clapp. "A Tutorial on Particle Filters for Online Nonlinear/Non-Gaussian Bayesian Tracking." *IEEE Transactions on Signal Processing.* Vol. 50, No. 2, Feb 2002, pp. 174-188.

[2] Chen, Z. "Bayesian Filtering: From Kalman Filters to Particle Filters, and Beyond." *Statistics*. Vol. 182, No. 1, 2003, pp. 1-69.

## Extended Capabilities

#### C/C++ Code Generation
Generate C and C++ code using MATLAB® Coder™.

## See Also
`resamplingPolicyPF` | `initialize` | `getStateEstimate` | `predict` | `correct`

#### Topics
“Track a Car-Like Robot Using Particle Filter” (Robotics System Toolbox)
“Particle Filter Parameters”
“Particle Filter Workflow”

# copy

Create copy of particle filter

## Syntax

```
b = copy(a)
```

## Description

`b = copy(a)` copies each element in the array of handles, `a`, to the new array of handles, `b`.

The `copy` method does not copy dependent properties. MATLAB does not call `copy` recursively on any handles contained in property values. MATLAB also does not call the class constructor or property-set methods during the copy operation.

## Input Arguments

**a — Object array**
handle

Object array, specified as a handle.

## Output Arguments

**b — Object array containing copies of the objects in a**
handle

Object array containing copies of the object in `a`, specified as a handle.

`b` has the same number of elements and is the same size and class of `a`. `b` is the same class as `a`. If `a` is empty, `b` is also empty. If `a` is heterogeneous, `b` is also heterogeneous. If `a` contains deleted handles, then `copy` creates deleted handles of the same class in `b`. Dynamic properties and listeners associated with objects in `a` are not copied to objects in `b`.

# Version History

**Introduced in R2016a**

## See Also

`stateEstimatorPF` | `resamplingPolicyPF` | `initialize` | `getStateEstimate` | `predict` | `correct`

**Topics**

"Track a Car-Like Robot Using Particle Filter" (Robotics System Toolbox)
"Particle Filter Parameters"
"Particle Filter Workflow"

# correct

Adjust state estimate based on sensor measurement

## Syntax

```
[stateCorr,stateCov] = correct(pf,measurement)
[stateCorr,stateCov] = correct(pf,measurement,varargin)
```

## Description

`[stateCorr,stateCov] = correct(pf,measurement)` calculates the corrected system state and its associated uncertainty covariance based on a sensor `measurement` at the current time step. `correct` uses the `MeasurementLikelihoodFcn` property from the particle filter object, `pf`, as a function to calculate the likelihood of the sensor measurement for each particle. The two inputs to the `MeasurementLikelihoodFcn` function are:

1. `pf` – The `stateEstimatorPF` object, which contains the particles of the current iteration
2. `measurement` – The sensor measurements used to correct the state estimate

The `MeasurementLikelihoodFcn` function then extracts the best state estimate and covariance based on the setting in the `StateEstimationMethod` property.

`[stateCorr,stateCov] = correct(pf,measurement,varargin)` passes all additional arguments in `varargin` to the underlying `MeasurementLikelihoodFcn` after the first three required inputs.

## Examples

### Particle Filter Prediction and Correction

Create a `stateEstimatorPF` object, and execute a prediction and correction step for state estimation. The particle filter gives a predicted state estimate based on the return value of `StateTransitionFcn`. It then corrects the state based on a given measurement and the return value of `MeasurementLikelihoodFcn`.

Create a particle filter with the default three states.

```
pf = stateEstimatorPF
```

```
pf = 
  stateEstimatorPF with properties:

           NumStateVariables: 3
                NumParticles: 1000
          StateTransitionFcn: @nav.algs.gaussianMotion
    MeasurementLikelihoodFcn: @nav.algs.fullStateMeasurement
     IsStateVariableCircular: [0 0 0]
            ResamplingPolicy: [1x1 resamplingPolicyPF]
            ResamplingMethod: 'multinomial'
       StateEstimationMethod: 'mean'
```

```
StateOrientation: 'row'
       Particles: [1000x3 double]
         Weights: [1000x1 double]
           State: 'Use the getStateEstimate function to see the value.'
 StateCovariance: 'Use the getStateEstimate function to see the value.'
```

Specify the mean state estimation method and systematic resampling method.

```
pf.StateEstimationMethod = 'mean';
pf.ResamplingMethod = 'systematic';
```

Initialize the particle filter at state [4 1 9] with unit covariance (`eye(3)`). Use 5000 particles.

```
initialize(pf,5000,[4 1 9],eye(3));
```

Assuming a measurement [4.2 0.9 9], run one predict and one correct step.

```
[statePredicted,stateCov] = predict(pf);
[stateCorrected,stateCov] = correct(pf,[4.2 0.9 9]);
```

Get the best state estimate based on the `StateEstimationMethod` algorithm.

```
stateEst = getStateEstimate(pf)
```

```
stateEst = 1×3

    4.1562    0.9185    9.0202
```

## Input Arguments

**pf — stateEstimatorPF object**
handle

`stateEstimatorPF` object, specified as a handle. See `stateEstimatorPF` for more information.

**measurement — Sensor measurements**
array

Sensor measurements, specified as an array. This input is passed directly into the `MeasurementLikelihoodFcn` property of `pf`. It is used to calculate the likelihood of the sensor measurement for each particle.

**varargin — Variable-length input argument list**
comma-separated list

Variable-length input argument list, specified as a comma-separated list. This input is passed directly into the `MeasurementLikelihoodFcn` property of `pf`. It is used to calculate the likelihood of the sensor measurement for each particle. When you call:

```
correct(pf,measurement,arg1,arg2)
```

MATLAB essentially calls `measurementLikelihoodFcn` as:

```
measurementLikelihoodFcn(pf,measurement,arg1,arg2)
```

## Output Arguments

**`stateCorr` — Corrected system state**
vector with length `NumStateVariables`

Corrected system state, returned as a row vector with length `NumStateVariables`. The corrected state is calculated based on the `StateEstimationMethod` algorithm and the `MeasurementLikelihoodFcn`.

**`stateCov` — Corrected system covariance**
*N*-by-*N* matrix | `[]`

Corrected system variance, returned as an *N*-by-*N* matrix, where *N* is the value of `NumStateVariables` property from `pf`. The corrected state is calculated based on the `StateEstimationMethod` algorithm and the `MeasurementLikelihoodFcn`. If you specify a state estimate method that does not support covariance, then the function returns `stateCov` as `[]`.

# Version History

**Introduced in R2016a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

`stateEstimatorPF` | `resamplingPolicyPF` | `initialize` | `getStateEstimate` | `predict`

**Topics**
“Track a Car-Like Robot Using Particle Filter” (Robotics System Toolbox)
“Particle Filter Parameters”
“Particle Filter Workflow”

# getStateEstimate

Extract best state estimate and covariance from particles

## Syntax

```
stateEst = getStateEstimate(pf)
[stateEst,stateCov] = getStateEstimate(pf)
```

## Description

`stateEst = getStateEstimate(pf)` returns the best state estimate based on the current set of particles. The estimate is extracted based on the `StateEstimationMethod` property from the `stateEstimatorPF` object, `pf`.

`[stateEst,stateCov] = getStateEstimate(pf)` also returns the covariance around the state estimate. The covariance is a measure of the uncertainty of the state estimate. Not all state estimate methods support covariance output. In this case, `getStateEstimate` returns `stateCov` as `[]`.

## Examples

### Particle Filter Prediction and Correction

Create a `stateEstimatorPF` object, and execute a prediction and correction step for state estimation. The particle filter gives a predicted state estimate based on the return value of `StateTransitionFcn`. It then corrects the state based on a given measurement and the return value of `MeasurementLikelihoodFcn`.

Create a particle filter with the default three states.

```
pf = stateEstimatorPF
```

```
pf = 
  stateEstimatorPF with properties:

           NumStateVariables: 3
                NumParticles: 1000
          StateTransitionFcn: @nav.algs.gaussianMotion
    MeasurementLikelihoodFcn: @nav.algs.fullStateMeasurement
     IsStateVariableCircular: [0 0 0]
            ResamplingPolicy: [1x1 resamplingPolicyPF]
            ResamplingMethod: 'multinomial'
       StateEstimationMethod: 'mean'
            StateOrientation: 'row'
                   Particles: [1000x3 double]
                     Weights: [1000x1 double]
                       State: 'Use the getStateEstimate function to see the value.'
             StateCovariance: 'Use the getStateEstimate function to see the value.'
```

Specify the mean state estimation method and systematic resampling method.

```
pf.StateEstimationMethod = 'mean';
pf.ResamplingMethod = 'systematic';
```

Initialize the particle filter at state [4 1 9] with unit covariance (`eye(3)`). Use 5000 particles.

```
initialize(pf,5000,[4 1 9],eye(3));
```

Assuming a measurement [4.2 0.9 9], run one predict and one correct step.

```
[statePredicted,stateCov] = predict(pf);
[stateCorrected,stateCov] = correct(pf,[4.2 0.9 9]);
```

Get the best state estimate based on the `StateEstimationMethod` algorithm.

```
stateEst = getStateEstimate(pf)
```

```
stateEst = 1×3

    4.1562    0.9185    9.0202
```

## Input Arguments

**`pf` — `stateEstimatorPF` object**
handle

`stateEstimatorPF` object, specified as a handle. See `stateEstimatorPF` for more information.

## Output Arguments

**`stateEst` — Best state estimate**
vector

Best state estimate, returned as a row vector with length `NumStateVariables`. The estimate is extracted based on the `StateEstimationMethod` algorithm specified in `pf`.

**`stateCov` — Corrected system covariance**
*N*-by-*N* matrix | `[]`

Corrected system variance, returned as an *N*-by-*N* matrix, where *N* is the value of `NumStateVariables` property from `pf`. The corrected state is calculated based on the `StateEstimationMethod` algorithm and the `MeasurementLikelihoodFcn`. If you specify a state estimate method that does not support covariance, then the function returns `stateCov` as `[]`.

# Version History

**Introduced in R2016a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

`stateEstimatorPF` | `resamplingPolicyPF` | `initialize` | `predict` | `correct`

### Topics

"Track a Car-Like Robot Using Particle Filter" (Robotics System Toolbox)
"Particle Filter Parameters"
"Particle Filter Workflow"

# initialize

Initialize the state of the particle filter

## Syntax

```
initialize(pf,numParticles,mean,covariance)
initialize(pf,numParticles,stateBounds)
initialize( ___ ,Name,Value)
```

## Description

`initialize(pf,numParticles,mean,covariance)` initializes the particle filter object, `pf`, with a specified number of particles, `numParticles`. The initial states of the particles in the state space are determined by sampling from the multivariate normal distribution with the specified `mean` and `covariance`.

`initialize(pf,numParticles,stateBounds)` determines the initial location of the particles by sample from the multivariate uniform distribution within the specified `stateBounds`.

`initialize( ___ ,Name,Value)` initializes the particles with additional options specified by one or more `Name,Value` pair arguments.

## Examples

### Particle Filter Prediction and Correction

Create a `stateEstimatorPF` object, and execute a prediction and correction step for state estimation. The particle filter gives a predicted state estimate based on the return value of `StateTransitionFcn`. It then corrects the state based on a given measurement and the return value of `MeasurementLikelihoodFcn`.

Create a particle filter with the default three states.

```
pf = stateEstimatorPF
```

```
pf = 
  stateEstimatorPF with properties:

           NumStateVariables: 3
                NumParticles: 1000
          StateTransitionFcn: @nav.algs.gaussianMotion
    MeasurementLikelihoodFcn: @nav.algs.fullStateMeasurement
     IsStateVariableCircular: [0 0 0]
            ResamplingPolicy: [1x1 resamplingPolicyPF]
            ResamplingMethod: 'multinomial'
       StateEstimationMethod: 'mean'
            StateOrientation: 'row'
                   Particles: [1000x3 double]
                     Weights: [1000x1 double]
                       State: 'Use the getStateEstimate function to see the value.'
```

```
        StateCovariance: 'Use the getStateEstimate function to see the value.'
```

Specify the mean state estimation method and systematic resampling method.

```
pf.StateEstimationMethod = 'mean';
pf.ResamplingMethod = 'systematic';
```

Initialize the particle filter at state [4 1 9] with unit covariance (`eye(3)`). Use 5000 particles.

```
initialize(pf,5000,[4 1 9],eye(3));
```

Assuming a measurement [4.2 0.9 9], run one predict and one correct step.

```
[statePredicted,stateCov] = predict(pf);
[stateCorrected,stateCov] = correct(pf,[4.2 0.9 9]);
```

Get the best state estimate based on the `StateEstimationMethod` algorithm.

```
stateEst = getStateEstimate(pf)
```

```
stateEst = 1×3

    4.1562    0.9185    9.0202
```

## Input Arguments

**`pf` — `stateEstimatorPF` object**
handle

`stateEstimatorPF` object, specified as a handle. See `stateEstimatorPF` for more information.

**`numParticles` — Number of particles used in the filter**
scalar

Number of particles used in the filter, specified as a scalar.

**`mean` — Mean of particle distribution**
vector

Mean of particle distribution, specified as a vector. The `NumStateVariables` property of `pf` is set based on the length of this vector.

**`covariance` — Covariance of particle distribution**
*N*-by-*N* matrix

Covariance of particle distribution, specified as an *N*-by-*N* matrix, where *N* is the value of `NumStateVariables` property from `pf`.

**`stateBounds` — Bounds of state variables**
*n*-by-2 matrix

Bounds of state variables, specified as an *n*-by-2 matrix. The `NumStateVariables` property of `pf` is set based on the value of *n*. Each row corresponds to the lower and upper limit of the corresponding state variable.

### Name-Value Pair Arguments

Specify optional pairs of arguments as `Name1=Value1,...,NameN=ValueN`, where `Name` is the argument name and `Value` is the corresponding value. Name-value arguments must appear after other arguments, but the order of the pairs does not matter.

*Before R2021a, use commas to separate each name and value, and enclose* `Name` *in quotes.*

Example: `"CircularVariables",[0 0 1]`

**`CircularVariables` — Circular variables**
logical vector

Circular variables, specified as a logical vector. Each state variable that uses circular or angular coordinates is indicated with a 1. The length of the vector is equal to the `NumStateVariables` property of `pf`.

# Version History

**Introduced in R2016a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`stateEstimatorPF` | `resamplingPolicyPF` | `getStateEstimate` | `predict` | `correct`

### Topics

"Track a Car-Like Robot Using Particle Filter" (Robotics System Toolbox)
"Particle Filter Parameters"
"Particle Filter Workflow"

# predict

Predict state of robot in next time step

## Syntax

```
[statePred,stateCov] = predict(pf)
[statePred,stateCov] = predict(pf,varargin)
```

## Description

`[statePred,stateCov] = predict(pf)` calculates the predicted system state and its associated uncertainty covariance. `predict` uses the `StateTransitionFcn` property of `stateEstimatorPF` object, `pf`, to evolve the state of all particles. It then extracts the best state estimate and covariance based on the setting in the `StateEstimationMethod` property.

`[statePred,stateCov] = predict(pf,varargin)` passes all additional arguments specified in `varargin` to the underlying `StateTransitionFcn` property of `pf`. The first input to `StateTransitionFcn` is the set of particles from the previous time step, followed by all arguments in `varargin`.

## Examples

### Particle Filter Prediction and Correction

Create a `stateEstimatorPF` object, and execute a prediction and correction step for state estimation. The particle filter gives a predicted state estimate based on the return value of `StateTransitionFcn`. It then corrects the state based on a given measurement and the return value of `MeasurementLikelihoodFcn`.

Create a particle filter with the default three states.

```
pf = stateEstimatorPF
```

```
pf = 
  stateEstimatorPF with properties:

           NumStateVariables: 3
                NumParticles: 1000
          StateTransitionFcn: @nav.algs.gaussianMotion
    MeasurementLikelihoodFcn: @nav.algs.fullStateMeasurement
     IsStateVariableCircular: [0 0 0]
            ResamplingPolicy: [1x1 resamplingPolicyPF]
            ResamplingMethod: 'multinomial'
       StateEstimationMethod: 'mean'
            StateOrientation: 'row'
                   Particles: [1000x3 double]
                     Weights: [1000x1 double]
                       State: 'Use the getStateEstimate function to see the value.'
             StateCovariance: 'Use the getStateEstimate function to see the value.'
```

Specify the mean state estimation method and systematic resampling method.

```
pf.StateEstimationMethod = 'mean';
pf.ResamplingMethod = 'systematic';
```

Initialize the particle filter at state [4 1 9] with unit covariance (`eye(3)`). Use 5000 particles.

```
initialize(pf,5000,[4 1 9],eye(3));
```

Assuming a measurement [4.2 0.9 9], run one predict and one correct step.

```
[statePredicted,stateCov] = predict(pf);
[stateCorrected,stateCov] = correct(pf,[4.2 0.9 9]);
```

Get the best state estimate based on the `StateEstimationMethod` algorithm.

```
stateEst = getStateEstimate(pf)
```

```
stateEst = 1×3

    4.1562    0.9185    9.0202
```

## Input Arguments

### **`pf` — `stateEstimatorPF` object**
handle

`stateEstimatorPF` object, specified as a handle. See `stateEstimatorPF` for more information.

### **`varargin` — Variable-length input argument list**
comma-separated list

Variable-length input argument list, specified as a comma-separated list. This input is passed directly into the `StateTransitionFcn` property of `pf` to evolve the system state for each particle. When you call:

```
predict(pf,arg1,arg2)
```

MATLAB essentially calls the `stateTranstionFcn` as:

```
stateTransitionFcn(pf,prevParticles,arg1,arg2)
```

## Output Arguments

### **`statePred` — Predicted system state**
vector

Predicted system state, returned as a vector with length `NumStateVariables`. The predicted state is calculated based on the `StateEstimationMethod` algorithm.

### **`stateCov` — Corrected system covariance**
*N*-by-*N* matrix | [ ]

Corrected system variance, returned as an *N*-by-*N* matrix, where *N* is the value of `NumStateVariables` property from `pf`. The corrected state is calculated based on the

`StateEstimationMethod` algorithm and the `MeasurementLikelihoodFcn`. If you specify a state estimate method that does not support covariance, then the function returns `stateCov` as `[]`.

# Version History

**Introduced in R2016a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`stateEstimatorPF` | `resamplingPolicyPF` | `initialize` | `getStateEstimate` | `correct`

### Topics

"Track a Car-Like Robot Using Particle Filter" (Robotics System Toolbox)
"Particle Filter Parameters"
"Particle Filter Workflow"

# stateSpaceSE2

SE(2) state space

## Description

The `stateSpaceSE2` object stores parameters and states in the SE(2) state space, which is composed of state vectors represented by [$x$, $y$, $\theta$]. $x$ and $y$ are Cartesian coordinates, and $\theta$ is the orientation angle. The object uses Euclidean distance to calculate distance and uses linear interpolation to calculate translation and rotation of the state.

## Creation

### Syntax

```
space = stateSpaceSE2
space = stateSpaceSE2(bounds)
```

#### Description

`space = stateSpaceSE2` creates an SE(2) state space object with default state bounds for $x$, $y$, and $\theta$.

`space = stateSpaceSE2(bounds)` specifies the `bounds` for $x$, $y$, and $\theta$. The state values beyond the bounds are truncated to the bounds. The input, `bounds`, allows you to set the value of the StateBounds property.

### Properties

**`Name` — Name of state space**
`'SE2'` (default) | string

Name of state space, specified as a string.

**`NumStateVariables` — Dimension of the state space**
3 (default) | positive integer

This property is read-only.

Dimension of the state space, specified as a positive integer.

**`StateBounds` — Bounds of state variables**
`[-100 100; -100 100; -3.1416 3.1416]` (default) | 3-by-2 real-valued matrix

Bounds of state variables, specified as a 3-by-2 real-valued matrix.

- The first row specifies the lower and upper bounds of the $x$ state in meters.
- The second row specifies the lower and upper bounds of the $y$ state in meters.

- The third row specifies the lower and upper bounds of the $\theta$ state in radians.

Data Types: `double`

**`WeightXY` — Weight applied to x and y distance calculation**
1 (default) | nonnegative real scalar

Weight applied to x and y distance calculation, specified as a nonnegative real scalar.

In the object, the distance calculated as:

$$d = \sqrt{\left(w_{xy}(d_x^2 + d_y^2)\right) + w_\theta d_\theta^2}$$

$w_{xy}$ is weight applied to $x$ and $y$ coordinates, and $w_\theta$ is the weight applied to the $\theta$ coordinate. $d_x$, $d_y$, and $d_\theta$ are the distances in the $x$, $y$, and $\theta$ direction, respectively.

Data Types: `double`

**`WeightTheta` — Weight applied to theta distance calculation**
0.1 (default) | nonnegative real scalar

Weight applied to $\theta$ distance calculation, specified as a nonnegative real scalar.

In the object, the distance calculated as:

$$d = \sqrt{\left(w_{xy}(d_x^2 + d_y^2)\right) + w_\theta d_\theta^2}$$

$w_{xy}$ is weight applied to $x$ and $y$ coordinates, and $w_\theta$ is the weight applied to the $\theta$ coordinate. $d_x$, $d_y$, and $d_\theta$ are the distances in the $x$, $y$, and $\theta$ direction, respectively.

Data Types: `double`

## Object Functions

| | |
|---|---|
| copy | Create deep copy of state space object |
| distance | Distance between two states |
| enforceStateBounds | Reduce state to state bounds |
| interpolate | Interpolate between states |
| sampleGaussian | Sample state using Gaussian distribution |
| sampleUniform | Sample state using uniform distribution |

## Examples

### Plan Path Between Two SE(2) States

Create an SE(2) state space.

```
ss = stateSpaceSE2;
```

Create an `occupancyMap`-based state validator using the created state space.

```
sv = validatorOccupancyMap(ss);
```

Create an occupancy map from an example map and set map resolution as 10 cells/meter.

```
load exampleMaps
map = occupancyMap(simpleMap,10);
sv.Map = map;
```

Set validation distance for the validator.

```
sv.ValidationDistance = 0.01;
```

Update state space bounds to be the same as map limits.

```
ss.StateBounds = [map.XWorldLimits;map.YWorldLimits; [-pi pi]];
```

Create the path planner and increase maximum connection distance.

```
planner = plannerRRT(ss,sv);
planner.MaxConnectionDistance = 0.3;
```

Set the start and goal states.

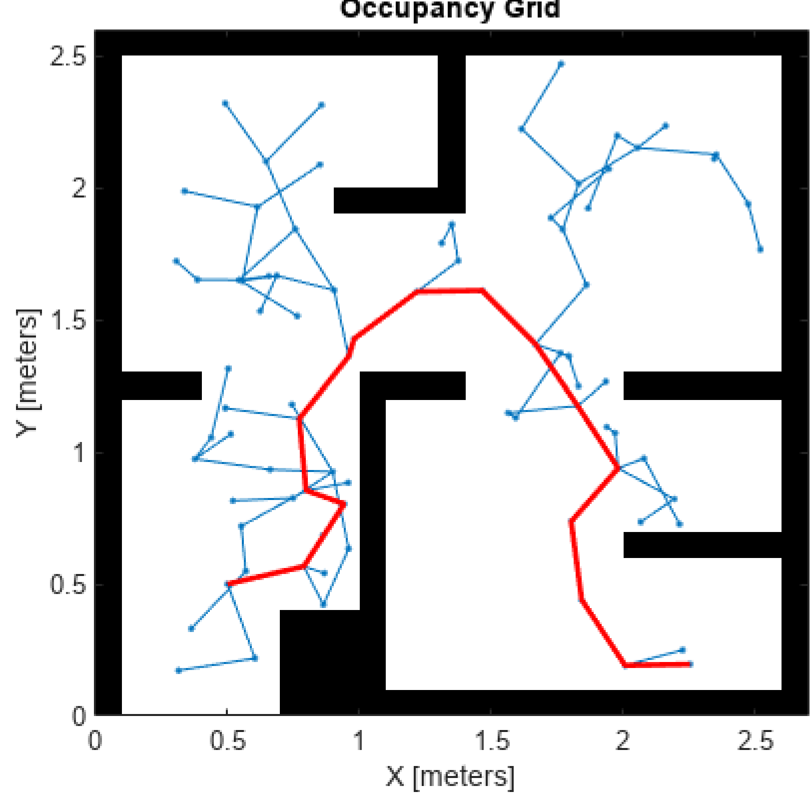
```
start = [0.5,0.5,0];
goal = [2.5,0.2,0];
```

Plan a path with default settings.

```
rng(100,'twister'); % for repeatable result
[pthObj,solnInfo] = planner.plan(start,goal);
```

Visualize the results.

```
map.show; hold on;
plot(solnInfo.TreeData(:,1),solnInfo.TreeData(:,2),'.-'); % tree expansion
plot(pthObj.States(:,1), pthObj.States(:,2),'r-','LineWidth',2) % draw path
```




## Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`stateSpaceDubins` | `stateSpaceReedsShepp`

# stateSpaceSE3

SE(3) state space

## Description

The `stateSpaceSE3` object stores parameters and states in the SE(3) state space, which is composed of state vectors represented by [*x*, *y*, *z*, *qw*, *qx*, *qy*, *qz*]. *x*, *y*, and *z* are Cartesian coordinates. *qw*, *qx*, *qy*, and *qz* represent the orientation in a quaternion. The object uses Euclidean distance calculation and linear interpolation for the translation component of the state. The object uses quaternion distance calculation and spherical linear interpolation for the rotation component of the state.

## Creation

### Syntax

```
space = stateSpaceSE3
space = stateSpaceSE3(bounds)
```

#### Description

`space = stateSpaceSE3` creates an SE(3) state space object with default state bounds for *x*, *y*, and *z*. The state variables *qw*, *qx*, *qy*, and *qz* corresponding to orientation are not bounded.

`space = stateSpaceSE3(bounds)` creates an SE(3) state space object with state bounds specified as a 7-by-2 matrix. Each row specifies the minimum and maximum value for a dimension of the state in the order *x*, *y*, *z*, *qw*, *qx*, *qy*, and *qz*. The input `bounds` sets the `StateBounds` property.

### Properties

**`Name` — Name of state space**
`'SE3'` (default) | character vector

This property is read-only.

Name of state space, specified as a character vector.

Data Types: `char`

**`NumStateVariables` — Number of state space dimensions**
`7` (default) | positive integer

This property is read-only.

Number of state space dimensions, specified dimensions, returned as a positive integer.

Data Types: `double`

**`StateBounds` — Bounds of state variables**
`[-100 100; -100 100; -100 100; Inf Inf; Inf Inf; Inf Inf; Inf Inf]` (default) | 7-by-2 matrix of real values

Bounds of state variables, specified as a 7-by-2 matrix of real values.

- The first row specifies the lower and upper bounds of the *x* state in meters.
- The second row specifies the lower and upper bounds of the *y* state in meters.
- The third row specifies the lower and upper bounds of the *z* state in meters.
- The fourth through the seventh rows specify the lower and upper bounds of the state variables *qw*, *qx*, *qy*, and *qz* respectively, corresponding to orientation as a quaternion.

**Note** The `StateBounds` property only affect the Cartesian components of the state. The state variables corresponding to orientation are not bounded.

Example: `stateSpaceSE3([-10 10; -10 10; -10 10; Inf Inf; Inf Inf; Inf Inf; Inf Inf])`

Example: `space.StateBounds = [-10 10; -10 10; -10 10; Inf Inf; Inf Inf; Inf Inf; Inf Inf]`

Data Types: `double`

**`WeightXYZ` — Weight applied to *x*, *y*, and *z* distance calculation**
`1` (default) | positive real scalar

Weight applied to the *x*, *y*, and *z* distance calculation, specified as a positive real scalar. By default, the weight for translation is chosen to be greater than the weight for rotation.

The object calculates distance as:

$$d = \sqrt{w_{xyz}(d_x^2 + d_y^2 + d_z^2) + w_q d_q^2}$$

,

where $w_{xyz}$ is the weight applied to *x*, *y*, and *z* coordinates, and $w_q$ is the weight applied to the orientation in quaternion. $d_x$, $d_y$, and $d_z$ are the distances in the *x*, *y*, and *z* directions, respectively. $d_q$ is the quaternion distance.

Example: `space.WeightXYZ = 2`

Data Types: `double`

**`WeightQuaternion` — Weight applied to quaternion distance calculation**
`0.1` (default) | positive real scalar

Weight applied to quaternion distance calculation, specified as a positive real scalar. By default, the weight for rotation is chosen to be less than the weight for translation.

The object calculates distance as:

$$d = \sqrt{w_{xyz}(d_x^2 + d_y^2 + d_z^2) + w_q d_q^2}$$

,

where $w_{xyz}$ is weight applied to $x$, $y$, and $z$ coordinates, and $w_q$ is the weight applied to the orientation in quaternion. $d_x$, $d_y$, and $d_z$ are the distances in the $x$, $y$, and $z$ direction, respectively. $d_q$ is the quaternion distance.

Example: `space.WeightQuaternion = 0.5`

Data Types: `double`

## Object Functions

| | |
|---|---|
| copy | Create deep copy of state space object |
| distance | Distance between two states |
| enforceStateBounds | Reduce state to state bounds |
| interpolate | Interpolate between states |
| sampleUniform | Sample state using uniform distribution |

## Examples

#### Validate Path Through 3-D Occupancy Map Environment

Create a 3-D occupancy map and associated state validator. Plan, validate, and visualize a path through the occupancy map.

#### Load and Assign Map to State Validator

Load a 3-D occupancy map of a city block into the workspace. Specify a threshold for which cells to consider as obstacle-free.

```
mapData = load('dMapCityBlock.mat');
omap = mapData.omap;
omap.FreeThreshold = 0.5;
```

Inflate the occupancy map to add a buffer zone for safe operation around the obstacles.

```
inflate(omap,1)
```

Create an SE(3) state space object with bounds for state variables.

```
ss = stateSpaceSE3([-20 220;
    -20 220;
    -10 100;
    inf inf;
    inf inf;
    inf inf;
    inf inf]);
```

Create a 3-D occupancy map state validator using the created state space.

```
sv = validatorOccupancyMap3D(ss);
```

Assign the occupancy map to the state validator object. Specify the sampling distance interval.

```
sv.Map = omap;
sv.ValidationDistance = 0.1;
```

### Plan and Visualize Path

Create a path planner with increased maximum connection distance. Reduce the maximum number of iterations.

```
planner = plannerRRT(ss,sv);
planner.MaxConnectionDistance = 50;
planner.MaxIterations = 1000;
```

Create a user-defined evaluation function for determining whether the path reaches the goal. Specify the probability of choosing the goal state during sampling.

```
planner.GoalReachedFcn = @(~,x,y)(norm(x(1:3)-y(1:3))<5);
planner.GoalBias = 0.1;
```

Set the start and goal states.

```
start = [40 180 25 0.7 0.2 0 0.1];
goal = [150 33 35 0.3 0 0.1 0.6];
```

Plan a path using the specified start, goal, and planner.

```
[pthObj,solnInfo] = plan(planner,start,goal);
```

Check that the points of the path are valid states.

```
isValid = isStateValid(sv,pthObj.States)
```

```
isValid = 7x1 logical array

   1
   1
   1
   1
   1
   1
   1
```

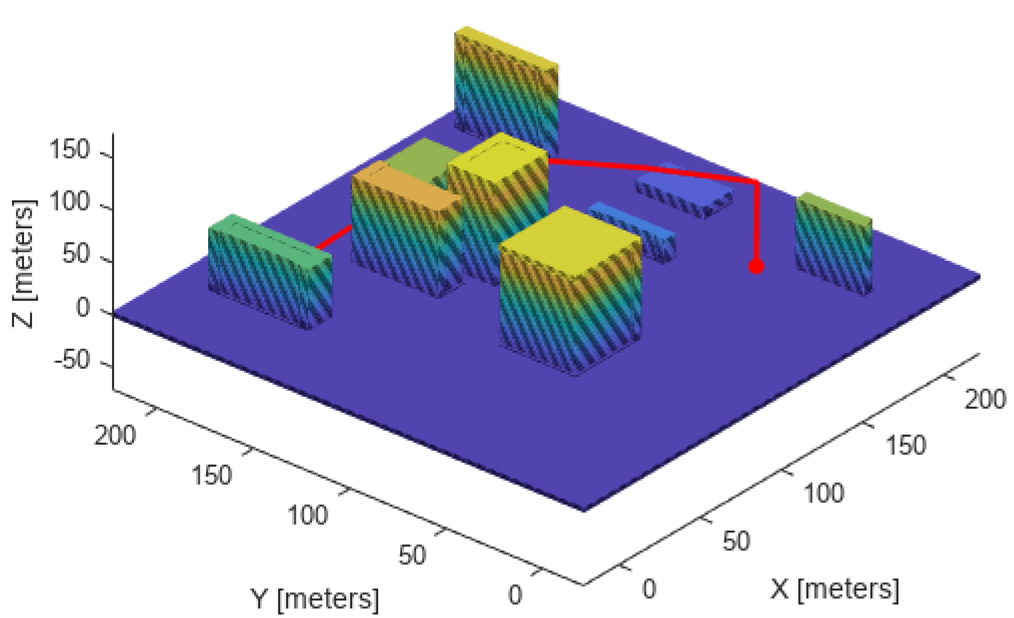
Check that the motion between each sequential path state is valid.

```
isPathValid = zeros(size(pthObj.States,1)-1,1,'logical');
for i = 1:size(pthObj.States,1)-1
    [isPathValid(i),~] = isMotionValid(sv,pthObj.States(i,:),...
        pthObj.States(i+1,:));
end
isPathValid
```

```
isPathValid = 6x1 logical array

   1
   1
   1
   1
   1
   1
```

Visualize the results.

```
show(omap)
hold on
scatter3(start(1,1),start(1,2),start(1,3),'g','filled') % draw start state
scatter3(goal(1,1),goal(1,2),goal(1,3),'r','filled')    % draw goal state
plot3(pthObj.States(:,1),pthObj.States(:,2),pthObj.States(:,3),...
    'r-','LineWidth',2) % draw path
```




# Version History

**Introduced in R2020b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

stateSpaceSE2 | validatorOccupancyMap3D

# stateSpaceDubins

State space for Dubins vehicles

## Description

The `stateSpaceDubins` object stores parameters and states in the Dubins state space, which is composed of state vectors represented by [$x$, $y$, $\theta$]. $x$ and $y$ are Cartesian coordinates, and $\theta$ is the orientation angle. The Dubins state space has a lower limit on the turning radius (specified by the `MinTurningRadius` property in the object) for navigating between states and uses the shortest feasible curve to connect states.

## Creation

### Syntax

```
space = stateSpaceDubins
space = stateSpaceDubins(bounds)
```

#### Description

`space = stateSpaceDubins` creates a Dubins state space object with default state bounds for $x$, $y$, and $\theta$.

`space = stateSpaceDubins(bounds)` specifies the `bounds` for $x$, $y$, and $\theta$. The state values beyond the bounds are truncated to the bounds. The input, `bounds`, allows you to set the value of the StateBounds property.

### Properties

**`Name` — Name of state space**
`'SE2 Dubins'` (default) | string

Name of state space, specified as a string.

**`NumStateVariables` — Dimension of the state space**
3 (default) | positive integer

This property is read-only.

Dimension of the state space, specified as a positive integer.

**`StateBounds` — Bounds of state variables**
`[-100 100; -100 100; -3.1416 3.1416]` (default) | 3-by-2 real-valued matrix

Bounds of state variables, specified as a 3-by-2 real-valued matrix.

- The first row specifies the lower and upper bounds for the $x$ state in meters.

- The second row specifies the lower and upper bounds for the $y$ state in meters.
- The third row specifies the lower and upper bounds for the $\theta$ state in radians.

Data Types: `double`

**`MinTurningRadius` — Minimum turning radius**
1 (default) | positive scalar

Minimum turning radius in meters, specified as a positive scalar. The minimum turning radius is for the smallest circle the vehicle can make with maximum steer in a single direction.

## Object Functions

| | |
|---|---|
| copy | Create deep copy of state space object |
| distance | Distance between two states |
| enforceStateBounds | Reduce state to state bounds |
| interpolate | Interpolate between states |
| sampleGaussian | Sample state using Gaussian distribution |
| sampleUniform | Sample state using uniform distribution |

## Examples

### Plan Path Between Two States in Dubins State Space

Create a Dubins state space and set the minimum turing radius to `0.2`.

```
ss = stateSpaceDubins;
ss.MinTurningRadius = 0.2;
```

Create an `occupancyMap`-based state validator using the created state space.

```
sv = validatorOccupancyMap(ss);
```

Create an occupancy map from an example map and set map resolution as 10 cells/meter.

```
load exampleMaps
map = occupancyMap(simpleMap,10);
sv.Map = map;
```

Set validation distance for the validator.

```
sv.ValidationDistance = 0.01;
```

Update state space bounds to be the same as map limits.

```
ss.StateBounds = [map.XWorldLimits;map.YWorldLimits; [-pi pi]];
```

Create the path planner and increase max connection distance.

```
planner = plannerRRT(ss,sv);
planner.MaxConnectionDistance = 0.3;
```

Set the start and goal states.

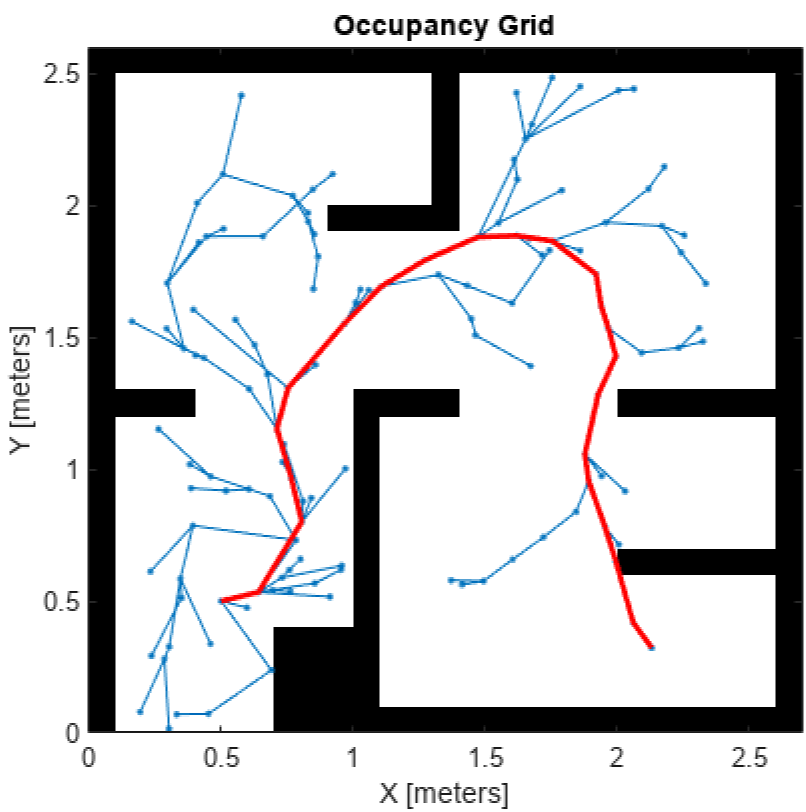
```
start = [0.5,0.5,0];
goal = [2.5,0.2,0];
```

Plan a path with default settings.

```
rng(100,'twister'); % repeatable result
[pthObj,solnInfo] = planner.plan(start,goal);
```

Visualize the results.

```
show(map);
hold on;
plot(solnInfo.TreeData(:,1),solnInfo.TreeData(:,2),'.-'); % tree expansion
plot(pthObj.States(:,1), pthObj.States(:,2),'r-','LineWidth',2) % draw path
```




## Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`stateSpaceSE2` | `stateSpaceReedsShepp` | `dubinsConnection`

# stateSpaceReedsShepp

State space for Reeds-Shepp vehicles

## Description

The `stateSpaceReedsShepp` object stores parameters and states in the Reeds-Shepp state space, which is composed of state vectors represented by [$x$, $y$, $\theta$]. $x$ and $y$ are Cartesian coordinates, and $\theta$ is the orientation angle. The Reeds-Shepp state space has a lower limit on the turning radius (specified by the `MinTurningRadius` property in the object) and forward and reverse costs (specified by the `ForwardCost` and `ReverseCost` properties in the object) for navigating between states.

## Creation

### Syntax

```
space = stateSpaceReedsShepp
sapce = stateSpaceReedsShepp(bounds)
```

#### Description

`space = stateSpaceReedsShepp` creates a Reeds-Shepp state space object with default state bounds for $x$, $y$, and $\theta$.

`sapce = stateSpaceReedsShepp(bounds)` specifies the `bounds` for $x$, $y$, and $\theta$. The state values beyond the bounds are truncated to the bounds. The input, `bounds`, sets the value of the StateBounds property.

### Properties

**`Name` — Name of state space**
`'SE2 Reeds-Shepp'` (default) | string

Name of state space, specified as a string.

**`NumStateVariables` — Dimension of the state space**
3 (default) | positive integer

This property is read-only.

Dimension of the state space, specified as a positive integer.

**`StateBounds` — Bounds of state variables**
`[-100 100; -100 100; -3.1416 3.1416]` (default) | 3-by-2 real-valued matrix

Bounds of state variables, specified as a 3-by-2 real-valued matrix.

- The first row specifies the lower and upper bounds for the *x* state in meters.
- The second row specifies the lower and upper bounds for the *y* state in meters.
- The third row specifies the lower and upper bounds for the $\theta$ state in radians.

Data Types: `double`

**`MinTurningRadius` — Minimum turning radius**
1 (default) | positive scalar

Minimum turning radius in meters, specified as a positive scalar. The minimum turning radius is for the smallest circle the vehicle can make with maximum steer in a single direction.

**`ForwardCost` — Cost multiplier for forward motion**
1 (default) | positive scalar

Cost multiplier for forward motion, specified as a positive scalar. Increase the cost to penalize forward motion.

**`ReverseCost` — Cost multiplier for reverse motion**
1 (default) | positive scalar

Cost multiplier for reverse motion, specified as a positive scalar. Increase the cost to penalize reverse motion.

## Object Functions

| | |
|---|---|
| copy | Create deep copy of state space object |
| distance | Distance between two states |
| enforceStateBounds | Reduce state to state bounds |
| interpolate | Interpolate between states |
| sampleGaussian | Sample state using Gaussian distribution |
| sampleUniform | Sample state using uniform distribution |

## Examples

### Plan Path Between Two States in ReedsShepp State Space

Create a ReedsShepp state space.

```
ss = stateSpaceReedsShepp;
```

Create an `occupanyMap`-based state validator using the created state space.

```
sv = validatorOccupancyMap(ss);
```

Create an occupany map from an example map and set map resolution as 10 cells/meter.

```
load exampleMaps
map = occupancyMap(simpleMap,10);
sv.Map = map;
```

Set validation distance for the validator.

```
sv.ValidationDistance = 0.01;
```

Update state space bounds to be the same as map limits.

```
ss.StateBounds = [map.XWorldLimits;map.YWorldLimits; [-pi pi]];
```

Create the path planner and increase max connection distance.

```
planner = plannerRRT(ss,sv);
planner.MaxConnectionDistance = 0.3;
```

Set the start and goal states.

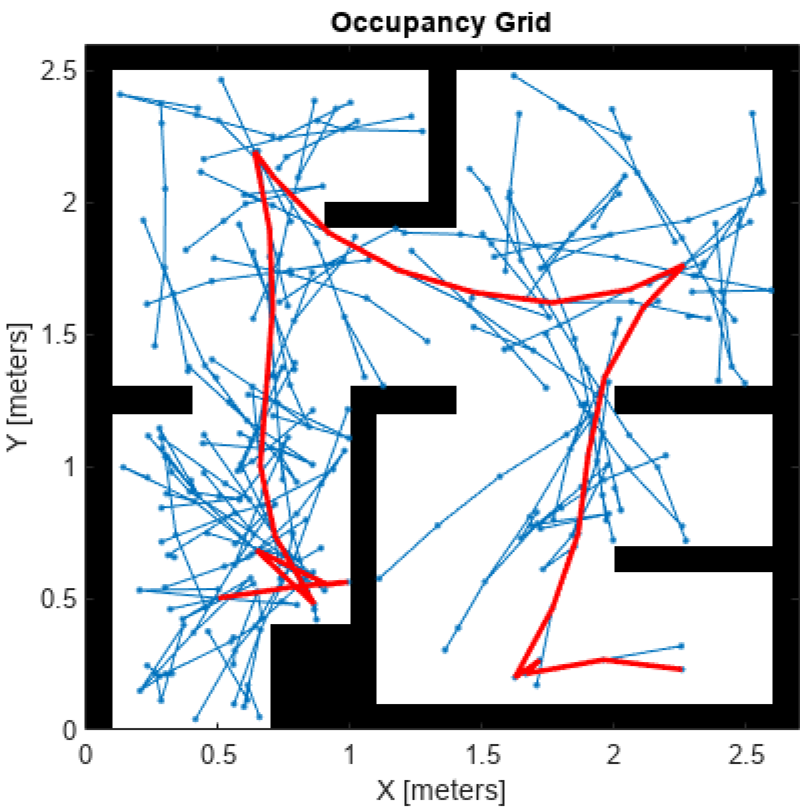
```
start = [0.5,0.5,0];
goal = [2.5,0.2,0];
```

Plan a path with default settings.

```
rng(100,'twister'); % repeatable result
[pthObj,solnInfo] = planner.plan(start,goal);
```

Visualize the results.

```
show(map);
hold on;
plot(solnInfo.TreeData(:,1),solnInfo.TreeData(:,2),'.-'); % tree expansion
plot(pthObj.States(:,1), pthObj.States(:,2),'r-','LineWidth',2) % draw path
```



## Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`stateSpaceDubins` | `stateSpaceSE2` | `reedsSheppConnection`

# distance

Distance between two states

## Syntax

```
dist = distance(space,states1,states2)
```

## Description

`dist = distance(space,states1,states2)` returns the distance between `states1` and `states2` in the specified state space `space`.

## Examples

### Calculate Distance Between Two States in SE3

Create an SE(3) state space.

```
space = stateSpaceSE3
```

```
space = 
  stateSpaceSE3 with properties:

                 Name: 'SE3'
          StateBounds: [7x2 double]
    NumStateVariables: 7
            WeightXYZ: 1
     WeightQuaternion: 0.1000
```

Calculate distance between two states.

```
dist = distance(space,[2 10 3 0.2 0 0 0.8],[0 -2.5 4 0.7 0.3 0 0])
```

```
dist = 12.7269
```

Calculate Euclidean distance between two states.

```
space.WeightQuaternion = 0;
distEuc = distance(space,[2 10 3 0.2 0 0 0.8; 4 5 2 1 2 4 2],[62 5 33 0.2 0 0 0.8; 9 9 3 3 1 3.1
```

```
distEuc = 2×1

   67.2681
    6.4807
```

## Input Arguments

**space — State space object**
stateSpaceSE2 object | stateSpaceSE3 object | stateSpaceDubins object | stateSpaceReedsShepp object

State space object, specified as a `stateSpaceSE2`, `stateSpaceSE3`, `stateSpaceDubins`, or `stateSpaceReedsShepp` object.

**states1 — Initial states for distance calculation**
*n*-by-3 matrix of real values | *n*-by-7 matrix of real values

Initial states for distance calculation, specified as an *n*-by-3 or *n*-by-7 matrix of real values. *n* is the number of specified states.

For the 2-D state space objects `stateSpaceSE2`, `stateSpaceDubins`, and `stateSpaceReedsShepp`, each row is of form `[x y theta]`, which defines the *xy*-position and orientation angle `theta` of a state in the state space.

For the 3-D state space object `stateSpaceSE3`, each row is of form `[x y z qw qx qy qz]`, which defines the *xyz*-position and quaternion orientation `[qw qx qy qz]` of a state in the state space.

The function supports following combinations for distance calculation:

- *n*-to-*n* — *n* number of states in `states1` and *n* number of states in `states2`.

  For example, `distance(space,rand(10,7),rand(10,7))`
- 1-to-*n* — 1 state in `states1` and *n* number of states in `states2`.

  For example, `distance(space,rand(1,7),rand(10,7))`
- *n*-to-1 — *n* number of states in `states1` and 1 state in `states2`.

  For example, `distance(space,rand(10,7),rand(1,7))`

Data Types: `single` | `double`

**states2 — Final states for distance calculation**
*n*-by-3 matrix of real values | *n*-by-7 matrix of real values

Final states for distance calculation, specified as an *n*-by-3 or *n*-by-7 matrix of real values. *n* is the number of specified states.

For the 2-D state space objects `stateSpaceSE2`, `stateSpaceDubins`, and `stateSpaceReedsShepp`, each row is of form `[x y theta]`, which defines the *xy*-position and orientation angle `theta` of a state in the state space.

For the 3-D state space object `stateSpaceSE3`, each row is of form `[x y z qw qx qy qz]`, which defines the *xyz*-position and quaternion orientation `[qw qx qy qz]` of a state in the state space.

The function supports following combinations for distance calculation:

- *n*-to-*n* — *n* number of states in `states1` and *n* number of states in `states2`.

  For example, `distance(space,rand(10,7),rand(10,7))`

- 1-to-*n* — 1 state in `states1` and *n* number of states in `states2`.

  For example, `distance(space,rand(1,7),rand(10,7))`
- *n*-to-1 — *n* number of states in `states1` and 1 state in `states2`.

  For example, `distance(space,rand(10,7),rand(1,7))`

Data Types: `single` | `double`

## Output Arguments

**`dist` — Distance between states**
*n*-element column vector

Distance between states, returned as an *n*-element column vector. *n* is the number of specified states.

The function supports following combinations for distance calculation:

- *n*-to-*n* — *n* number of states in `states1` and *n* number of states in `states2`.
- 1-to-*n* — 1 state in `states1` and *n* number of states in `states2`.
- *n*-to-1 — *n* number of states in `states1` and 1 state in `states2`.

Data Types: `single` | `double`

# Version History

**Introduced in R2019b**

## See Also

`stateSpaceSE2` | `stateSpaceSE3` | `stateSpaceDubins` | `stateSpaceReedsShepp`

# interpolate

Interpolate between states

## Syntax

```
interpStates = interpolate(space,state1,state2,ratio)
```

## Description

`interpStates = interpolate(space,state1,state2,ratio)` interpolates states between the specified start state `state1` and end state `state2` based on the specified interpolation ratio `ratio`.

## Examples

### Interpolate Between States in SE(2)

Create an SE(2) state space with default properties.

```
space = stateSpaceSE2
```

```
space = 
  stateSpaceSE2 with properties:

                 Name: 'SE2'
          StateBounds: [3x2 double]
    NumStateVariables: 3
             WeightXY: 1
          WeightTheta: 0.1000
```

Create a pair of states in 2-D space.

```
state1 = [2 10 -pi];
state2 = [0 -2.5 -pi/4];
```

Interpolate halfway between two states.

```
state = interpolate(space,state1,state2,0.5)
```

```
state = 1×3

    1.0000    3.7500   -1.9635
```

Interpolate multiple points with a fixed interval.

```
states = interpolate(space,state1,state2,0:0.02:1)
```

```
states = 51×3

    2.0000   10.0000   -3.1416
    1.9600    9.7500   -3.0945
```

```
    1.9200    9.5000   -3.0473
    1.8800    9.2500   -3.0002
    1.8400    9.0000   -2.9531
    1.8000    8.7500   -2.9060
    1.7600    8.5000   -2.8588
    1.7200    8.2500   -2.8117
    1.6800    8.0000   -2.7646
    1.6400    7.7500   -2.7175
      ⋮
```

#### Interpolate Between States in SE(3)

Create an SE(3) state space with default properties.

```
space = stateSpaceSE3
```

```
space = 
  stateSpaceSE3 with properties:

                 Name: 'SE3'
          StateBounds: [7x2 double]
    NumStateVariables: 7
            WeightXYZ: 1
     WeightQuaternion: 0.1000
```

Create a pair of states in 3-D space.

```
state1 = [2 10 3 0.2 0 0 0.8];
state2 = [0 -2.5 4 0.7 0.3 0 0];
```

Interpolate halfway between two states.

```
state = interpolate(space,state1,state2,0.5)
```

```
state = 1×7

    1.0000    3.7500    3.5000    0.7428    0.2519         0    0.6203
```

Interpolate multiple points with a fixed interval.

```
states = interpolate(space,state1,state2,0:0.02:1)
```

```
states = 51×7

    2.0000   10.0000    3.0000    0.2425         0         0    0.9701
    1.9600    9.7500    3.0200    0.2663    0.0109         0    0.9638
    1.9200    9.5000    3.0400    0.2899    0.0217         0    0.9568
    1.8800    9.2500    3.0600    0.3133    0.0326         0    0.9491
    1.8400    9.0000    3.0800    0.3365    0.0434         0    0.9407
    1.8000    8.7500    3.1000    0.3594    0.0542         0    0.9316
    1.7600    8.5000    3.1200    0.3821    0.0650         0    0.9218
    1.7200    8.2500    3.1400    0.4045    0.0757         0    0.9114
    1.6800    8.0000    3.1600    0.4266    0.0864         0    0.9003
```

```
    1.6400    7.7500    3.1800    0.4484    0.0969         0    0.8886
      ⋮
```

## Input Arguments

**space — State space object**
stateSpaceSE2 object | stateSpaceSE3 object | stateSpaceDubins object | stateSpaceReedsShepp object

State space object, specified as a `stateSpaceSE2`, `stateSpaceSE3`, `stateSpaceDubins`, or `stateSpaceReedsShepp` object.

**state1 — Start state for interpolation**
three-element vector of real values | seven-element vector of real values

Start state for interpolation, specified as a three-element or seven-element vector of real values.

For the 2-D state space objects `stateSpaceSE2`, `stateSpaceDubins`, and `stateSpaceReedsShepp`, the state is a vector of form `[x y theta]`, which defines the *xy*-position and orientation angle `theta` of a state in the state space.

For the 3-D state space object `stateSpaceSE3`, the state is a vector of form `[x y z qw qx qy qz]`, which defines the *xyz*-position and quaternion orientation `[qw qx qy qz]` of a state in the state space.

Data Types: single | double

**state2 — End state for interpolation**
three-element vector of real values | seven-element vector of real values

End state for interpolation, specified as a three-element or seven-element vector of real values.

For the 2-D state space objects `stateSpaceSE2`, `stateSpaceDubins`, and `stateSpaceReedsShepp`, the state is a vector of form `[x y theta]`, which defines the *xy*-position and orientation angle `theta` of a state in the state space.

For the 3-D state space object `stateSpaceSE3`, the state is a vector of form `[x y z qw qx qy qz]`, which defines the *xyz*-position and quaternion orientation `[qw qx qy qz]` of a state in the state space.

Data Types: single | double

**ratio — Interpolation ratio**
scalar in range [0, 1] | *n*-element column vector of values in the range [0, 1]

Interpolation ratio, specified as a scalar in the range of [0, 1], or an *n*-element column vector of values in the range [0, 1] . *n* is the number of desired interpolation points.

Data Types: single | double

## Output Arguments

**interpStates — Interpolated states**
*n*-by-3 matrix of real values | *n*-by-7 matrix of real values

Interpolated states, returned as an *n*-by-3 or *n*-by-7 matrix of real values. *n* is the number of interpolation points specified by the `ratio` input argument.

For the 2-D state space objects `stateSpaceSE2`, `stateSpaceDubins`, and `stateSpaceReedsShepp`, each row is of form `[x y theta]`, which defines the *xy*-position and orientation angle `theta` of the interpolated states.

For the 3-D state space object `stateSpaceSE3`, each row is of form `[x y z qw qx qy qz]`, which defines the *xyz*-position and quaternion orientation `[qw qx qy qz]` of the interpolated states.

Data Types: `single` | `double`

# Version History

**Introduced in R2019b**

## See Also

`stateSpaceSE2` | `stateSpaceSE3` | `stateSpaceDubins` | `stateSpaceReedsShepp`

# enforceStateBounds

Reduce state to state bounds

## Syntax

```
boundedStates = enforceStateBounds(space,states)
```

## Description

`boundedStates = enforceStateBounds(space,states)` reduces the specified states `states` to the state bounds in the `StateBounds` property of the specified state space object `space`.

## Examples

### Enforce State Bounds for SE(3) States

Create an SE(3) state space object.

```
space = stateSpaceSE3([-1 1; ...
    -2 2; ...
    -10 10; ...
    -inf inf; ...
    -inf inf; ...
    -inf inf; ...
    -inf inf])
```

```
space =
  stateSpaceSE3 with properties:

                 Name: 'SE3'
          StateBounds: [7x2 double]
    NumStateVariables: 7
            WeightXYZ: 1
     WeightQuaternion: 0.1000
```

Create a pair of states in 3-D space.

```
state1 = [2 10 3 2 0 0 0.8];
state2 = [223 100 3 2 2 12 5];
```

Enforce state bounds for a single state.

```
boundedState = enforceStateBounds(space,state1)
```

```
boundedState = 1×7

    1.0000    2.0000    3.0000    2.0000         0         0    0.8000
```

Enforce state bounds for multiple states.

```
boundedStates = enforceStateBounds(space,[state1; state2])
```

```
boundedStates = 2×7

    1.0000    2.0000    3.0000    2.0000         0         0    0.8000
    1.0000    2.0000    3.0000    2.0000    2.0000   12.0000    5.0000
```

## Input Arguments

**space — State space object**
`stateSpaceSE2` object | `stateSpaceSE3` object | `stateSpaceDubins` object | `stateSpaceReedsShepp` object

State space object, specified as a `stateSpaceSE2`, `stateSpaceSE3`, `stateSpaceDubins`, or `stateSpaceReedsShepp` object.

**states — Unbounded states**
*n*-by-3 matrix of real values | *n*-by-7 matrix of real values

Unbounded states, specified as an *n*-by-3 or *n*-by-7 matrix of real values.

For the 2-D state space objects `stateSpaceSE2`, `stateSpaceDubins`, and `stateSpaceReedsShepp`, each row is of form `[x y theta]`, which defines the *xy*-position and orientation angle `theta` of a state in the state space.

For the 3-D state space object `stateSpaceSE3`, each row is of form `[x y z qw qx qy qz]`, which defines the *xyz*-position and quaternion orientation `[qw qx qy qz]` of a state in the state space.

Data Types: `single` | `double`

## Output Arguments

**boundedStates — Bounded states**
*n*-by-3 matrix of real values | *n*-by-7 matrix of real values

Bounded states, returned as an *n*-by-3 or *n*-by-7 matrix of real values. The value of *n* is same as for `states` input argument.

The function truncates each of the specified unbounded states to the bounds specified in the `StateBounds` property of the state space object `space`.

For the 2-D state space objects `stateSpaceSE2`, `stateSpaceDubins`, and `stateSpaceReedsShepp`, each row is of form `[x y theta]`, which defines the *xy*-position and orientation angle `theta` of the bounded states.

For the 3-D state space object `stateSpaceSE3`, each row is of form `[x y z qw qx qy qz]`, which defines the *xyz*-position and quaternion orientation `[qw qx qy qz]` of the bounded states.

Data Types: `single` | `double`

# Version History

**Introduced in R2019b**

## See Also
`stateSpaceSE2` | `stateSpaceSE3` | `stateSpaceDubins` | `stateSpaceReedsShepp`

# copy

Create deep copy of state space object

## Syntax

```
space2 = copy(space1)
```

## Description

`space2 = copy(space1)` creates a deep copy of the specified state space object.

## Examples

### Create Deep Copy of SE(3) State Space Object

Create a default SE(3) state space object.

```
space = stateSpaceSE3;
```

Specify weight for the quaternion distance in state space calculation.

```
space.WeightQuaternion = 2/3
```

```
space = 
  stateSpaceSE3 with properties:

                 Name: 'SE3'
          StateBounds: [7x2 double]
    NumStateVariables: 7
            WeightXYZ: 1
     WeightQuaternion: 0.6667
```

Create a deep copy of the state space object.

```
space2 = copy(space)
```

```
space2 = 
  stateSpaceSE3 with properties:

                 Name: 'SE3'
          StateBounds: [7x2 double]
    NumStateVariables: 7
            WeightXYZ: 1
     WeightQuaternion: 0.6667
```

Verify that the `WeightQuaternion` property values of the two state space objects are equal.

```
isequal(space.WeightQuaternion,space2.WeightQuaternion)
```

```
ans = logical
   1
```

## Input Arguments

**space1 — State space object**
stateSpaceSE2 object | stateSpaceSE3 object | stateSpaceDubins object | stateSpaceReedsShepp object

State space object, specified as a `stateSpaceSE2`, `stateSpaceSE3`, `stateSpaceDubins`, or `stateSpaceReedsShepp` object.

## Output Arguments

**space2 — State space object**
stateSpaceSE2 object | stateSpaceSE3 object | stateSpaceDubins object | stateSpaceReedsShepp object

State space object, returned as a `stateSpaceSE2`, `stateSpaceSE3`, `stateSpaceDubins`, or `stateSpaceReedsShepp` object.

# Version History

**Introduced in R2019b**

## See Also

`stateSpaceSE2` | `stateSpaceSE3` | `stateSpaceDubins` | `stateSpaceReedsShepp`

# sampleGaussian

Sample state using Gaussian distribution

## Syntax

```
state = sampleGaussian(space,meanState,stdDev)
state = sampleGaussian(space,meanState,stdDev,numSamples)
```

## Description

`state = sampleGaussian(space,meanState,stdDev)` returns a sample state of the state space based on a Gaussian (normal) distribution with specified mean, `meanState`, and standard deviation, `stdDev`.

`state = sampleGaussian(space,meanState,stdDev,numSamples)` returns a number of state samples. The number is equal to `numSamples`.

## Examples

### Sample States of State Space Using Gaussian Distribution

Create an SE(2) state space.

```
space = stateSpaceSE2;
```

Specify the mean state, standard deviation, and the number of state samples to return.

```
meanState = [5 5 pi/3];
stdDev = [0.1 0.1 pi/18];
numSamples = 2;
```

Sample states of the state space based on a Gaussian distribution.

```
state = sampleGaussian(space,meanState,stdDev,numSamples)
```

```
state = 2×3

    5.0538    5.1834    0.6530
    5.0862    5.0319    0.8190
```

## Input Arguments

**space — State space object**
`spaceSE2` object | `spaceDubins` object | `spaceReedsShepp` object

State space object, specified as a `stateSpaceSE2`, a `stateSpaceDubins`, or a `stateSpaceReedsShepp` object.

Data Types: `object`

**`meanState` — Mean state**
3-element vector of real values

Mean state of the Gaussian distribution for sampling, specified as a 3-element vector of real values.

Example: `[5 5 pi/3]`

Data Types: `single` | `double`

**`stdDev` — Standard deviation**
3-element vector of nonnegative values

Standard deviation of the Gaussian distribution for sampling, specified as a 3-element vector of nonnegative values.

Example: `[0.1 0.1 pi/18]`

Data Types: `single` | `double`

**`numSamples` — Number of samples**
positive integer

Number of samples, specified as a positive integer.

Data Types: `single` | `double`

## Output Arguments

**`state` — State samples**
*N*-by-3 real-valued matrix

State samples, returned as an *N*-by-3 real-valued matrix. *N* is the number of samples. Each row of the matrix corresponds to one incidence of state in the state space.

Data Types: `single` | `double`

# Version History

**Introduced in R2019b**

## See Also

`stateSpaceSE2` | `stateSpaceDubins` | `stateSpaceReedsShepp`

# sampleUniform

Sample state using uniform distribution

## Syntax

```
state = sampleUniform(space)
state = sampleUniform(space,numSamples)
state = sampleUniform(space,nearState,distVector,numSamples)
```

## Description

`state = sampleUniform(space)` samples a state within the bounds in the `StateBounds` property of the specified state space object `space` using a uniform probability distribution. For a `stateSpaceSE3` object, the state variables corresponding to orientation are bound to a unit quaternion using a uniform distribution of random rotations.

`state = sampleUniform(space,numSamples)` returns a specified number of state samples `numSamples` within the bounds of the state space object.

`state = sampleUniform(space,nearState,distVector,numSamples)` samples states in a specified subregion of the bounds of the state space object. Specify the center of the sampling region `nearState` and the distance from the center of the sampling region to its boundaries `distVector`.

**Note** The `stateSpaceSE3` object does not support this syntax.

## Examples

### Sample State Using Uniform Distribution in SE(3)

Create an SE(3) state space.

```
space = stateSpaceSE3([-10 10; -10 10; -10 10; inf inf; inf inf; inf inf; inf inf])
```

```
space = 
  stateSpaceSE3 with properties:

                 Name: 'SE3'
          StateBounds: [7x2 double]
    NumStateVariables: 7
            WeightXYZ: 1
     WeightQuaternion: 0.1000
```

Sample 3 states within full state bounds.

```
state = sampleUniform(space,3)
```

```
state = 3×7
```

```
    6.2945    8.1158   -7.4603    0.6316    0.3078   -0.6921   -0.1654
    8.2675    2.6472   -8.0492   -0.0834   -0.9448    0.2709    0.1641
   -4.4300    0.9376    9.1501    0.5771   -0.5458   -0.5490   -0.2601
```

## Input Arguments

**space — State space object**
stateSpaceSE2 object | stateSpaceSE3 object | stateSpaceDubins object | stateSpaceReedsShepp object

State space object, specified as a `stateSpaceSE2`, `stateSpaceSE3`, `stateSpaceDubins`, or `stateSpaceReedsShepp` object.

**numSamples — Number of samples**
positive integer

Number of samples, specified as a positive integer.

Data Types: single | double

**nearState — Center of sampling region**
three-element vector of real values

Center of the sampling region, specified as a three-element vector of real values.

For the 2-D state space objects `stateSpaceSE2`, `stateSpaceDubins`, and `stateSpaceReedsShepp`, the state is a vector of form `[x y theta]`, which defines the *xy*-position and orientation angle `theta` of a state in the state space.

**Note** The `stateSpaceSE3` object does not support this argument.

Data Types: single | double

**distVector — Distance of sampling region boundary from center**
three-element vector of positive numbers

Distance of sampling region boundary from the center, specified as a three-element vector of positive numbers.

For the 2-D state space objects `stateSpaceSE2`, `stateSpaceDubins`, and `stateSpaceReedsShepp`, the state is a vector of form `[x y theta]`, which defines the *xy*-position and orientation angle `theta` of a state in the state space.

**Note** The `stateSpaceSE3` object does not support this argument.

Data Types: single | double

## Output Arguments

**`state` — State samples**

*n*-by-3 matrix of real values | *n*-by-7 matrix of real values

State samples, returned as an *n*-by-3 or *n*-by-7 matrix of real values. *n* is the number of samples.

For the 2-D state space objects `stateSpaceSE2`, `stateSpaceDubins`, and `stateSpaceReedsShepp`, each row is of form `[x y theta]`, which defines the *xy*-position and orientation angle `theta` of the sampled states.

For the 3-D state space object `stateSpaceSE3`, each row is of form `[x y z qw qx qy qz]`, which defines the *xyz*-position and quaternion orientation `[qw qx qy qz]` of the sampled states.

Data Types: `single` | `double`

# Version History

**Introduced in R2019b**

## See Also

`stateSpaceSE2` | `stateSpaceSE3` | `stateSpaceDubins` | `stateSpaceReedsShepp`

# trajectoryGeneratorFrenet

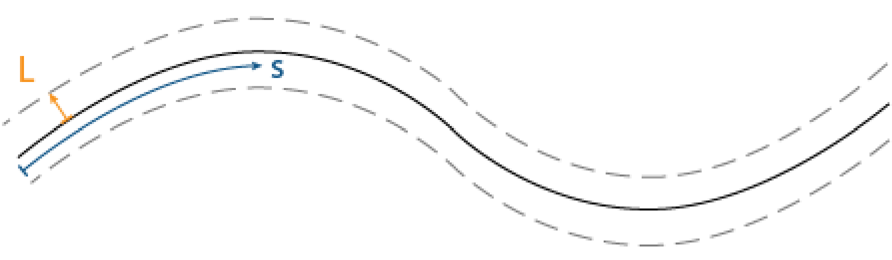
Find optimal trajectory along reference path

## Description

The `trajectoryGeneratorFrenet` object generates alternate trajectories using fourth or fifth-order polynomials relative to a given reference path. Each trajectory defines a motion between Frenet states over a specified time span.

Frenet states describe their position, velocity and acceleration relative to a static reference path, specified as a `referencePathFrenet` object.

The object expresses Frenet states as a vector of form `[S dS ddS L dL ddL]`, where `S` is the arc length and `L` is the perpendicular deviation from the direction of the reference path. Derivatives of `S` are relative to time. Derivatives of `L` are relative to the arc length, `S`.




Frenet States: [s δs $\delta^2$s L δL $\delta^2$L]

To generate alternative trajectories, specify the initial and terminal frenet states with a given time span to the `connect` object function.

## Creation

### Syntax

```
connectorFrenet = trajectoryGeneratorFrenet(refPath)
connectorFrenet = trajectoryGeneratorFrenet(
refPath,'TimeResolution',timeValue)
```

#### Description

`connectorFrenet = trajectoryGeneratorFrenet(refPath)` generates trajectories between initial and terminal states relative to a reference path `refPath` specified as a `referencePathFrenet` object. The `refPath` input argument sets the ReferencePath property.

`connectorFrenet = trajectoryGeneratorFrenet( refPath,'TimeResolution',timeValue)` specifies the time interval for discretization. The `timeValue` argument sets the TimeResolution property.

## Properties

**`TimeResolution` — Discretization time interval between sampled Frenet states**
`0.1` (default) | positive scalar in seconds

Discretization time interval between sampled Frenet states, specified as a positive scalar in seconds. When using the `connect` object function, this property determines the resolution of the `Times` field of the generated trajectory structures, `frenetTrajectory` and `globalTrajectory`.

Data Types: `double`

**`ReferencePath` — Reference path in Frenet coordinates**
`referencePathFrenet`

Reference path in Frenet coordinates, specified as a `referencePathFrenet` object.

## Object Functions

| | |
|---|---|
| connect | Connect initial and terminal Frenet states |
| createParallelState | Create states using Frenet and global parameters |

## Examples

### Generate Alternative Trajectories for Reference Path

Generate alternative trajectories for a reference path using Frenet coordinates. Specify different initial and terminal states for your trajectories. Tune your states based on the generated trajectories.

Generate a reference path from a set of waypoints. Create a `trajectoryGeneratorFrenet` object from the reference path.

```
waypoints = [0 0; ...
    50 20; ...
    100 0; ...
    150 10];
refPath = referencePathFrenet(waypoints);
connector = trajectoryGeneratorFrenet(refPath);
```

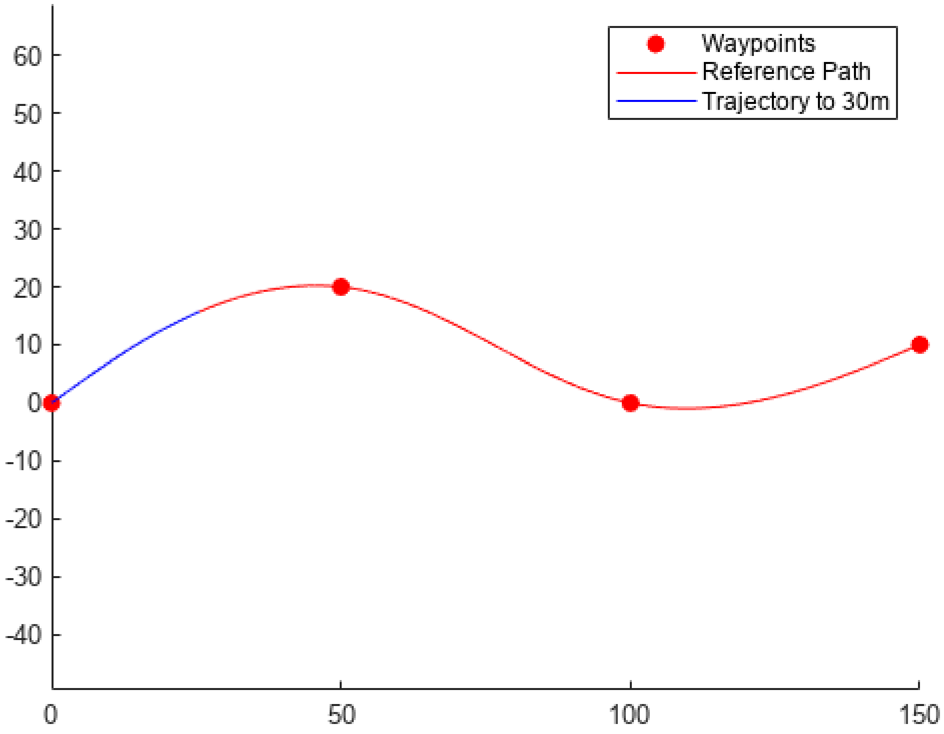
Generate a five-second trajectory between the path origin and a point 30 m down the path as Frenet states.

```
initState = [0 0 0 0 0 0];  % [S ds ddS L dL ddL]
termState = [30 0 0 0 0 0]; % [S ds ddS L dL ddL]
[~,trajGlobal] = connect(connector,initState,termState,5);
```

Display the trajectory in global coordinates.

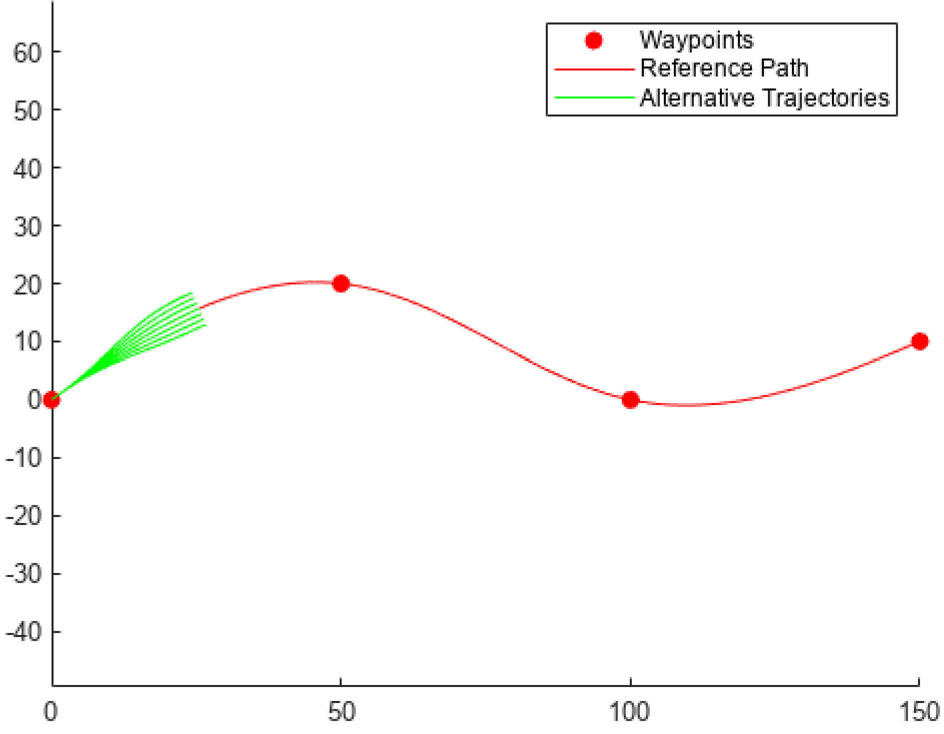
```
show(refPath);
hold on
axis equal
```

```
plot(trajGlobal.Trajectory(:,1),trajGlobal.Trajectory(:,2),'b')
legend(["Waypoints","Reference Path","Trajectory to 30m"])
```



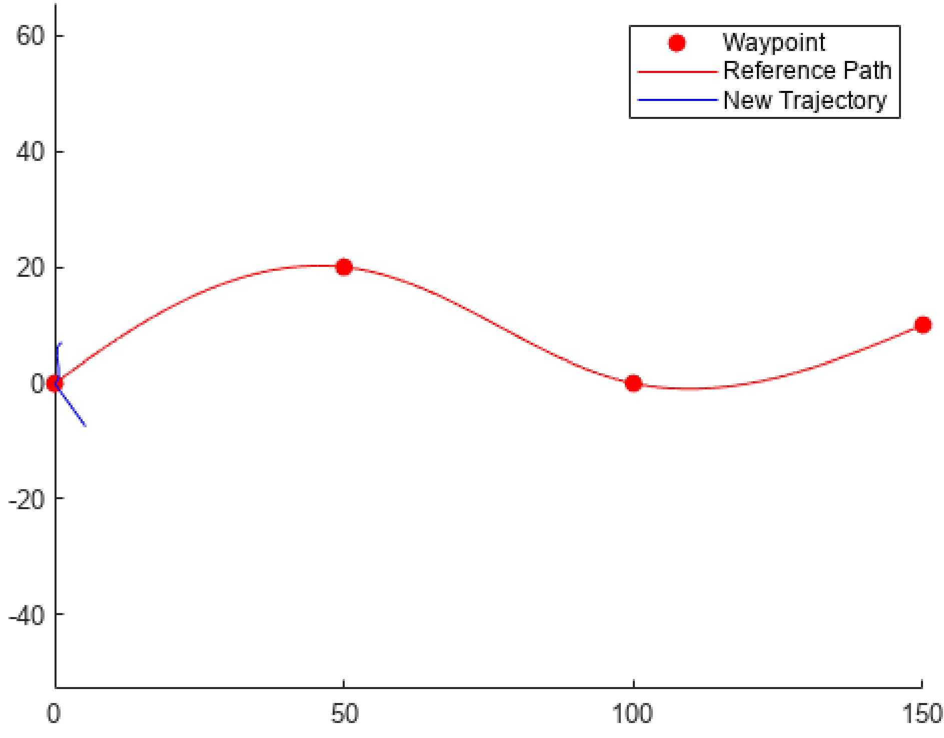

Create a matrix of terminal states with lateral deviations between –3 m and 3 m. Generate trajectories that cover the same arc length in 10 seconds, but deviate laterally from the reference path. Display the new alternative paths.

```
termStateDeviated = termState + ([-3:3]' * [0 0 0 1 0 0]);
[~,trajGlobal] = connect(connector,initState,termStateDeviated,10);

clf
show(refPath);
hold on
axis equal
for i = 1:length(trajGlobal)
    plot(trajGlobal(i).Trajectory(:,1),trajGlobal(i).Trajectory(:,2),'g')
end
legend(["Waypoints","Reference Path","Alternative Trajectories"])
hold off
```



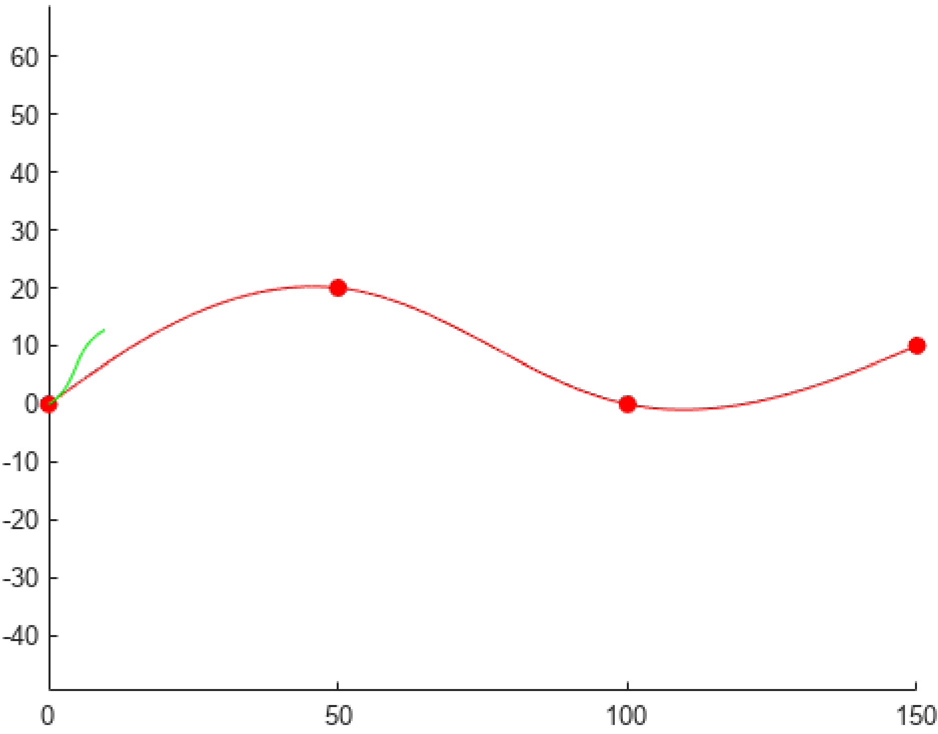

Specify a new terminal state to generate a new trajectory. This trajectory is not desirable because it requires reverse motion to achieve a lateral velocity of 10 m/s.

```
newTermState = [5 10 0 5 0 0];
[~,newTrajGlobal] = connect(connector,initState,newTermState,3);

clf
show(refPath);
hold on
axis equal
plot(newTrajGlobal.Trajectory(:,1),newTrajGlobal.Trajectory(:,2),'b');
legend(["Waypoint","Reference Path","New Trajectory"])
hold off
```




Relax the restriction on the longitudinal state by specifying an arc length of NaN. Generate and display the trajectory again. The new position shows a good alternative trajectory that deviates off the reference path.

```
relaxedTermState = [NaN 10 0 5 0 0];
[~,trajGlobalRelaxed] = connect(connector,initState,relaxedTermState,3);

clf
show(refPath);
hold on
axis equal
plot(trajGlobalRelaxed.Trajectory(:,1),trajGlobalRelaxed.Trajectory(:,2),'g');
hold off
```




## Version History

**Introduced in R2020b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

`trajectoryGeneratorFrenet` now supports code generation with `DynamicMemoryAllocation='off'`.

## See Also

**Objects**
`referencePathFrenet`

**Functions**
`connect` | `closestPoint` | `closestPointsToSequence` | `closestProjections` | `curvature` | `changeInCurvature` | `tangentAngle` | `frenet2global` | `global2frenet` | `interpolate` | `show`

**Topics**
"Highway Trajectory Planning Using Frenet Reference Path"

# connect

Connect initial and terminal Frenet states

## Syntax

```
frenetTrajectory = connect(connectorFrenet,initialState,terminalState,
timeSpan)
[ ___ ,globalTrajectory] = connect( ___ )
```

## Description

`frenetTrajectory = connect(connectorFrenet,initialState,terminalState, timeSpan)` connects the specified initial Frenet states to the specified terminal states over a span of time in seconds. This object function supports 1-to-*n*, *n*-to-1, or *n*-to-*n* pairwise trajectory connections.

`[ ___ ,globalTrajectory] = connect( ___ )` returns the trajectories in global coordinates in addition to all arguments in the previous syntax.

## Examples

### Generate Alternative Trajectories for Reference Path

Generate alternative trajectories for a reference path using Frenet coordinates. Specify different initial and terminal states for your trajectories. Tune your states based on the generated trajectories.

Generate a reference path from a set of waypoints. Create a `trajectoryGeneratorFrenet` object from the reference path.

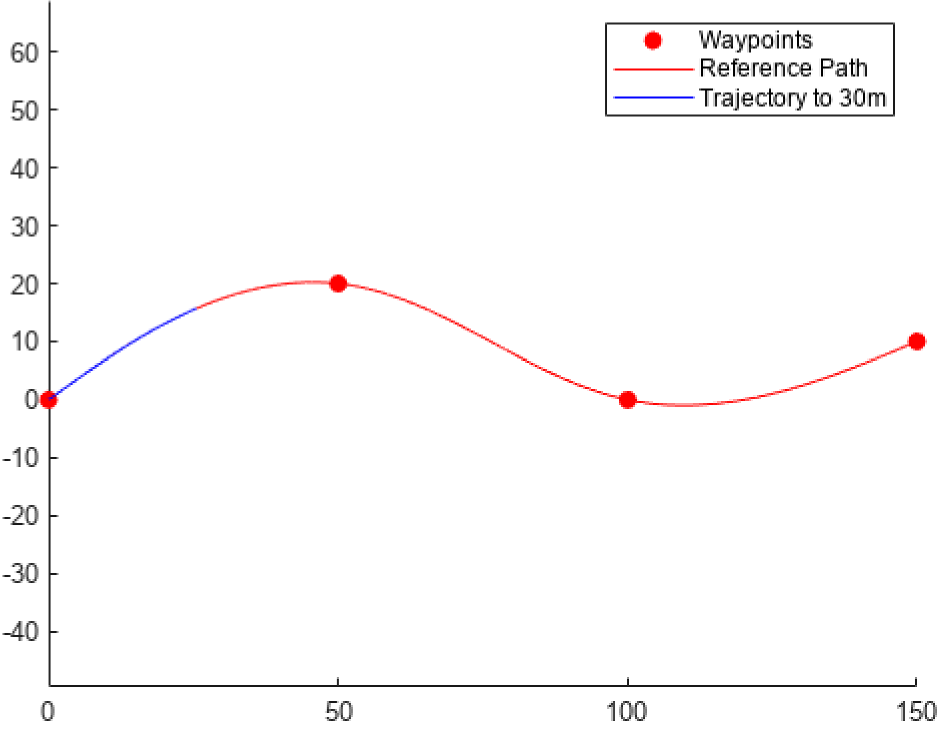
```
waypoints = [0 0; ...
    50 20; ...
    100 0; ...
    150 10];
refPath = referencePathFrenet(waypoints);
connector = trajectoryGeneratorFrenet(refPath);
```

Generate a five-second trajectory between the path origin and a point 30 m down the path as Frenet states.

```
initState = [0 0 0 0 0 0];  % [S ds ddS L dL ddL]
termState = [30 0 0 0 0 0]; % [S ds ddS L dL ddL]
[~,trajGlobal] = connect(connector,initState,termState,5);
```

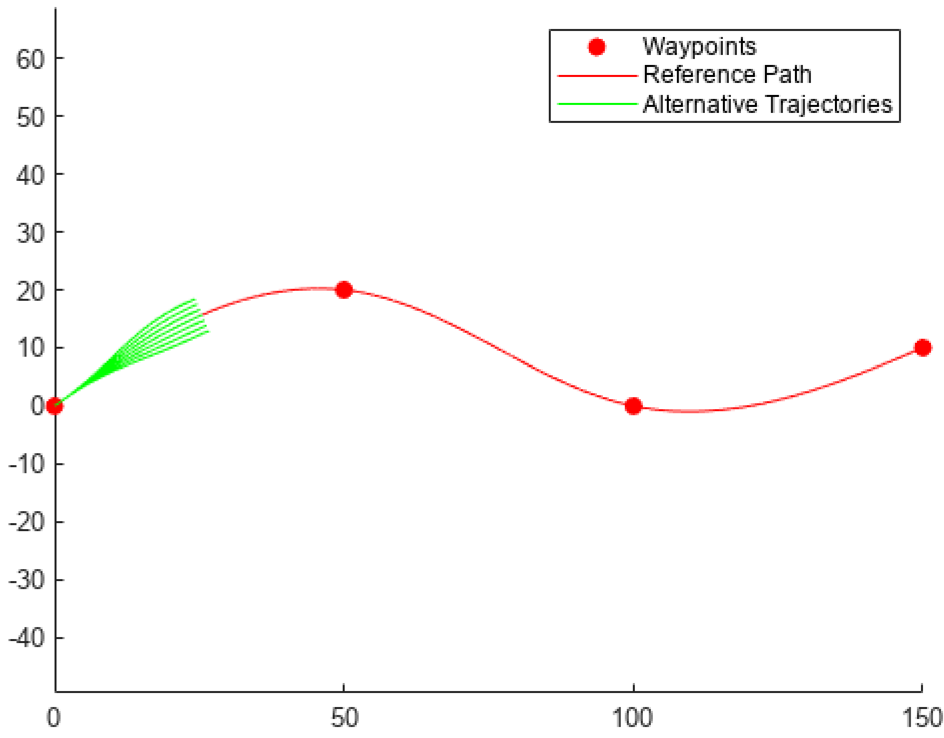
Display the trajectory in global coordinates.

```
show(refPath);
hold on
axis equal
plot(trajGlobal.Trajectory(:,1),trajGlobal.Trajectory(:,2),'b')
legend(["Waypoints","Reference Path","Trajectory to 30m"])
```



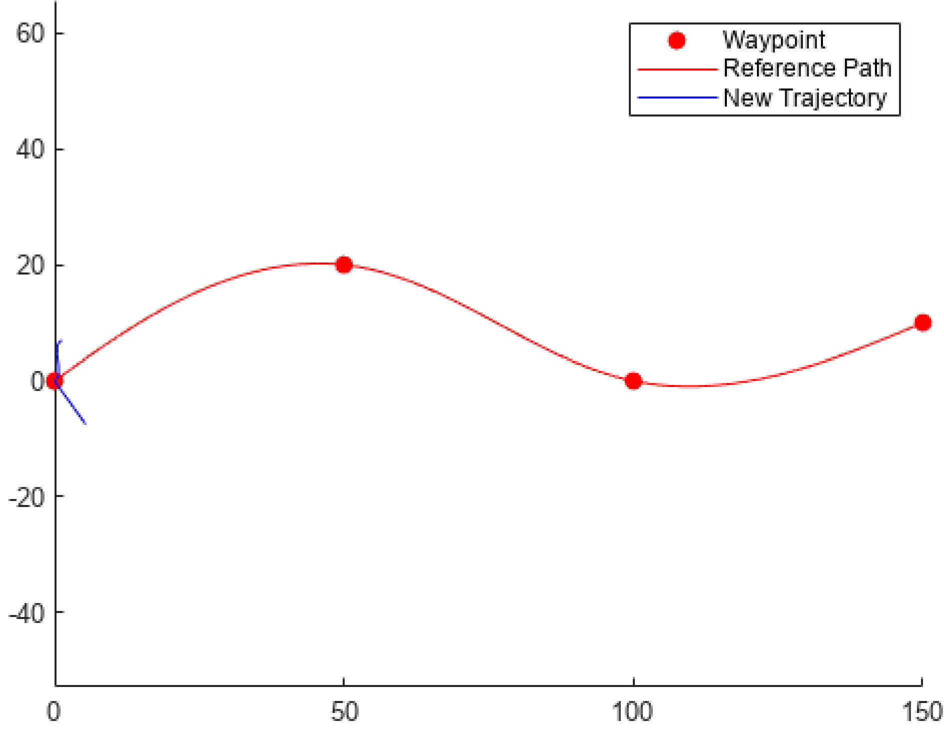

Create a matrix of terminal states with lateral deviations between –3 m and 3 m. Generate trajectories that cover the same arc length in 10 seconds, but deviate laterally from the reference path. Display the new alternative paths.

```
termStateDeviated = termState + ([-3:3]' * [0 0 0 1 0 0]);
[~,trajGlobal] = connect(connector,initState,termStateDeviated,10);

clf
show(refPath);
hold on
axis equal
for i = 1:length(trajGlobal)
    plot(trajGlobal(i).Trajectory(:,1),trajGlobal(i).Trajectory(:,2),'g')
end
legend(["Waypoints","Reference Path","Alternative Trajectories"])
hold off
```



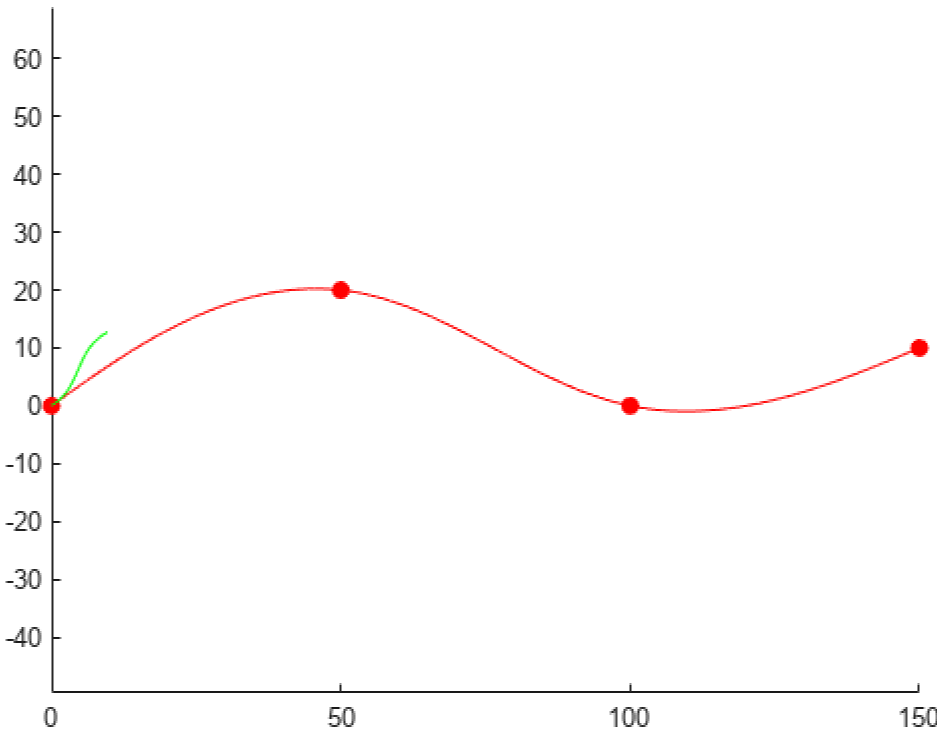

Specify a new terminal state to generate a new trajectory. This trajectory is not desirable because it requires reverse motion to achieve a lateral velocity of 10 m/s.

```
newTermState = [5 10 0 5 0 0];
[~,newTrajGlobal] = connect(connector,initState,newTermState,3);

clf
show(refPath);
hold on
axis equal
plot(newTrajGlobal.Trajectory(:,1),newTrajGlobal.Trajectory(:,2),'b');
legend(["Waypoint","Reference Path","New Trajectory"])
hold off
```




Relax the restriction on the longitudinal state by specifying an arc length of `NaN`. Generate and display the trajectory again. The new position shows a good alternative trajectory that deviates off the reference path.

```
relaxedTermState = [NaN 10 0 5 0 0];
[~,trajGlobalRelaxed] = connect(connector,initState,relaxedTermState,3);

clf
show(refPath);
hold on
axis equal
plot(trajGlobalRelaxed.Trajectory(:,1),trajGlobalRelaxed.Trajectory(:,2),'g');
hold off
```




## Input Arguments

**connectorFrenet — Frenet trajectory generator**
trajectoryGeneratorFrenet object

Frenet trajectory generator, specified as a `trajectoryGeneratorFrenet` object.

**initialState — Initial Frenet states**
*n*-by-6 numeric matrix

Initial Frenet states, specified as an *n*-by-6 numeric matrix. Each row of the matrix is a set of Frenet coordinates for the initial state of a trajectory in the form `[S dS ddS L dL ddL]`. The value of *n* must be equal to the number of rows in the `terminalState` argument or `1`.

**terminalState — Final Frenet states**
*n*-by-6 numeric matrix

Final Frenet states, specified as an *n*-by-6 numeric matrix. Each row of the matrix is a set of Frenet coordinates for the initial state of a trajectory in the form `[S dS ddS L dL ddL]`. The value of *n* must be equal to the number of rows in the `initialState` argument or `1`.

**timeSpan — Time horizon for all trajectories**
positive scalar in seconds

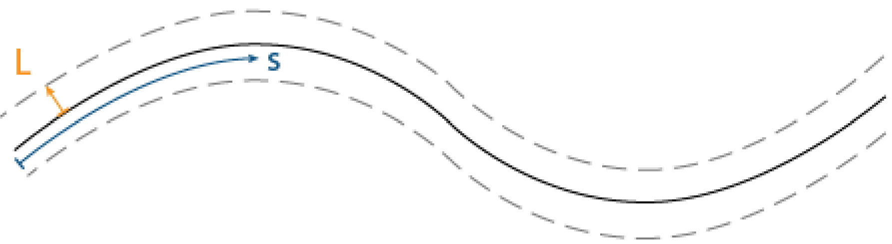
Time horizon for all trajectories, specified as a positive scalar in seconds. The generated trajectories are sampled evenly across this time span based on the TimeResolution property of the `trajectoryGeneratorFrenet` object specified in the `connectorFrenet` argument.

## Output Arguments

**`frenetTrajectory` — Frenet trajectories**
structure | structure array

Frenet trajectories between all initial and final states, returned as a structure array with these fields:

- `Trajectory` — *n*-by-6 numeric matrix. Each row of the matrix is a set of Frenet coordinates for the initial state of a trajectory in the form `[S dS ddS L dL ddL]`.
- `Time` — Vector of positive scalars from `0` to `timeSpan` in seconds.

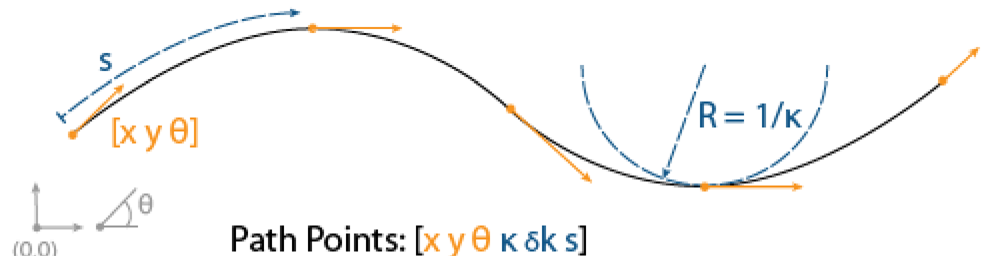



This function supports 1-to-*n*, *n*-to-1, or *n*-to-*n* pairwise trajectory connections based on the number of rows of `initialState` and `terminalState`.

**`globalTrajectory` — Global trajectories**
structure | structure array

Global trajectories between all initial and final states, returned as structure or structure array with fields:

- `Trajectory` — *n*-by-6 numeric matrix. Each row of the matrix is a set of global sates of the form `[x y theta kappa v a]`.
- `Time` — Vector of positive scalars from `0` to `timeSpan` in seconds.




This function supports 1-to-*n*, *n*-to-1, or *n*-to-*n* pairwise trajectory connections based on the number of rows of `initialState` and `terminalState`.

# Version History

**Introduced in R2020b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
`referencePathFrenet` | `trajectoryGeneratorFrenet`

**Functions**
`closestPoint` | `closestPointsToSequence` | `closestProjections` | `curvature` | `changeInCurvature` | `tangentAngle` | `frenet2global` | `global2frenet` | `interpolate` | `show`

**Topics**
"Highway Trajectory Planning Using Frenet Reference Path"

# createParallelState

Create states using Frenet and global parameters

## Syntax

```
[globalState,frenetState,latTimeDerivatives] = createParallelState(refPath,S,
L,V,A)
[_] = createParallelState(refPath,S,L,V,A,invertHeading)
```

## Description

`[globalState,frenetState,latTimeDerivatives] = createParallelState(refPath,S,L,V,A)` takes an arclength `S`, lateral deviation `L`, body velocity `V`, and body acceleration `A`, and returns the global states `globalState`, Frenet states `frenetState` which run parallel to the reference path, and the lateral time derivatives of the Frenet states `latTimeDerivatives`.

`[_] = createParallelState(refPath,S,L,V,A,invertHeading)` optionally accepts a vector `invertHeading`, indicating whether the state heading of each waypoint should be inverted or not.

## Input Arguments

**`refPath` — Reference path**
`referencePathFrenet` object

Reference path, specified as a `referencePathFrenet` object.

**`S` — Path arclengths**
*N*-element column vector

Path arclengths, specified as an *N*-element column vector in meters, where *N* is the total number of desired arclengths to calculate.

**`L` — Lateral deviations**
*N*-element column vector

Lateral deviation, specified as an *N*-element vector in meters. The lateral deviation is measured as the distance along the normal vector of the current path to the original path.

Data Types: `single` | `double`

**`V` — Body velocity**
*N*-element column vector

Body velocity, specified as an *N*-element vector in meters per second. The velocity is derived by transforming the global velocity to the Frenet frame located at `S` along the path.

Data Types: `single` | `double`

**`A` — Body acceleration**
*N*-element column vector

Body velocity, specified as an *N*-element vector in meters per second squared. The acceleration is derived by transforming the global acceleration to the Frenet frame located at `S` along the path.

Data Types: `single` | `double`

**`invertHeading` — Invert heading flag**
*N*-element column vector

Invert heading flag, specified as an *N*-element column vector of binary values, indicating whether the state heading of each waypoint should be inverted or not. `0` indicates to not invert the heading, and `1` indicates to invert the heading.

Data Types: `single` | `double`

## Output Arguments

**`globalState` — States in global coordinate frame**
*P*-by-6 numeric matrix

States in the global coordinate frame, specified as a *P*-by-6 numeric matrix with rows of form `[x y theta kappa speed accel]`, where:

- *x y* and *theta* -- SE(2) state expressed in global coordinates, with *x* and *y* in meters and *theta* in radians.
- *kappa* -- Curvature, or inverse of the radius, in $m^{-1}$.
- *speed* -- Speed in the `theta` direction in `m/s`.
- *accel* -- Acceleration in the `theta` direction in $m/s^2$.

*P* is the total number of Global states.

**`frenetState` — States in Frenet coordinate frame**
*P*-by-6 numeric matrix

States in the Frenet coordinate frame, returned as a *P*-by-6 numeric matrix with rows of form `[S dS ddS L dL ddL]`, where `S` is the arc length and `L` is the perpendicular deviation from the direction of the reference path. Derivatives of `S` are relative to time. Derivatives of `L` are relative to the arc length, `S`. *P* is the total number of Frenet states.

**`latTimeDerivatives` — Lateral time derivatives**
*N*-by-3 matrix

Lateral time derivatives, specified as an *N*-by-3 matrix where each row is of the form [*dL/dt ddL/dt^2 invertHeading*] and *N* is the total number of points in `points`. `createParallelState` derives the first and second derivatives by transforming the global velocity and acceleration to the Frenet frame at the arclength along the path. Each row contains the 1st and 2nd order time derivatives of lateral deviation and a flag, *invertHeading*, which indicates whether the heading should be flipped when converting to global coordinates (`true`) or not (`false`).

---

**Note** If defining `latTimeDerivatives` without the use of `global2frenet`, the following rules should be followed:

1. The *invertHeading* flag should be true when:

   a. The vehicle is moving in reverse (speed is less than 0)
   b. The vehicle is stationary (speed is equal to 0), and the vehicle is facing away from the path's tangent vector. i.e. cos(|tangentAngle(obj,S)-thetaExpected|) < 0
2. If 1b is true, then *dL/dS* must be negated.

---

## Version History

**Introduced in R2022a**

## See Also

**Objects**
`referencePathFrenet` | `trajectoryGeneratorFrenet`

**Functions**
`closestPoint` | `closestPointsToSequence` | `closestProjections` | `curvature` | `changeInCurvature` | `tangentAngle` | `frenet2global` | `global2frenet` | `interpolate` | `show`

**Topics**
"Highway Trajectory Planning Using Frenet Reference Path"

# trajectoryOptimalFrenet

Find optimal trajectory along reference path

## Description

The `trajectoryOptimalFrenet` object is a path planner which samples and evaluates local trajectories based on a reference path. The planner generates a set of terminal states based on the reference path and other parameters in the object. The planner then connects the state to each terminal state using $4^{th}$ or $5^{th}$ order polynomials. To choose an optimal path, sampled trajectories are evaluated for kinematic feasibility, collision, and cost.

## Creation

### Syntax

```
trajectoryOptimalFrenet(refPath,validator)
planner = trajectoryOptimalFrenet( ___ ,Name,Value)
```

#### Description

`trajectoryOptimalFrenet(refPath,validator)` creates a `trajectoryOptimalFrenet` object with reference path, `refPath`, in the form of an *n*-by-2 array of `[x y]` waypoints and a state validator, `validator`, specified as a `validatorOccupancyMap` object.

`planner = trajectoryOptimalFrenet( ___ ,Name,Value)` sets additional properties using one or more name-value pairs in any order.

#### Input Arguments

**`refPath` — Reference path**
*n*-by-2 matrix

Reference path, specified as an *n*-by-2 matrix of `[x y]` pairs, where *n* is the number of waypoints.

Example: [100,100;400,400]

Data Types: `double`

**`validator` — State validator object**
`validatorOccupancyMap` object

State validator object, specified as a `validatorOccupancyMap` object.

## Properties

---

**Note** For the `'Weights'` and `'FeasibilityParameters'` properties, you cannot specify the entire structures at once. Instead, set their fields individually as name-value pairs. For example,

`trajectoryOptimalFrenet(refPath,validator,'Deviation',0)` sets the `'Deviation'` field of the structure `'Weights'`.

**`Weights` — Weights for all trajectory costs**
structure

The weights for all trajectory costs, specified as a structure containing scalars for the cost multipliers of the corresponding trajectory attributes. The total trajectory cost is a sum of all attributes multiplied by their weights. The structure has the these fields.

**`Time` — Weight for time cost**
`0` (default) | positive scalar

The cost function multiplies the weight by the total time taken to reach the terminal state. Specify this value as the comma-separated pair of `'Time'` and a positive scalar in seconds.

Data Types: `double`

**`ArcLength` — Weight for arc length cost**
`0` (default) | positive scalar

The cost function multiplies the weight by the total length of the generated trajectories. Specify this value as the comma-separated pair of `'ArcLength'` and a positive scalar in meters.

Data Types: `double`

**`LateralSmoothness` — Weight for lateral jerk cost**
`0` (default) | positive scalar

The cost function multiplies the weight by the integral of lateral jerk squared. This value determines the aggressiveness of the trajectory in the lateral direction (perpendicular to the reference path). Specify this value as the comma-separated pair of `'LateralSmoothness'` and a positive scalar. To penalize lateral jerk in the planned trajectory increase this cost value.

Data Types: `double`

**`LongitudinalSmoothness` — Weight for longitudinal jerk cost**
`0` (default) | positive scalar

The cost function multiplies the weight by the integral of longitudinal jerk squared. This value determines the aggressiveness of the trajectories in the longitudinal direction (direction of the reference path). Specify this value as the comma-separated pair of `'LongitudinalSmoothness'` and a positive scalar. To penalize large change in forward and backward acceleration increase this cost value.

Data Types: `double`

**`Deviation` — Weight for deviation from reference path**
`1` (default) | positive scalar

The cost function multiplies the weight by the perpendicular distance from the reference path at the end of the trajectory in meters. Specify this value as the comma-separated pair of `'Deviation'` and a positive scalar in meters.

Data Types: `double`

Data Types: `struct`

**`FeasibilityParameters` — Structure containing feasibility parameters**
structure

Feasibility parameters, specified as a structure containing scalar values to check the validity of a trajectory. The structure has the these fields.

**`MaxCurvature` — Maximum curvature that vehicle can execute**
`0.1` (default) | positive real scalar

Maximum curvature that the vehicle can execute. Specify this value as the comma-separated pair of `'MaxCurvature'` and a positive real scalar in $m^{-1}$. This value determines the kinematic feasibility of the trajectory.

Data Types: `double`

**`MaxAcceleration` — Maximum acceleration in direction of motion of vehicle**
`2.5` (default) | positive real scalar

Maximum acceleration in the direction of motion of the vehicle. Specify this value as the comma-separated pair of `'MaxAcceleration'` and a positive real scalar in $m/s^2$. To lower the limit on the acceleration of the vehicle in the forward or reverse direction decrease this value.

Data Types: `double`

Data Types: `struct`

**`TimeResolution` — Trajectory discretization interval**
`0.1` (default) | positive real scalar

Time interval between discretized states of the trajectory. Specify this value as the comma-separated pair of `'TimeResolution'` and a positive real scalar in seconds. These discretized states determine state validity and cost function.

Data Types: `double`

**`CostFunction` — User-defined cost function**
nullCost (default) | function handle

The user-defined cost function, specified as a function handle. The function must accept a matrix of *n*-by-7 states, `TRAJSTATES`, for each trajectory and return a cost value as a scalar. The `plan` function returns the path with the lowest cost.

For example, `leftLaneChangeCost = @(states)((states(end,2) < refPath(end,2))*10)` creates a cost function handle to prioritize left lane changes.

Data Types: `function handle`

**`TrajectoryList` — List of all possible trajectories**
structure array

This property is read-only.

The `'TrajectoryList'` property, returned as a structure array of all the candidate trajectories and their corresponding parameters. Each structure has the these fields:

- `Trajectory` — An *n*-by-7 matrix of [*x*, *y*, *theta*, *kappa*, *speed*, *acceleration*, *time*], where *n* is the number of trajectory waypoints.
- `Cost` — Cost of the trajectory.
- `MaxAcceleration` — Maximum acceleration of the trajectory.
- `MaxCurvature` — Maximum curvature of the trajectory.
- `Feasible` — A four-element vector [*velocity*, *acceleration*, *curvature*, *collision*] indicating the validity of the trajectory.

  The value of the elements can be either,

  - `1` — The trajectory is valid.
  - `0` — The trajectory is invalid.
  - `-1` — The trajectory is not checked.

Data Types: `struct`

**`TerminalStates` — Structure of all goal states**
structure

A structure that contains a list of goal states relative to the reference path. These parameters define the sampling behavior for generating alternative trajectory segments between start and each goal state. The structure has the these fields.

**`Longitudinal` — Lengths of the trajectory segment**
`30:15:90` (default) | vector

Lengths of the trajectory segment, specified as a vector in meters.

Data Types: `double`

**`Lateral` — Array of deviations from reference path in perpendicular direction at goal state**
`-2:1:2` (default) | vector

Array of deviations from reference path in perpendicular direction at goal state, specified as a vector in meters.

Data Types: `double`

**Speed — Velocity at goal state in direction of motion**
`10` (default) | positive scalar

Velocity at the goal state in the direction of motion, specified as a positive scalar in m/s.

Data Types: `double`

**`Acceleration` — Acceleration at goal state in direction of motion**
`0` (default) | positive scalar

Acceleration at the goal state in the direction of motion, specified as a positive scalar in m/s$^2$.

Data Types: `double`

**`Time` — Array of end-times for executing trajectory segment**
`7` (default) | positive vector

Array of end-times for executing the trajectory segment, specified as a positive vector in seconds.

Data Types: `double`

Data Types: `struct`

#### `Waypoints` — Waypoints of reference path

[ ] (default) | *n*-by-2 matrix

Waypoints of reference path, specified as an *n*-by-2 matrix of `[x y]` pairs, where *n* is the number of waypoints. Waypoints act as a reference for planning alternative trajectories optimized by this planner.

Data Types: `double`

#### `NumSegments` — Number of longitudinal segments for each trajectory

`1` (default) | positive scalar

Number of longitudinal segments for each trajectory. Specify this value as the comma-separated pair of `'NumSegments'` and a positive scalar. This property generates intermediate longitudinal terminal states to which all lateral terminal states are combined with for generating more motion primitives to each terminal state.

For example, `'NumSegments',2` creates two partitions between each longitudinal terminal state. Trajectories are generated to reach the intermediate longitudinal states with all the available lateral terminal states.

Data Types: `double`

#### `DeviationOffset` — Deviation offset from reference path in lateral direction

`0` (default) | scalar

Deviation offset from the reference path in the lateral direction. Specify this value as the comma-separated pair of `'DeviationOffset'` and a scalar. A negative value offset the deviation to the right, and a positive value offset the deviation to the left of the reference path in the lateral direction. Set this property to bias your solution to a certain turn direction when avoiding obstacles in the reference path.

Data Types: `double`

## Object Functions

| | |
|---|---|
| cart2frenet | Convert Cartesian states to Frenet states |
| copy | Create deep copy of object |
| frenet2cart | Convert Frenet states to Cartesian states |
| plan | Plan optimal trajectory |
| show | Visualize trajectories |

## Examples

### Optimal Trajectory Planning in Frenet Space

This example shows how to plan an optimal trajectory using a `trajectoryOptimalFrenet` object.

### Create and Assign Map to State Validator

Create a state validator object for collision checking.

```
stateValidator = validatorOccupancyMap;
```

Create an obstacle grid map.

```
grid = zeros(50,100);
grid(24:26,48:53) = 1;
```

Create a `binaryOccupancyMap` with the grid map.

```
map = binaryOccupancyMap(grid);
```

Assign the map and the state bounds to the state validator.

```
stateValidator.Map = map;
stateValidator.StateSpace.StateBounds(1:2,:) = [map.XWorldLimits; map.YWorldLimits];
```

### Plan and Visualize Trajectory

Create a reference path for the planner to follow.

```
refPath = [0,25;100,25];
```

Initialize the planner object with the reference path, and the state validator.

```
planner = trajectoryOptimalFrenet(refPath,stateValidator);
```

Assign longitudinal terminal state, lateral deviation, and maximum acceleration values.

```
planner.TerminalStates.Longitudinal = 100;
planner.TerminalStates.Lateral = -10:5:10;
planner.FeasibilityParameters.MaxAcceleration = 10;
```

Specify the deviation offset value close to the left lateral terminal state to prioritize left lane changes.

```
planner.DeviationOffset = 5;
```

### Trajectory Planning

Initial cartesian state of vehicle.

```
initCartState = [0 25 pi/9 0 0 0];
```

Convert cartesian state of vehicle to Frenet state.

```
initFrenetState = cart2frenet(planner,initCartState);
```

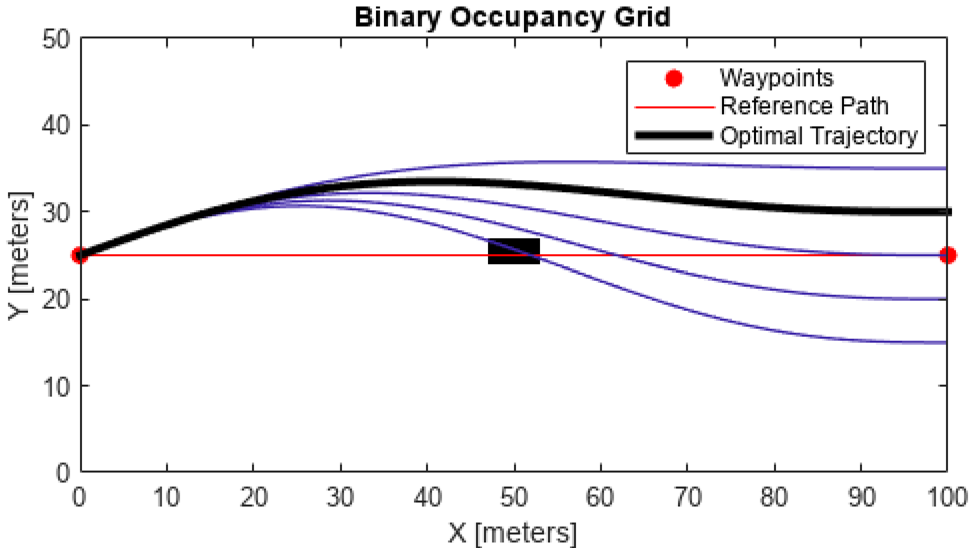
Plan a trajectory from initial Frenet state.

```
plan(planner,initFrenetState);
```

### Trajectory Visualization

Visualize the map and the trajectories.

```
show(map)
hold on
show(planner,'Trajectory','all')
```




### Partitioning Longitudinal Terminal States in Trajectory Generation

This example shows how to partition the longitudinal terminal states in optimal trajectory planning using a `trajectoryOptimalFrenet` object.

#### Create and Assign Map to State Validator

Create a state validator object for collision checking.

```
stateValidator = validatorOccupancyMap;
```

Create an obstacle grid map.

```
grid = zeros(50,100);
grid(25:27,28:33) = 1;
grid(16:18,37:42) = 1;
grid(29:31,72:77) = 1;
```

Create a `binaryOccupancyMap` with the grid map.

```
map = binaryOccupancyMap(grid);
```

Assign the map and the state bounds to the state validator.

```
stateValidator.Map = map;
stateValidator.StateSpace.StateBounds(1:2,:) = [map.XWorldLimits; map.YWorldLimits];
```

### Plan and Visualize Trajectory

Create a reference path for the planner to follow.

```
refPath = [0,25;30,30;75,20;100,25];
```

Initialize the planner object with the reference path, and the state validator.

```
planner = trajectoryOptimalFrenet(refPath,stateValidator);
```

Assign longitudinal terminal state, lateral deviation, and maximum acceleration values.

```
planner.TerminalStates.Longitudinal = 100;
planner.TerminalStates.Lateral = -5:5:5;
planner.FeasibilityParameters.MaxAcceleration = 10;
```

Assign the number of partitions for the longitudinal terminal state.

```
planner.NumSegments = 3;
```

### Trajectory Planning

Initial Frenet state of vehicle.

```
initFrenetState = zeros(1,6);
```

Plan a trajectory from initial Frenet state.

```
plan(planner,initFrenetState);
```

### Trajectory Visualization

Visualize the map and the trajectories.

```
show(map)
hold on
show(planner,'Trajectory','all')
hold on
```

### Generate Lane Boundaries

Calculate end of reference path as Frenet state.

```
refPathEnd = cart2frenet(planner,[planner.Waypoints(end,:) 0 0 0 0]);
```

Calculate lane offsets on both sides of the lateral terminal states with half lane width value.

```
laneOffsets = unique([planner.TerminalStates.Lateral+2.5 planner.TerminalStates.Lateral-2.5]);
```

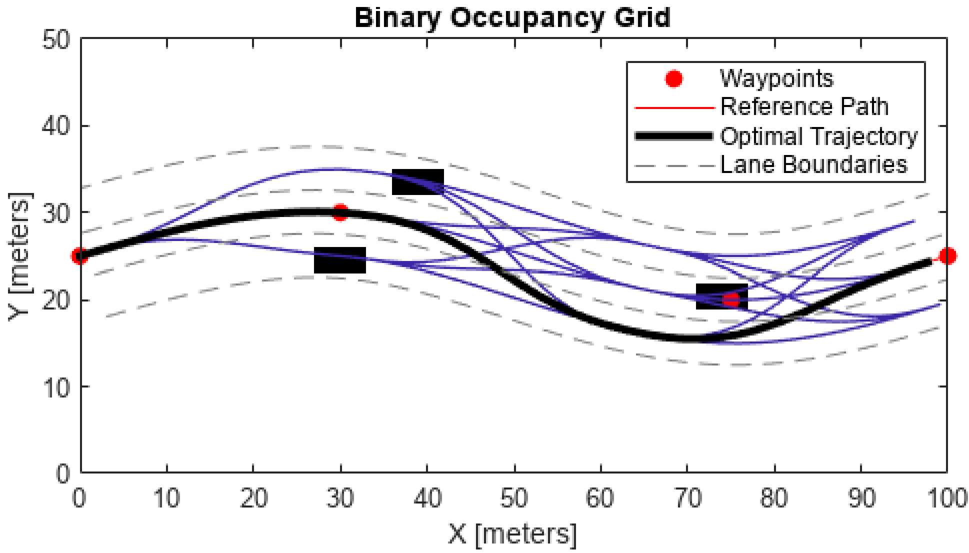
Calculate positions of lanes in Cartesian state.

```
numLaneOffsets = numel(laneOffsets);
xRefPathEnd = ceil(refPathEnd(1));
laneXY = zeros((numLaneOffsets*xRefPathEnd)+numLaneOffsets,2);
```

```
xIndex = 0;

for laneID = 1:numLaneOffsets
    for x = 1:xRefPathEnd
        laneCart = frenet2cart(planner,[x 0 0 laneOffsets(laneID) 0 0]);
        xIndex = xIndex + 1;
        laneXY(xIndex,:) = laneCart(1:2);
    end
    xIndex = xIndex + 1;
    laneXY(xIndex,:) = NaN(1,2);
end
```

Plot lane boundaries.

```
plot(laneXY(:,1),laneXY(:,2),'LineWidth',0.5,'Color',[0.5 0.5 0.5],'DisplayName','Lane Boundaries
```




## Limitations

- Self-intersections in the reference path can lead to unexpected behavior.
- The planner does not support reverse driving.
- Initial orientation for planning should be within `-pi/2` and `pi/2` to the reference path.
- Limit the number of TerminalStates for real-time applications since computational complexity grows with it.

# Version History

**Introduced in R2019b**

## References

[1] Werling, Moritz, Julius Ziegler, Sören Kammel, and Sebastian Thrun. "Optimal Trajectory Generation for Dynamic Street Scenarios in a Frenet Frame." *2010 IEEE International Conference on Robotics and Automation*. 2010, pp. 987–993.

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`validatorOccupancyMap` | `nav.StateValidator` | `plannerHybridAStar`

# cart2frenet

Convert Cartesian states to Frenet states

## Syntax

`cart2frenet(planner,cartesianStates)`

## Description

`cart2frenet(planner,cartesianStates)` converts a six-element vector of `cartesianStates` [*x*, *y*, *theta*, *kappa*, *speed*, *acceleration*] to a six-element vector of Frenet states [*s*, *ds/dt*, $d^2s/dt^2$, *l*, *dl/ds*, $d^2l/ds^2$], where *s* is arc length from the first point in reference path, and *l* is normal distance from the closest point at *s* on the reference path.

## Examples

### Optimal Trajectory Planning in Frenet Space

This example shows how to plan an optimal trajectory using a `trajectoryOptimalFrenet` object.

#### Create and Assign Map to State Validator

Create a state validator object for collision checking.

```
stateValidator = validatorOccupancyMap;
```

Create an obstacle grid map.

```
grid = zeros(50,100);
grid(24:26,48:53) = 1;
```

Create a `binaryOccupancyMap` with the grid map.

```
map = binaryOccupancyMap(grid);
```

Assign the map and the state bounds to the state validator.

```
stateValidator.Map = map;
stateValidator.StateSpace.StateBounds(1:2,:) = [map.XWorldLimits; map.YWorldLimits];
```

#### Plan and Visualize Trajectory

Create a reference path for the planner to follow.

```
refPath = [0,25;100,25];
```

Initialize the planner object with the reference path, and the state validator.

```
planner = trajectoryOptimalFrenet(refPath,stateValidator);
```

Assign longitudinal terminal state, lateral deviation, and maximum acceleration values.

```
planner.TerminalStates.Longitudinal = 100;
planner.TerminalStates.Lateral = -10:5:10;
planner.FeasibilityParameters.MaxAcceleration = 10;
```

Specify the deviation offset value close to the left lateral terminal state to prioritize left lane changes.

```
planner.DeviationOffset = 5;
```

**Trajectory Planning**

Initial cartesian state of vehicle.

```
initCartState = [0 25 pi/9 0 0 0];
```

Convert cartesian state of vehicle to Frenet state.

```
initFrenetState = cart2frenet(planner,initCartState);
```

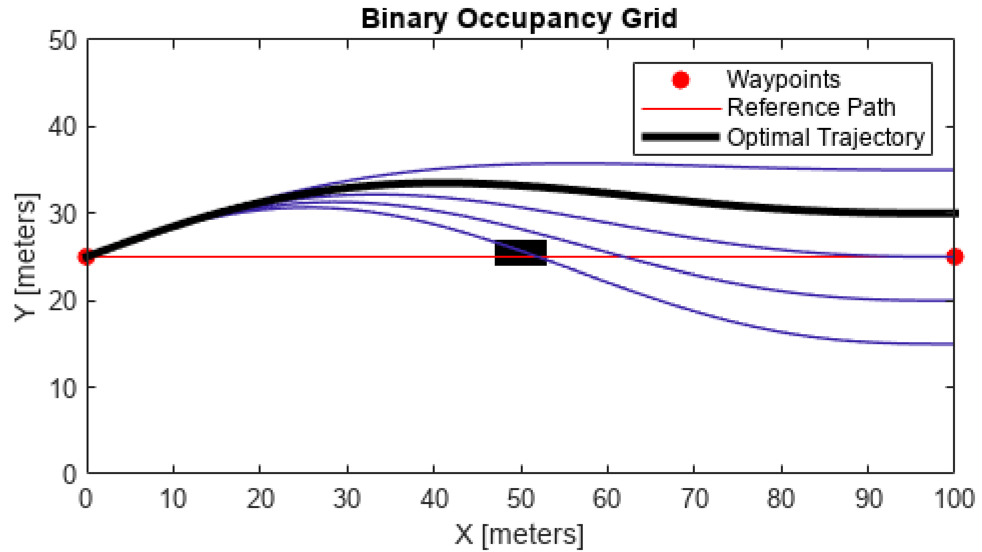
Plan a trajectory from initial Frenet state.

```
plan(planner,initFrenetState);
```

**Trajectory Visualization**

Visualize the map and the trajectories.

```
show(map)
hold on
show(planner,'Trajectory','all')
```




### Partitioning Longitudinal Terminal States in Trajectory Generation

This example shows how to partition the longitudinal terminal states in optimal trajectory planning using a `trajectoryOptimalFrenet` object.

#### Create and Assign Map to State Validator

Create a state validator object for collision checking.

```
stateValidator = validatorOccupancyMap;
```

Create an obstacle grid map.

```
grid = zeros(50,100);
grid(25:27,28:33) = 1;
grid(16:18,37:42) = 1;
grid(29:31,72:77) = 1;
```

Create a `binaryOccupancyMap` with the grid map.

```
map = binaryOccupancyMap(grid);
```

Assign the map and the state bounds to the state validator.

```
stateValidator.Map = map;
stateValidator.StateSpace.StateBounds(1:2,:) = [map.XWorldLimits; map.YWorldLimits];
```

#### Plan and Visualize Trajectory

Create a reference path for the planner to follow.

```
refPath = [0,25;30,30;75,20;100,25];
```

Initialize the planner object with the reference path, and the state validator.

```
planner = trajectoryOptimalFrenet(refPath,stateValidator);
```

Assign longitudinal terminal state, lateral deviation, and maximum acceleration values.

```
planner.TerminalStates.Longitudinal = 100;
planner.TerminalStates.Lateral = -5:5:5;
planner.FeasibilityParameters.MaxAcceleration = 10;
```

Assign the number of partitions for the longitudinal terminal state.

```
planner.NumSegments = 3;
```

**Trajectory Planning**

Initial Frenet state of vehicle.

```
initFrenetState = zeros(1,6);
```

Plan a trajectory from initial Frenet state.

```
plan(planner,initFrenetState);
```

**Trajectory Visualization**

Visualize the map and the trajectories.

```
show(map)
hold on
show(planner,'Trajectory','all')
hold on
```

**Generate Lane Boundaries**

Calculate end of reference path as Frenet state.

```
refPathEnd = cart2frenet(planner,[planner.Waypoints(end,:) 0 0 0 0]);
```

Calculate lane offsets on both sides of the lateral terminal states with half lane width value.

```
laneOffsets = unique([planner.TerminalStates.Lateral+2.5 planner.TerminalStates.Lateral-2.5]);
```

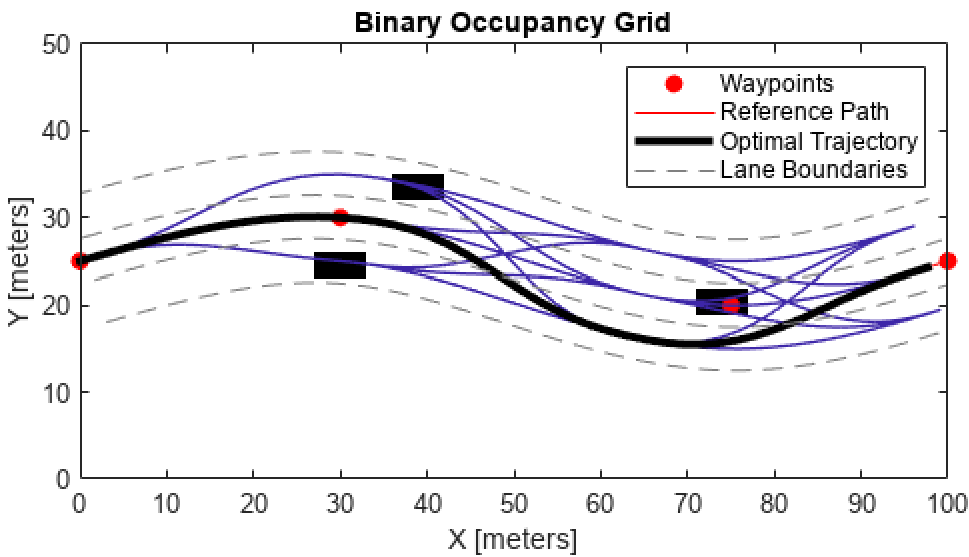
Calculate positions of lanes in Cartesian state.

```
numLaneOffsets = numel(laneOffsets);
xRefPathEnd = ceil(refPathEnd(1));
laneXY = zeros((numLaneOffsets*xRefPathEnd)+numLaneOffsets,2);
xIndex = 0;

for laneID = 1:numLaneOffsets
    for x = 1:xRefPathEnd
        laneCart = frenet2cart(planner,[x 0 0 laneOffsets(laneID) 0 0]);
```

```
        xIndex = xIndex + 1;
        laneXY(xIndex,:) = laneCart(1:2);
    end
    xIndex = xIndex + 1;
    laneXY(xIndex,:) = NaN(1,2);
end
```

Plot lane boundaries.

```
plot(laneXY(:,1),laneXY(:,2),'LineWidth',0.5,'Color',[0.5 0.5 0.5],'DisplayName','Lane Boundaries
```




## Input Arguments

**planner — Optimal trajectory planner in Frenet space**
`trajectoryOptimalFrenet` object

Optimal trajectory planner in Frenet space, specified as a `trajectoryOptimalFrenet` object.

**cartesianStates — Vector of Cartesian states**
six-element vector

Vector of Cartesian states, specified as a 1-by-6 vector [*x*, *y*, *theta*, *kappa*, *speed*, *acceleration*].

- *x* and *y* specify the position in meters.

- *theta* specifies the orientation angle in radians.
- *kappa* specifies the curvature in `m`$^{-1}$.
- *speed* specifies the velocity in `m/s`.
- *acceleration* specifies the acceleration in `m/s`$^{2}$.

Example: `[110 110 pi/4 0 0 0]`

Data Types: `double`

# Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`trajectoryOptimalFrenet` | `frenet2cart`

# copy

Create deep copy of object

## Syntax

```
plannerCopy = copy(planner)
```

## Description

`plannerCopy = copy(planner)` creates a deep copy of the `trajectoryOptimalFrenet` object with the same properties.

## Examples

### Create Copy of trajectoryOptimalFrenet Object

Create a `binaryOccupancyMap` with a obstacle grid map.

```
grid = zeros(50,100);
grid(24:26,48:53) = 1;
map = binaryOccupancyMap(grid);
```

Create a state validator. Assign the map and the state bounds to the state validator.

```
validator = validatorOccupancyMap;
validator.Map = map;
validator.StateSpace.StateBounds(1:2,:) = [map.XWorldLimits; map.YWorldLimits];
```

Create a reference path for the planner.

```
refPath = [0,25;100,25];
```

Create a `trajectoryOptimalFrenet` object.

```
planner = trajectoryOptimalFrenet(refPath,validator)
```

```
planner = 
  trajectoryOptimalFrenet with properties:

                  Weights: [1x1 struct]
    FeasibilityParameters: [1x1 struct]
           TimeResolution: 0.1000
              NumSegments: 1
          DeviationOffset: 0
             CostFunction: @trajectoryOptimalFrenet.nullCost
           TrajectoryList: [1x1 struct]
           TerminalStates: [1x1 struct]
                Waypoints: [2x2 double]
```

Create a copy of `trajectoryOptimalFrenet` object.

```
plannerNew = copy(planner)
```

```
plannerNew = 
  trajectoryOptimalFrenet with properties:

                   Weights: [1x1 struct]
    FeasibilityParameters: [1x1 struct]
           TimeResolution: 0.1000
              NumSegments: 1
          DeviationOffset: 0
             CostFunction: @trajectoryOptimalFrenet.nullCost
           TrajectoryList: [1x1 struct]
           TerminalStates: [1x1 struct]
                Waypoints: [2x2 double]
```

## Input Arguments

### planner — Trajectory optimal Frenet object

trajectoryOptimalFrenet object

Trajectory optimal Frenet object, specified as a trajectoryOptimalFrenet object.

## Output Arguments

### plannerCopy — Copy of trajectory optimal Frenet object

trajectoryOptimalFrenet object

Copy of trajectory optimal Frenet object, returned as a trajectoryOptimalFrenet object with the same properties.

# Version History

**Introduced in R2020b**

## See Also

trajectoryOptimalFrenet

# frenet2cart

Convert Frenet states to Cartesian states

## Syntax

```
frenet2cart(planner,frenetStates)
```

## Description

`frenet2cart(planner,frenetStates)` converts a six-element vector of `frenetStates` [*s*, *ds/dt*, $d^2s/dt^2$, *l*, *dl/ds*, $d^2l/ds^2$] to a six-element vector of Cartesian states [*x*, *y*, *theta*, *kappa*, *speed*, *acceleration*].

## Examples

### Optimal Trajectory Planning in Frenet Space

This example shows how to plan an optimal trajectory using a `trajectoryOptimalFrenet` object.

#### Create and Assign Map to State Validator

Create a state validator object for collision checking.

```
stateValidator = validatorOccupancyMap;
```

Create an obstacle grid map.

```
grid = zeros(50,100);
grid(24:26,48:53) = 1;
```

Create a `binaryOccupancyMap` with the grid map.

```
map = binaryOccupancyMap(grid);
```

Assign the map and the state bounds to the state validator.

```
stateValidator.Map = map;
stateValidator.StateSpace.StateBounds(1:2,:) = [map.XWorldLimits; map.YWorldLimits];
```

#### Plan and Visualize Trajectory

Create a reference path for the planner to follow.

```
refPath = [0,25;100,25];
```

Initialize the planner object with the reference path, and the state validator.

```
planner = trajectoryOptimalFrenet(refPath,stateValidator);
```

Assign longitudinal terminal state, lateral deviation, and maximum acceleration values.

```
planner.TerminalStates.Longitudinal = 100;
planner.TerminalStates.Lateral = -10:5:10;
planner.FeasibilityParameters.MaxAcceleration = 10;
```

Specify the deviation offset value close to the left lateral terminal state to prioritize left lane changes.

```
planner.DeviationOffset = 5;
```

**Trajectory Planning**

Initial cartesian state of vehicle.

```
initCartState = [0 25 pi/9 0 0 0];
```

Convert cartesian state of vehicle to Frenet state.

```
initFrenetState = cart2frenet(planner,initCartState);
```

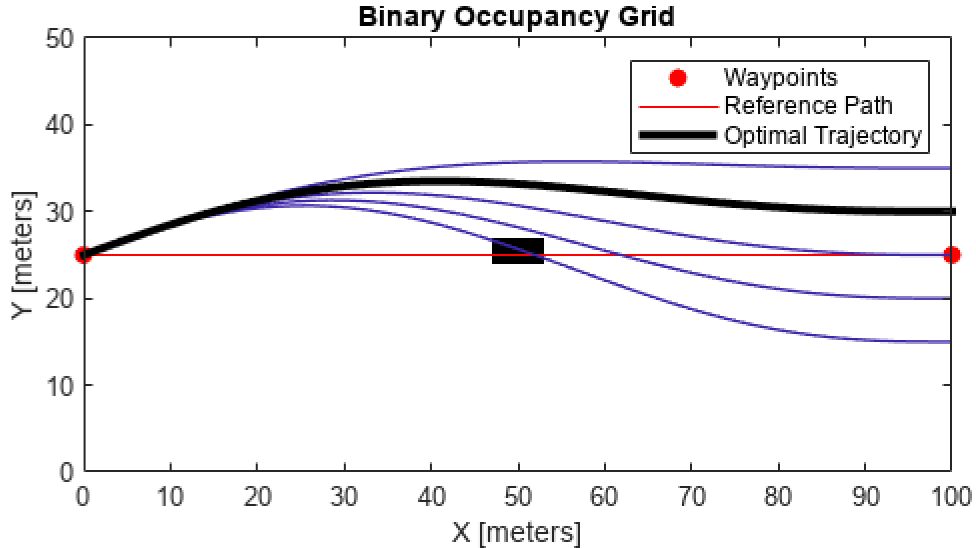
Plan a trajectory from initial Frenet state.

```
plan(planner,initFrenetState);
```

**Trajectory Visualization**

Visualize the map and the trajectories.

```
show(map)
hold on
show(planner,'Trajectory','all')
```




#### Partitioning Longitudinal Terminal States in Trajectory Generation

This example shows how to partition the longitudinal terminal states in optimal trajectory planning using a `trajectoryOptimalFrenet` object.

**Create and Assign Map to State Validator**

Create a state validator object for collision checking.

```
stateValidator = validatorOccupancyMap;
```

Create an obstacle grid map.

```
grid = zeros(50,100);
grid(25:27,28:33) = 1;
grid(16:18,37:42) = 1;
grid(29:31,72:77) = 1;
```

Create a `binaryOccupancyMap` with the grid map.

```
map = binaryOccupancyMap(grid);
```

Assign the map and the state bounds to the state validator.

```
stateValidator.Map = map;
stateValidator.StateSpace.StateBounds(1:2,:) = [map.XWorldLimits; map.YWorldLimits];
```

### Plan and Visualize Trajectory

Create a reference path for the planner to follow.

```
refPath = [0,25;30,30;75,20;100,25];
```

Initialize the planner object with the reference path, and the state validator.

```
planner = trajectoryOptimalFrenet(refPath,stateValidator);
```

Assign longitudinal terminal state, lateral deviation, and maximum acceleration values.

```
planner.TerminalStates.Longitudinal = 100;
planner.TerminalStates.Lateral = -5:5:5;
planner.FeasibilityParameters.MaxAcceleration = 10;
```

Assign the number of partitions for the longitudinal terminal state.

```
planner.NumSegments = 3;
```

#### Trajectory Planning

Initial Frenet state of vehicle.

```
initFrenetState = zeros(1,6);
```

Plan a trajectory from initial Frenet state.

```
plan(planner,initFrenetState);
```

#### Trajectory Visualization

Visualize the map and the trajectories.

```
show(map)
hold on
show(planner,'Trajectory','all')
hold on
```

#### Generate Lane Boundaries

Calculate end of reference path as Frenet state.

```
refPathEnd = cart2frenet(planner,[planner.Waypoints(end,:) 0 0 0 0]);
```

Calculate lane offsets on both sides of the lateral terminal states with half lane width value.

```
laneOffsets = unique([planner.TerminalStates.Lateral+2.5 planner.TerminalStates.Lateral-2.5]);
```

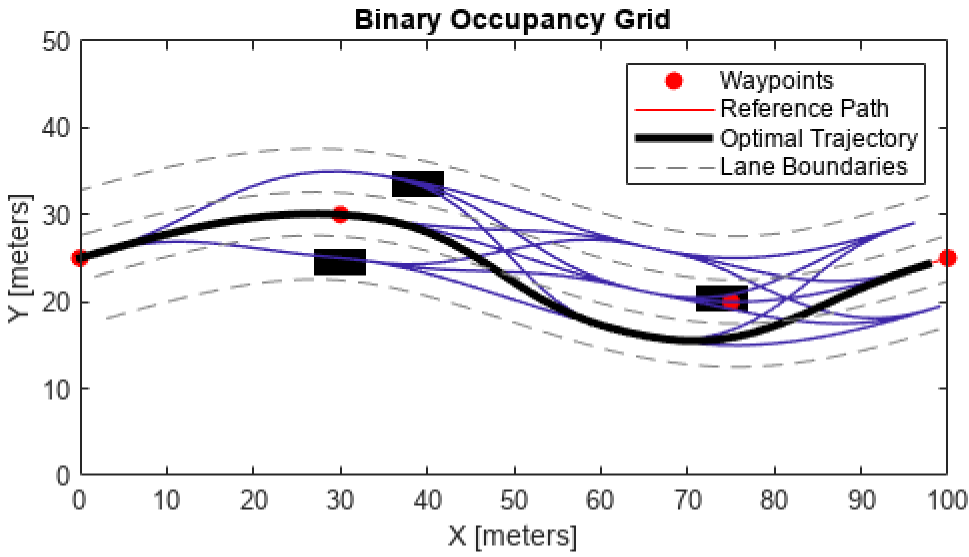
Calculate positions of lanes in Cartesian state.

```
numLaneOffsets = numel(laneOffsets);
xRefPathEnd = ceil(refPathEnd(1));
laneXY = zeros((numLaneOffsets*xRefPathEnd)+numLaneOffsets,2);
xIndex = 0;

for laneID = 1:numLaneOffsets
    for x = 1:xRefPathEnd
        laneCart = frenet2cart(planner,[x 0 0 laneOffsets(laneID) 0 0]);
```

```
        xIndex = xIndex + 1;
        laneXY(xIndex,:) = laneCart(1:2);
    end
    xIndex = xIndex + 1;
    laneXY(xIndex,:) = NaN(1,2);
end
```

Plot lane boundaries.

```
plot(laneXY(:,1),laneXY(:,2),'LineWidth',0.5,'Color',[0.5 0.5 0.5],'DisplayName','Lane Boundaries
```




## Input Arguments

**`planner` — Optimal trajectory planner in Frenet space**
`trajectoryOptimalFrenet` object

Optimal trajectory planner in Frenet space, specified as a `trajectoryOptimalFrenet` object.

**`frenetStates` — Vector of Frenet states**
six-element vector

Vector of Frenet states, specified as a 1-by-6 vector, `[s, ds/dt, d²s/dt², l, dl/ds, d²l/ds²]`.

- *s* specifies the arc length from the first point in reference path in meters.
- *ds/dt* specifies the first derivative of arc length.

- $d^2s/dt^2$ specifies the second derivative of arc length.
- $l$ specifies the normal distance from the closest point in the reference path in meters.
- $dl/ds$ specifies the first derivative of normal distance.
- $d^2l/ds^2$ specifies the second derivative of normal distance.

Example: `[10 1 0 3 0 0]`

Data Types: `double`

# Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`trajectoryOptimalFrenet` | `cart2frenet`

# plan

Plan optimal trajectory

## Syntax

`[traj,index,cost,flag] = plan(planner,start)`

## Description

`[traj,index,cost,flag] = plan(planner,start)` computes a feasible trajectory, `traj`, from a list of candidate trajectories generated from the `trajectoryOptimalFrenet` object, `planner`. `start` is specified as a six-element vector [*s*, *ds/dt*, $d^2s/dt^2$, *l*, *dl/ds*, $d^2l/ds^2$], where *s* is the arc length from the first point in the reference path, and *l* is normal distance from the closest point at *s* on the reference path.

The output trajectory, `traj`, also has an associated `cost` and `index` for the TrajectoryList property of the planner. `flag` is a numeric exit flag indicating status of the solution.

To improve the results of the planning output, modify the parameters on the `planner` object.

## Examples

### Optimal Trajectory Planning in Frenet Space

This example shows how to plan an optimal trajectory using a `trajectoryOptimalFrenet` object.

#### Create and Assign Map to State Validator

Create a state validator object for collision checking.

```
stateValidator = validatorOccupancyMap;
```

Create an obstacle grid map.

```
grid = zeros(50,100);
grid(24:26,48:53) = 1;
```

Create a `binaryOccupancyMap` with the grid map.

```
map = binaryOccupancyMap(grid);
```

Assign the map and the state bounds to the state validator.

```
stateValidator.Map = map;
stateValidator.StateSpace.StateBounds(1:2,:) = [map.XWorldLimits; map.YWorldLimits];
```

#### Plan and Visualize Trajectory

Create a reference path for the planner to follow.

```
refPath = [0,25;100,25];
```

Initialize the planner object with the reference path, and the state validator.

```
planner = trajectoryOptimalFrenet(refPath,stateValidator);
```

Assign longitudinal terminal state, lateral deviation, and maximum acceleration values.

```
planner.TerminalStates.Longitudinal = 100;
planner.TerminalStates.Lateral = -10:5:10;
planner.FeasibilityParameters.MaxAcceleration = 10;
```

Specify the deviation offset value close to the left lateral terminal state to prioritize left lane changes.

```
planner.DeviationOffset = 5;
```

**Trajectory Planning**

Initial cartesian state of vehicle.

```
initCartState = [0 25 pi/9 0 0 0];
```

Convert cartesian state of vehicle to Frenet state.

```
initFrenetState = cart2frenet(planner,initCartState);
```

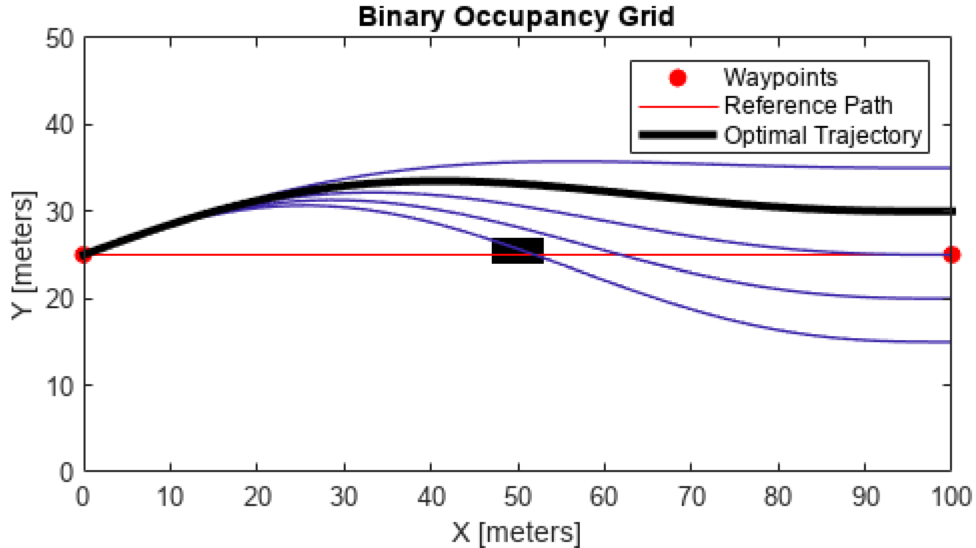
Plan a trajectory from initial Frenet state.

```
plan(planner,initFrenetState);
```

**Trajectory Visualization**

Visualize the map and the trajectories.

```
show(map)
hold on
show(planner,'Trajectory','all')
```




### Partitioning Longitudinal Terminal States in Trajectory Generation

This example shows how to partition the longitudinal terminal states in optimal trajectory planning using a `trajectoryOptimalFrenet` object.

#### Create and Assign Map to State Validator

Create a state validator object for collision checking.

```
stateValidator = validatorOccupancyMap;
```

Create an obstacle grid map.

```
grid = zeros(50,100);
grid(25:27,28:33) = 1;
grid(16:18,37:42) = 1;
grid(29:31,72:77) = 1;
```

Create a `binaryOccupancyMap` with the grid map.

```
map = binaryOccupancyMap(grid);
```

Assign the map and the state bounds to the state validator.

```
stateValidator.Map = map;
stateValidator.StateSpace.StateBounds(1:2,:) = [map.XWorldLimits; map.YWorldLimits];
```

### Plan and Visualize Trajectory

Create a reference path for the planner to follow.

```
refPath = [0,25;30,30;75,20;100,25];
```

Initialize the planner object with the reference path, and the state validator.

```
planner = trajectoryOptimalFrenet(refPath,stateValidator);
```

Assign longitudinal terminal state, lateral deviation, and maximum acceleration values.

```
planner.TerminalStates.Longitudinal = 100;
planner.TerminalStates.Lateral = -5:5:5;
planner.FeasibilityParameters.MaxAcceleration = 10;
```

Assign the number of partitions for the longitudinal terminal state.

```
planner.NumSegments = 3;
```

**Trajectory Planning**

Initial Frenet state of vehicle.

```
initFrenetState = zeros(1,6);
```

Plan a trajectory from initial Frenet state.

```
plan(planner,initFrenetState);
```

**Trajectory Visualization**

Visualize the map and the trajectories.

```
show(map)
hold on
show(planner,'Trajectory','all')
hold on
```

**Generate Lane Boundaries**

Calculate end of reference path as Frenet state.

```
refPathEnd = cart2frenet(planner,[planner.Waypoints(end,:) 0 0 0 0]);
```

Calculate lane offsets on both sides of the lateral terminal states with half lane width value.

```
laneOffsets = unique([planner.TerminalStates.Lateral+2.5 planner.TerminalStates.Lateral-2.5]);
```

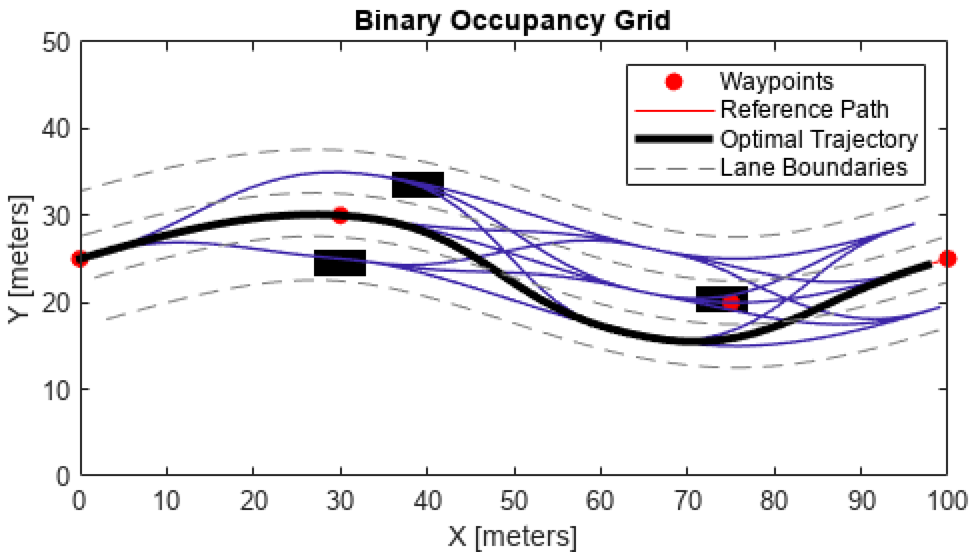
Calculate positions of lanes in Cartesian state.

```
numLaneOffsets = numel(laneOffsets);
xRefPathEnd = ceil(refPathEnd(1));
laneXY = zeros((numLaneOffsets*xRefPathEnd)+numLaneOffsets,2);
xIndex = 0;

for laneID = 1:numLaneOffsets
    for x = 1:xRefPathEnd
        laneCart = frenet2cart(planner,[x 0 0 laneOffsets(laneID) 0 0]);
```

```
        xIndex = xIndex + 1;
        laneXY(xIndex,:) = laneCart(1:2);
    end
    xIndex = xIndex + 1;
    laneXY(xIndex,:) = NaN(1,2);
end
```

Plot lane boundaries.

```
plot(laneXY(:,1),laneXY(:,2),'LineWidth',0.5,'Color',[0.5 0.5 0.5],'DisplayName','Lane Boundaries
```




## Input Arguments

**planner — Optimal trajectory planner in Frenet space**
`trajectoryOptimalFrenet` object

Optimal trajectory planner in Frenet space, specified as a `trajectoryOptimalFrenet` object.

**start — Initial Frenet state**
six-element vector

Initial Frenet state, specified as a 1-by-6 vector [$s$, $ds/dt$, $d^2s/dt^2$, $l$, $dl/ds$, $d^2l/ds^2$].

- $s$ specifies the arc length from the first point in reference path in meters.
- $ds/dt$ specifies the first derivative of arc length.

- $d^2s/dt^2$ specifies the second derivative of arc length.
- $l$ specifies the normal distance from the closest point in the reference path in meters.
- $dl/ds$ specifies the first derivative of normal distance.
- $d^2l/ds^2$ specifies the second derivative of normal distance.

## Output Arguments

### `traj` — Feasible trajectory with minimum cost

*n*-by-7 matrix

Feasible trajectory with minimum cost, returned as an *n*-by-7 matrix of `[x, y, theta, kappa, speed, acceleration, time]`, where *n* is the number of trajectory waypoints.

- *x* and *y* specify the position in meters.
- *theta* specifies the orientation angle in radians.
- *kappa* specifies the curvature in $m^{-1}$.
- *speed* specifies the velocity in `m/s`.
- *acceleration* specifies the acceleration in $m/s^2$.
- *time* specifies the time in `s`.

### `index` — Index of feasible trajectory with minimum cost

positive integer scalar

Index of feasible trajectory with minimum cost, returned as a positive integer scalar.

### `cost` — Least cost of feasible trajectory

positive scalar

Least cost of feasible trajectory, returned as a positive scalar.

### `flag` — Exit flag indicating solution status

`0` | `1`

Exit flag indicating the solution status, returned either as `0` or `1`.

- `0` — Optimal trajectory was found.
- `1` — No feasible trajectory exists.

When no feasible trajectory exists, the planner returns an empty trajectory.

# Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`trajectoryOptimalFrenet` | `show`

# show

Visualize trajectories

## Syntax

```
show(planner)
show(planner,Name,Value)
axHandle = show(planner)
```

## Description

`show(planner)` visualizes the reference path and trajectory from the candidates generated by the `plan` function. The trajectory is shown as a line plot. The plot also includes datatip mode, which can be used to visualize the feasibility vector and index of the trajectory from the TrajectoryList property.

`show(planner,Name,Value)` specifies additional options using one or more `Name,Value` pair arguments.

`axHandle = show(planner)` returns the axes handle of the figure used to plot the trajectory.

## Examples

### Optimal Trajectory Planning in Frenet Space

This example shows how to plan an optimal trajectory using a `trajectoryOptimalFrenet` object.

#### Create and Assign Map to State Validator

Create a state validator object for collision checking.

```
stateValidator = validatorOccupancyMap;
```

Create an obstacle grid map.

```
grid = zeros(50,100);
grid(24:26,48:53) = 1;
```

Create a `binaryOccupancyMap` with the grid map.

```
map = binaryOccupancyMap(grid);
```

Assign the map and the state bounds to the state validator.

```
stateValidator.Map = map;
stateValidator.StateSpace.StateBounds(1:2,:) = [map.XWorldLimits; map.YWorldLimits];
```

#### Plan and Visualize Trajectory

Create a reference path for the planner to follow.

```
refPath = [0,25;100,25];
```

Initialize the planner object with the reference path, and the state validator.

```
planner = trajectoryOptimalFrenet(refPath,stateValidator);
```

Assign longitudinal terminal state, lateral deviation, and maximum acceleration values.

```
planner.TerminalStates.Longitudinal = 100;
planner.TerminalStates.Lateral = -10:5:10;
planner.FeasibilityParameters.MaxAcceleration = 10;
```

Specify the deviation offset value close to the left lateral terminal state to prioritize left lane changes.

```
planner.DeviationOffset = 5;
```

**Trajectory Planning**

Initial cartesian state of vehicle.

```
initCartState = [0 25 pi/9 0 0 0];
```

Convert cartesian state of vehicle to Frenet state.

```
initFrenetState = cart2frenet(planner,initCartState);
```

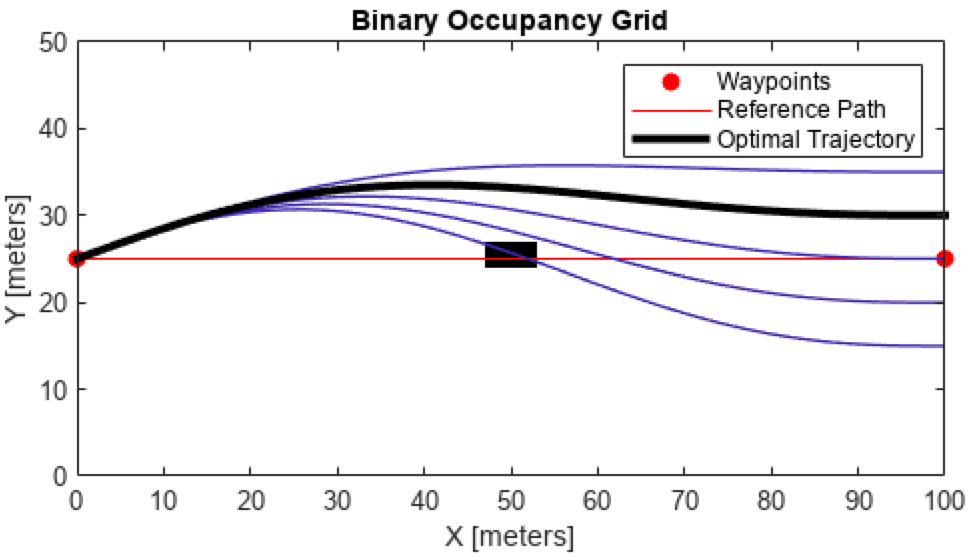
Plan a trajectory from initial Frenet state.

```
plan(planner,initFrenetState);
```

**Trajectory Visualization**

Visualize the map and the trajectories.

```
show(map)
hold on
show(planner,'Trajectory','all')
```




### Partitioning Longitudinal Terminal States in Trajectory Generation

This example shows how to partition the longitudinal terminal states in optimal trajectory planning using a `trajectoryOptimalFrenet` object.

#### Create and Assign Map to State Validator

Create a state validator object for collision checking.

```
stateValidator = validatorOccupancyMap;
```

Create an obstacle grid map.

```
grid = zeros(50,100);
grid(25:27,28:33) = 1;
grid(16:18,37:42) = 1;
grid(29:31,72:77) = 1;
```

Create a `binaryOccupancyMap` with the grid map.

```
map = binaryOccupancyMap(grid);
```

Assign the map and the state bounds to the state validator.

```
stateValidator.Map = map;
stateValidator.StateSpace.StateBounds(1:2,:) = [map.XWorldLimits; map.YWorldLimits];
```

### Plan and Visualize Trajectory

Create a reference path for the planner to follow.

```
refPath = [0,25;30,30;75,20;100,25];
```

Initialize the planner object with the reference path, and the state validator.

```
planner = trajectoryOptimalFrenet(refPath,stateValidator);
```

Assign longitudinal terminal state, lateral deviation, and maximum acceleration values.

```
planner.TerminalStates.Longitudinal = 100;
planner.TerminalStates.Lateral = -5:5:5;
planner.FeasibilityParameters.MaxAcceleration = 10;
```

Assign the number of partitions for the longitudinal terminal state.

```
planner.NumSegments = 3;
```

#### Trajectory Planning

Initial Frenet state of vehicle.

```
initFrenetState = zeros(1,6);
```

Plan a trajectory from initial Frenet state.

```
plan(planner,initFrenetState);
```

#### Trajectory Visualization

Visualize the map and the trajectories.

```
show(map)
hold on
show(planner,'Trajectory','all')
hold on
```

#### Generate Lane Boundaries

Calculate end of reference path as Frenet state.

```
refPathEnd = cart2frenet(planner,[planner.Waypoints(end,:) 0 0 0 0]);
```

Calculate lane offsets on both sides of the lateral terminal states with half lane width value.

```
laneOffsets = unique([planner.TerminalStates.Lateral+2.5 planner.TerminalStates.Lateral-2.5]);
```

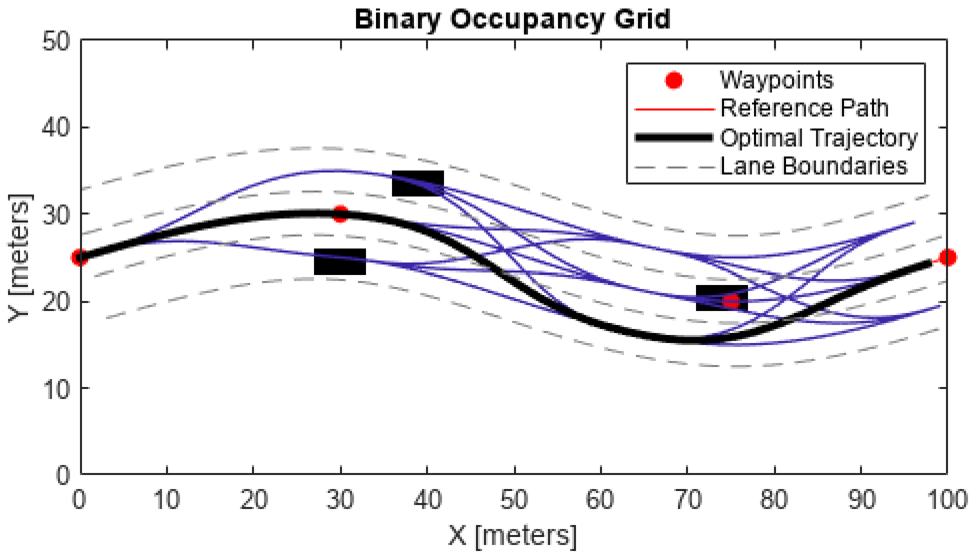
Calculate positions of lanes in Cartesian state.

```
numLaneOffsets = numel(laneOffsets);
xRefPathEnd = ceil(refPathEnd(1));
laneXY = zeros((numLaneOffsets*xRefPathEnd)+numLaneOffsets,2);
xIndex = 0;

for laneID = 1:numLaneOffsets
    for x = 1:xRefPathEnd
        laneCart = frenet2cart(planner,[x 0 0 laneOffsets(laneID) 0 0]);
```

```
        xIndex = xIndex + 1;
        laneXY(xIndex,:) = laneCart(1:2);
    end
    xIndex = xIndex + 1;
    laneXY(xIndex,:) = NaN(1,2);
end
```

Plot lane boundaries.

```
plot(laneXY(:,1),laneXY(:,2),'LineWidth',0.5,'Color',[0.5 0.5 0.5],'DisplayName','Lane Boundaries
```




## Input Arguments

**planner — Optimal trajectory planner in Frenet space**
`trajectoryOptimalFrenet` object

Optimal trajectory planner in Frenet space, specified as a `trajectoryOptimalFrenet` object.

### Name-Value Pair Arguments

Specify optional pairs of arguments as `Name1=Value1,...,NameN=ValueN`, where `Name` is the argument name and `Value` is the corresponding value. Name-value arguments must appear after other arguments, but the order of the pairs does not matter.

*Before R2021a, use commas to separate each name and value, and enclose* `Name` *in quotes.*

Example: `'Trajectory','all'`

**Parent — Axes to plot trajectory**
Axes object | UIAxes object

Axes to plot trajectory, specified as the comma-separated pair consisting of 'Parent' and either an Axes or UIAxes object. See axes or uiaxes.

**Trajectory — Trajectory display option**
'optimal' (default) | 'all'

Trajectory display option, specified as the comma-separated pair consisting of 'Trajectory' and either 'optimal' or 'all'.

**ReferencePath — Reference path display option**
'on' (default) | 'off'

Reference path display option, specified as the comma-separated pair consisting of 'ReferencePath' and either 'on' or 'off'.

**TrajectoryColor — Trajectory color display option**
'velocity' (default) | 'acceleration' | 'cost' | 'none'

Trajectory color display option, specified as the comma-separated pair consisting of 'TrajectoryColor' and one of the following:

- 'acceleration'
- 'cost'
- 'velocity'
- 'none'

Set this property to display the specified trajectory as a color-gradient along the specified path.

## Output Arguments

**axHandle — Axes handle used to plot trajectory**
Axes object | UIAxes object

Axes handle used to plot trajectory, returned as either an axes, or uiaxes object.

# Version History

**Introduced in R2019b**

## See Also

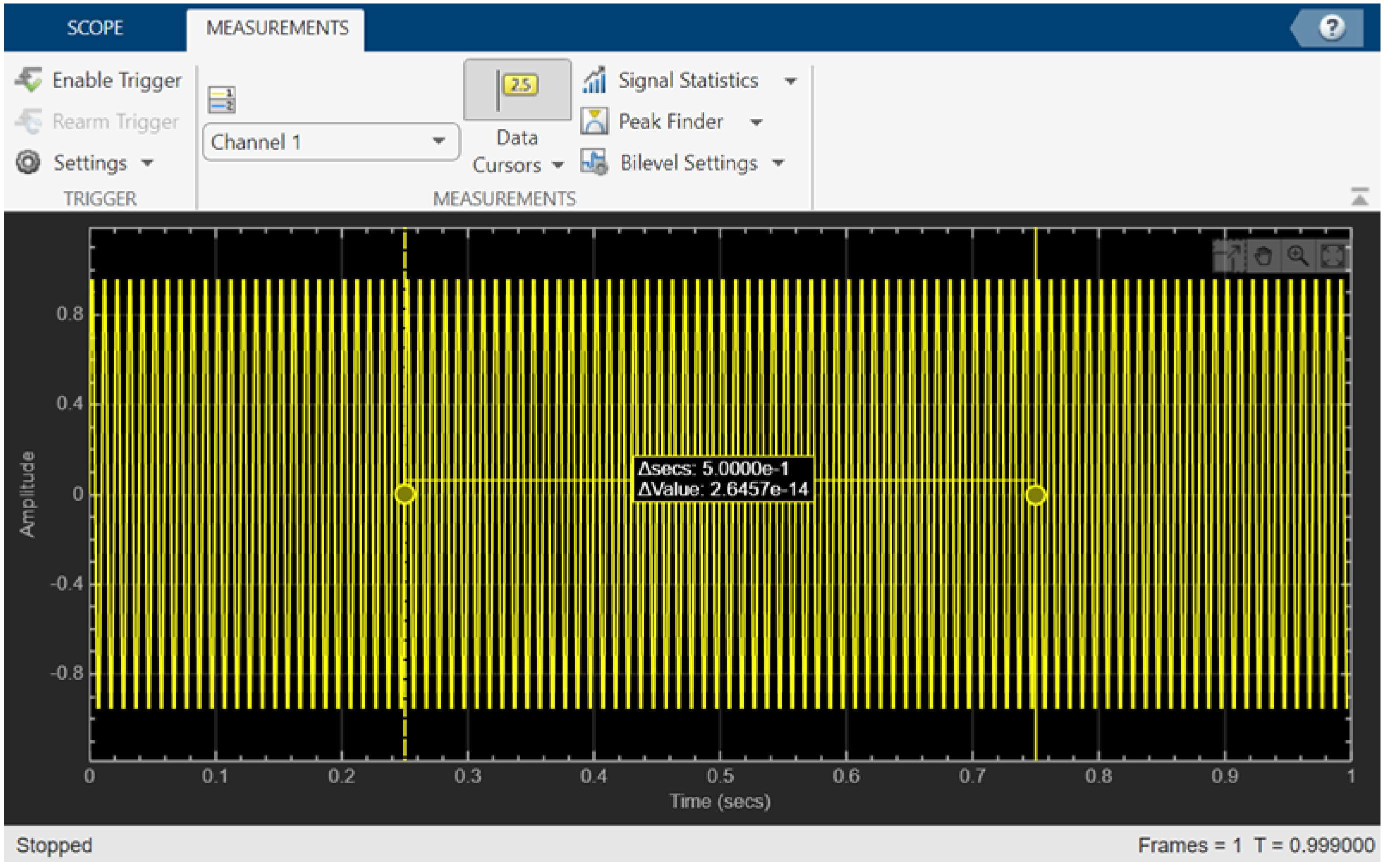
trajectoryOptimalFrenet | plan

# timescope

Display time-domain signals

## Description

The `timescope` object displays signals in the time domain.




Scope features:

- “Data Cursors” — Measure signal values using vertical and horizontal cursors.
- “Signal Statistics” — Display the maximum, minimum, peak-to-peak difference, mean, median, and RMS values of a selected signal.
- “Peak Finder” — Find maxima, showing the *x*-axis values at which they occur.
- “Bilevel Measurements” — Measure transitions, overshoots, undershoots, and cycles.
- “Triggers” — Set triggers to sync repeating signals and pause the display when events occur.

Use “Object Functions” on page 2-1640 to show, hide, and determine visibility of the scope window.

You can enable these measurements either programmatically or on the scope UI. For more details, see “Measurements” on page 2-1636.

# Creation

## Syntax

```
scope = timescope
scope = timescope(Name=Value)
```

### Description

`scope = timescope` returns a `timescope` object, `scope`. This object displays real- and complex-valued floating and fixed-point signals in the time domain.

`scope = timescope(Name=Value)` returns a `timescope` sets properties using `Name=Value` arguments. You can specify the name-value arguments in any order.

# Properties

Most properties can be changed from the `timescope` UI.

### Frequently Used

**`SampleRate` — Sample rate of inputs**
1 (default) | finite numeric scalar | vector

Sampling rate of the input signal, in hertz, specified as a finite numeric scalar or vector of scalars.

The inverse of the sample rate determines the *x*-axis (time axis) spacing between points in the displayed signal. When the value of `NumInputPorts` is greater than 1 and the sample rate is scalar, the object uses the same sample rate for all inputs. To specify different sample rates for each input, use a vector.

You can only set this property when creating the object or after calling `release`.

#### Scope Window Use

On the **Scope** tab, click **Settings**. In the Time Scope Settings dialog box, under **Data and Axes**, specify the sample rate in the **Sample Rate** box.

Data Types: `single` | `double` | `int8` | `int16` | `int32` | `int64` | `uint8` | `uint16` | `uint32` | `uint64`

**`TimeSpanSource` — Source of time span**
`"auto"` (default) | `"property"`

Source of the time span for frame-based input signals, specified as one of the following:

- `"property"` – The object derives the *x*-axis limits from the `TimeDisplayOffset` and `TimeSpan` properties.
- `"auto"` – The *x*-axis limits are derived from the `TimeDisplayOffset` property, `SampleRate` property, and the number of rows in each input signal (*FrameSize* in the equations below). The limits are calculated as:
  - Minimum time-axis limit = `TimeDisplayOffset`
  - Maximum time-axis limit = `TimeDisplayOffset + max(1/SampleRate.*FrameSize)`

#### Dependency

When you set the `TimeSpan` property, `TimeSpanSource` is automatically set to `"property"`.

#### Scope Window Use

On the **Scope** tab, click **Settings**. In the Time Scope Settings dialog box, under **Data and Axes**, select `Auto` or specify the time span in the **Time Span** box.

Data Types: `char` | `string`

### `TimeSpan` — Time span
`10` (default) | positive scalar

Time span, in seconds, specified as a positive, numeric scalar value. The time-axis limits are calculated as:

- Minimum time-axis limit = `TimeDisplayOffset`
- Maximum time-axis limit = `TimeDisplayOffset` + `TimeSpan`

#### Dependencies

To enable this property, set `TimeSpanSource` to `"property"`.

#### Scope Window Use

On the **Scope** tab, click **Settings**. In the Time Scope Settings dialog box, under **Data and Axes**, specify the time span in the **Time Span** box.

Data Types: `single` | `double` | `int8` | `int16` | `int32` | `int64` | `uint8` | `uint16` | `uint32` | `uint64`

### `TimeSpanOverrunAction` — Data overrun behavior
`"scroll"` (default) | `"wrap"`

Specify how the scope displays new data beyond the visible time span as either:

- `"scroll"` — In this mode, the scope scrolls old data to the left to make room for new data on the right of the scope display. This mode is beneficial for debugging and monitoring time-varying signals.
- `"wrap"` — In this mode, the scope adds data to the left of the plot after overrunning the right of the plot.

#### Scope Window Use

On the **Scope** tab, click **Settings**. In the Time Scope Settings dialog box, under **Data and Axes**, select the overrun behavior in **Overrun Action**.

Data Types: `char` | `string`

### `PlotType` — Type of plot
`"line"` (default) | `"stairs"`

Type of plot, specified as either:

- `"line"` — Line graph, similar to the `line` or `plot` function.
- `"stairs"` — Stair-step graph, similar to the `stairs` function. Stair-step graphs are useful for drawing time history graphs of digitally sampled data.

#### Scope Window Use

On the **Scope** tab, click **Settings**. In the Time Scope Settings dialog box, under **Data and Axes**, select the plot type in **Plot Type**.

Data Types: `char` | `string`

### `AxesScaling` — Axes scaling mode

`"onceatstop"` (default) | `"auto"` | `"manual"` | `"updates"`

When this property is set to:

- `"onceatstop"` –– The limits are updated once at the end of the simulation (when `release` is called).
- `"auto"` –– The scope attempts to always keep the data in the display while minimizing the number of updates to the axes limits.
- `"manual"` –– The scope takes no action unless specified by the user.
- `"updates"` –– The scope scales the axes once after a set number of visual updates. The number of updates is determined by the value of the `AxesScalingNumUpdates` property.

You can set this property only when creating the object.

Data Types: `char` | `string`

### `AxesScalingNumUpdates` — Number of updates before scaling

100 (default) | real positive integer

Specify the number of updates before scaling as a real, positive scalar integer.

#### Dependency

To enable this property, set `AxesScaling` to `"updates"`.

Data Types: `double`

## Advanced

### `LayoutDimensions` — Display layout grid dimensions

`[1,1]` (default) | `[numberOfRows, numberOfColumns]`

Specify the layout grid dimensions as a two-element vector: `[numberOfRows,numberOfColumns]`. The grid can have a maximum of 4 rows and 4 columns.

If you create a grid of multiple axes, to modify the settings of individual axes, use the `ActiveDisplay`.

Example: `scope.LayoutDimensions = [2,4]`

#### Scope Window Use

On the **Scope** tab, click **Display Grid** ( ) and select a specific number of rows and columns in the grid.

Data Types: `single` | `double` | `int8` | `int16` | `int32` | `int64` | `uint8` | `uint16` | `uint32` | `uint64`

### `TimeUnits` — Units of x-axis

`"seconds"` (default) | `"none"` | `"metric"`

Specify the units used to describe the x-axis (time axis). You can select one of the following options:

- `"seconds"` —The scope always displays the units on the x-axis as seconds. The scope shows the word `Time(s)` on the x-axis.
- `"none"` — The scope does not display any units on the x-axis. The scope only shows the word `Time` on the x-axis.
- `"metric"` — The scope displays the units on the x-axis as `Time (s)` changing the units to day, weeks, months, or years as you plot more data points.

#### Scope Window Use

On the **Scope** tab, click **Settings**. In the Time Scope Settings dialog box, under **Data and Axes**, specify the *x*-axis units in **Time Units**.

Data Types: `char` | `string`

### `TimeDisplayOffset` — Offset *x*-axis limits

0 (default) | scalar | vector

Specify, in seconds, how far to move the data on the *x*-axis. The signal value does not change, only the limits displayed on the *x*-axis change.

If you specify this property as a scalar, then that value is the time display offset for all channels. If you specify this property as a vector, each input channel can be a different time display offset

#### Scope Window Use

On the **Scope** tab, click **Settings**. In the Time Scope Settings dialog box, under **Data and Axes**, specify the *x*-axis offset in **Time Offset**.

### `TimeAxisLabels` — Time-axis labels

`"all"` (default) | `"bottom"` | `"none"`

Time-axis labels, specified as:

- `"all"` — Time-axis labels appear in all displays.
- `"bottom"` — Time-axis labels appear in the bottom display of each column.
- `"none"` — No labels appear in any display.

#### Scope Window Use

On the **Scope** tab, click **Settings**. In the Time Scope Settings dialog box, under **Data and Axes**, select which *x*-axis label to display in **Time Labels**.

Data Types: `char` | `string`

### `MaximizeAxes` — Maximize axes control

`"auto"` (default) | `"on"` | `"off"`

Specify whether to display the scope in the maximized-axes mode. In this mode, the axes are expanded to fit into the entire display. To conserve space, labels do not appear in each display. Instead, the tick-marks and their values appear on top of the plotted data. You can select one of the following options:

- "auto" — The axes appear maximized in all displays only if the Title and YLabel properties are empty for every display. If you enter any value in any display for either of these properties, the axes are not maximized.
- "on" — The axes appear maximized in all displays. Any values entered into the Title and YLabel properties are hidden.
- "off" — None of the axes appear maximized.

**Scope Window Use**

On the scope window, click to maximize axes, hide all labels and inset the axes values.

Data Types: char | string

**BufferLength — Buffer length**
50000 (default) | positive integer

Specify the length of the buffer used for each input signal as a positive integer.

You can set this property only when creating the object.

**Scope Window Use**

On the **Scope** tab, click **Settings**. In the Time Scope Settings dialog box, under **Data and Axes**, specify the buffer length in the **Buffer Length** box.

Data Types: single | double | int8 | int16 | int32 | int64 | uint8 | uint16 | uint32 | uint64

### Measurements

**MeasurementChannel — Channel for which to obtain measurements**
1 (default) | positive integer

Channel for which to obtain measurements, specified as a positive integer in the range [1 *N*], where *N* is the number of input channels.

**Scope Window Use**

On the **Measurements** tab, select a **Channel**.

Data Types: double

**BilevelMeasurements — Bilevel measurements**
BilevelMeasurementsConfiguration object

Bilevel measurements to measure transitions, aberrations, and cycles of bilevel signals, specified as a BilevelMeasurementsConfiguration object.

All BilevelMeasurementsConfiguration properties are tunable.

**Scope Window Use**

On the **Measurements** tab, in the **Measurements** section, click **Bilevel Settings** to modify the bilevel measurements.

**CursorMeasurements — Cursor measurements**
CursorMeasurementsConfiguration object

Cursor measurements to display screen or waveform cursors, specified as a `CursorMeasurementsConfiguration` object.

All `CursorMeasurementsConfiguration` properties are tunable.

**Scope Window Use**

On the **Measurements** tab, in the **Measurements** section, select **Data Cursors** to enable the cursors on the display. Click **Data Cursors** to modify the cursor settings.

### `PeakFinder` — Peak finder measurements

`PeakFinderConfiguration` object

Peak finder measurements to compute and display the largest calculated peak values, specified as a `PeakFinderConfiguration` object.

All `PeakFinderConfiguration` properties are tunable.

**Scope Window Use**

On the **Measurements** tab, in the **Measurements** section, select **Peak Finder** to enable the peak finder. Click **Peak Finder** to modify the peak finder settings.

### `SignalStatistics` — Signal statistics measurements

`SignalStatisticsConfiguration` object

Signal statistics measurements to compute and display signal statistics, specified as a `SignalStatisticsConfiguration` object.

All `SignalStatisticsConfiguration` properties are tunable.

**Scope Window Use**

On the **Measurements** tab, in the **Measurements** section, select **Signal Statistics**. Click **Signal Statistics** to choose the statistics to compute.

### `Trigger` — Trigger measurements

`TriggerConfiguration` object

Trigger measurements, specified as a `TriggerConfiguration` object. Define a trigger event to identify the simulation time of specified input signal characteristics. You can use trigger events to stabilize periodic signals such as a sine wave or capture non-periodic signals such as a pulse that occurs intermittently.

All `TriggerConfiguration` properties are tunable.

**Scope Window Use**

On the **Measurements** tab, in the **Trigger** section, select **Enable Trigger** and click **Settings** to modify the trigger settings.

## Visualization

### `Name` — Window name

`"Time Scope"` (default) | character vector | string scalar

Specify the name of the scope as a character vector or string scalar. This name appears as the title of the scope's figure window. To specify a title of a scope plot, use the `Title` property.

Data Types: `char` | `string`

**`Position` — Window position**
screen center (default) | `[left bottom width height]`

Scope window position in pixels, specified by the size and location of the scope window as a four-element vector of the form `[left bottom width height]`. You can place the scope window in a specific position on your screen by modifying the values of this property.

By default, the window appears in the center of your screen with a width of `800` pixels and height of `500` pixels. The exact values of the position depend on your screen resolution.

**`ChannelNames` — Channel names**
`{''}` (default) | cell array of character vectors | array of strings

Specify the input channel names as a cell array of character vectors or an array of strings. The channel names appear in the legend, and on the **Measurements** tab under **Select Channel**. If you do not specify names, the channels are labeled as `Channel 1`, `Channel 2`, etc.

**Dependency**

To enable this property, set `ShowLegend` to `true`.

Data Types: `char`

**`ActiveDisplay` — Active display for setting properties**
`1` (default) | integer

Active display used to set properties, specified by the integer display number. The number of a display corresponds to the display's row-wise placement index. Setting this property controls which display is used for the following properties: `YLimits`, `YLabel`, `ShowLegend`, `ShowGrid`, `Title`, and `PlotAsMagnitudePhase`.

**Scope Window Use**

On the **Scope** tab, click **Settings**. In the Time Scope Settings dialog box, under **Display and Labels**, specify the active display using **Active Display**.

**`Title` — Display title**
`''` (default) | character vector | string scalar

Specify the display title as a character vector or a string scalar.

**Dependency**

When you set this property, `ActiveDisplay` controls the display that is updated.

**Scope Window Use**

On the **Scope** tab, click **Settings**. In the Time Scope Settings dialog box, under **Display and Labels**, specify the display title in the **Title** box.

Data Types: `char` | `string`

**`YLabel` — *y*-axis label**
`"Amplitude"` (default) | character vector | string scalar

Specify the text for the scope to display to the left of the *y*-axis.

#### Dependencies

This property applies only when `PlotAsMagnitudePhase` is `false`. When `PlotAsMagnitudePhase` is `true`, the two *y*-axis labels are read-only values `"Magnitude"` and `"Phase"`, for the magnitude plot and the phase plot, respectively.

When you set this property, `ActiveDisplay` controls the display that is updated.

#### Scope Window Use

On the **Scope** tab, click **Settings**. In the Time Scope Settings dialog box, under **Display and Labels**, specify a label for the *y*-axis in the **Y-Label** box.

Data Types: `char` | `string`

### `YLimits` — *y*-axis limits
`[-10,10]` (default) | `[ymin, ymax]`

Specify the *y*-axis limits as a two-element numeric vector, `[ymin, ymax]`.

- If `PlotAsMagnitudePhase` is `false`, the default is `[-10,10]`.
- If `PlotAsMagnitudePhase` is `true`, the default is `[0,10]`. This property specifies the *y*-axis limits of only the magnitude plot. The *y*-axis limits of the phase plot are always `[-180,180]`

#### Dependency

When you set this property, `ActiveDisplay` controls the display that is updated.

#### Scope Window Use

On the **Scope** tab, click **Settings**. In the Time Scope Settings dialog box, under **Display and Labels**, specify the limits for the *y*-axis in the **Y-Axis Limits** box.

### `ShowLegend` — Show legend
`false` (default) | `true`

To show a legend with the input names, set this property to `true`.

From the legend, you can control which signals are visible. In the scope legend, click a signal name to hide the signal in the scope. To show the signal, click the signal name again.

#### Scope Window Use

On the **Scope** tab, click **Settings**. In the Time Scope Settings dialog box, under **Display and Labels**, select **Show Legend**.

Data Types: `logical`

### `ShowGrid` — Grid visibility
`true` (default) | `false`

Set this property to `true` to show grid lines on the plot.

#### Scope Window Use

On the **Scope** tab, click **Settings**. In the Time Scope Settings dialog box, under **Display and Labels**, select **Show Grid**.

**`PlotAsMagnitudePhase` — Plot signal as magnitude and phase**
`false` (default) | `true`

Plot signal as magnitude and phased, specified as either:

- `true` – The scope plots the magnitude and phase of the input signal on two separate axes within the same active display.
- `false` – The scope plots the real and imaginary parts of the input signal on two separate axes within the same active display.

This property is useful for complex-valued input signals. Turning on this property affects the phase for real-valued input signals. When the amplitude of the input signal is nonnegative, the phase is 0 degrees. When the amplitude of the input signal is negative, the phase is 180 degrees.

#### Scope Window Use

On the **Scope** tab, click **Settings**. In the Time Scope Settings dialog box, under **Display and Labels**, select **Magnitude Phase Plot**.

## Object Functions

To use an object function, specify the object as the first input argument.

| | |
|---|---|
| hide | Hide scope window |
| show | Display scope window |
| isVisible | Determine visibility of scope |
| generateScript | Generate MATLAB script to create scope with current settings |
| step | Run System object algorithm |
| release | Release resources and allow changes to System object property values and input characteristics |
| reset | Reset internal states of System object |

If you want to restart the simulation from the beginning, call `reset` to clear the scope window displays. Do not call `reset` after calling `release`.

## Examples

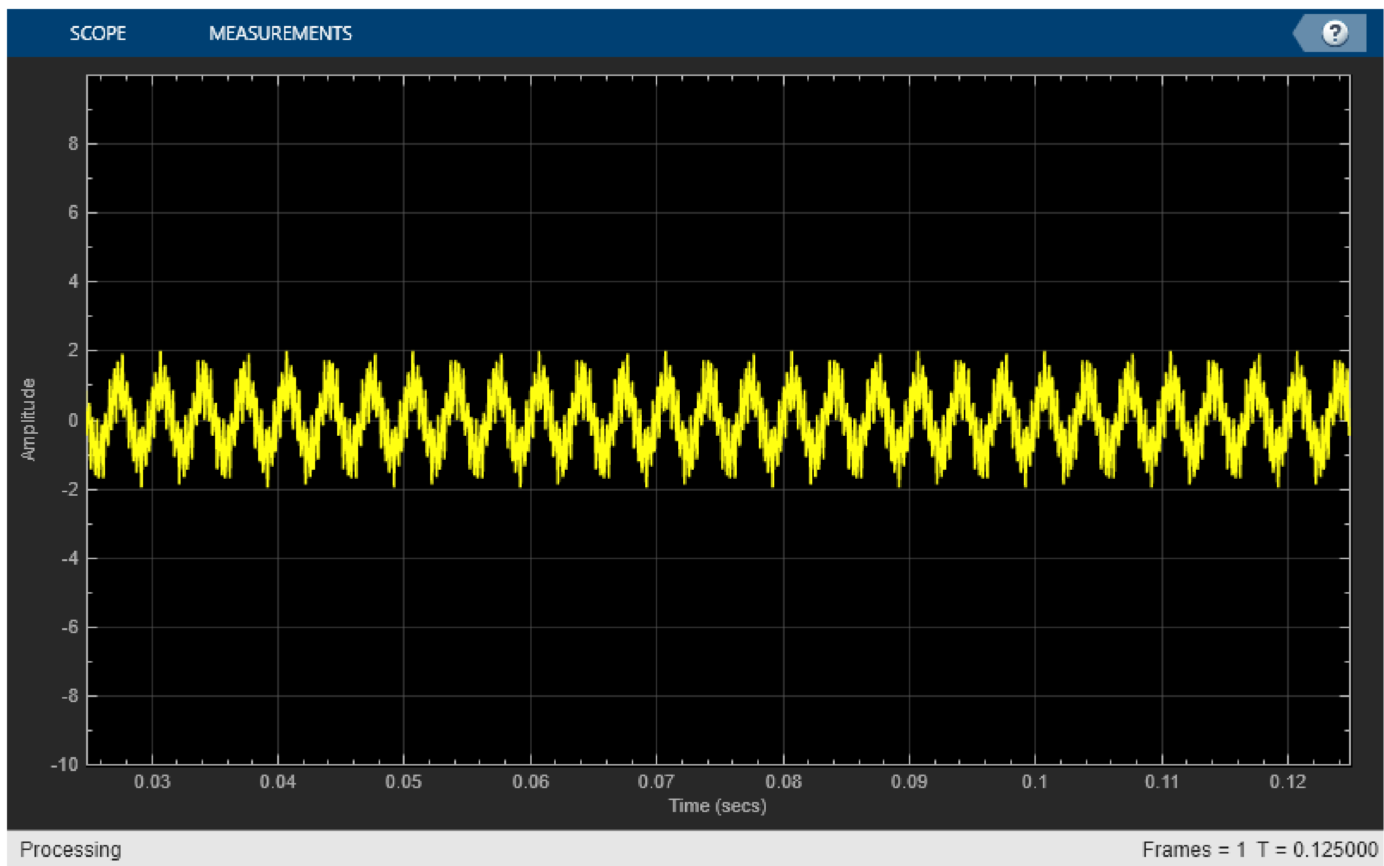
### View Sine Wave on Time Scope

Create a sinusoidal signal with two tones, one at 0.3 kHz and the other at 3 kHz.

```
t = (0:1000)'/8e3;
xin = sin(2*pi*0.3e3*t)+sin(2*pi*3e3*t);
```

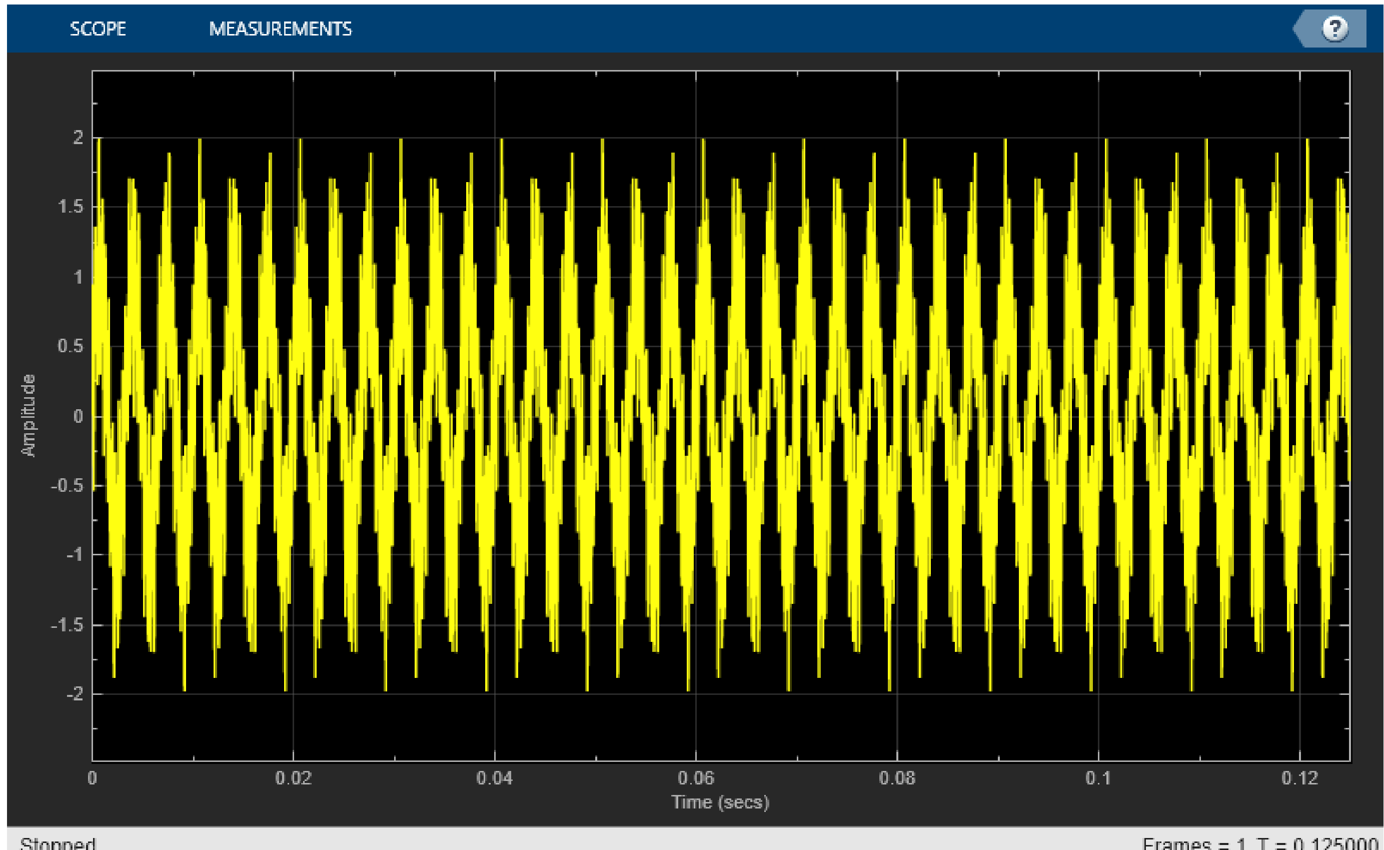
Create a `timescope` object and view the sinusoidal signal by calling the time scope object `scope`.

```
scope = timescope(SampleRate=8e3,...
    TimeSpanSource="property",...
    TimeSpan=0.1);
scope(xin)
```




Run `release` to allow changes to property values and input characteristics. The scope automatically scales the axes.

```
release(scope);
```

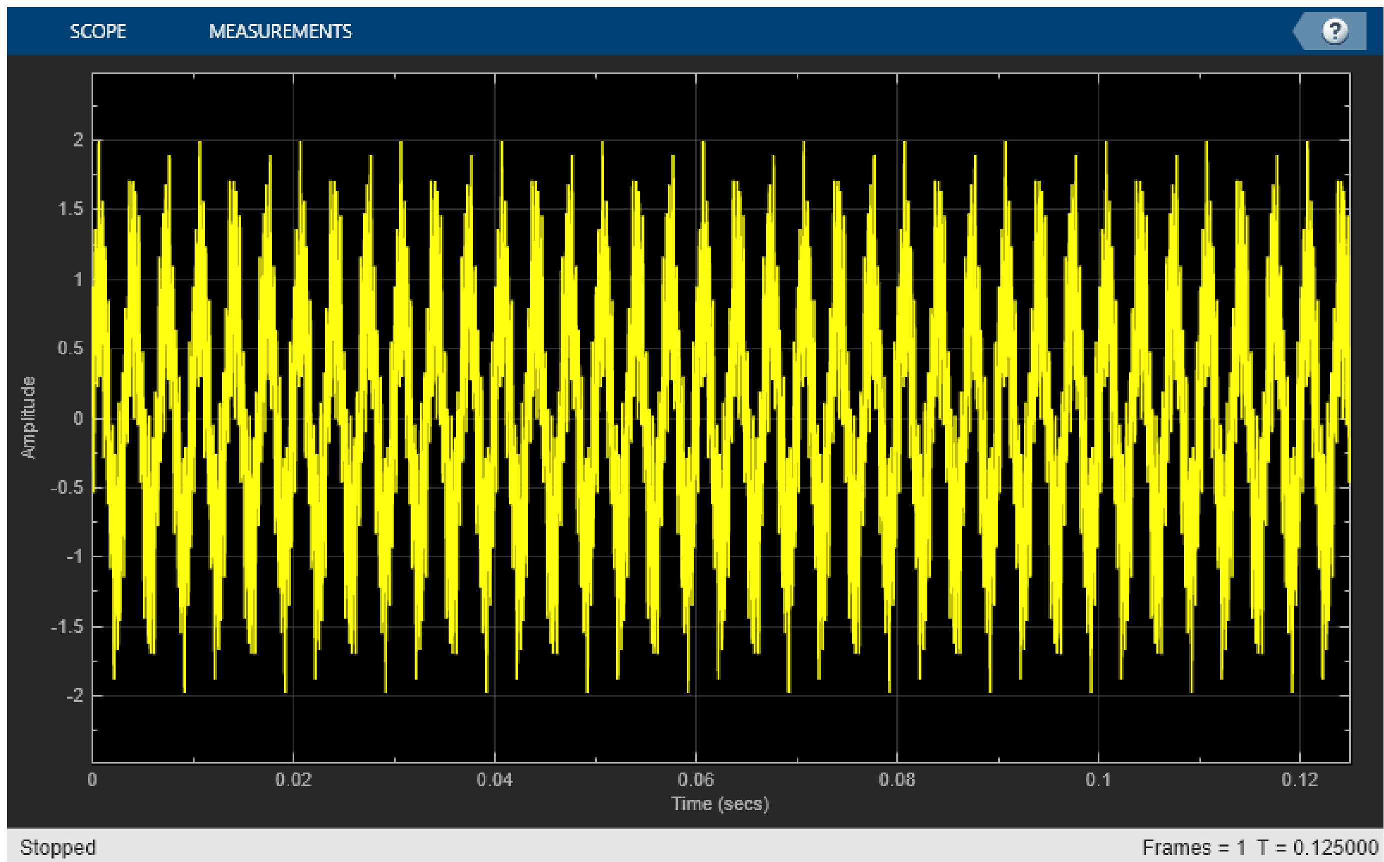



Hide the scope window.

```
if(isVisible(scope))
    hide(scope)
end
```

Show the scope window.

```
if(~isVisible(scope))
    show(scope)
end
```




### Use Bilevel Measurements Panel with Clock Input Signal

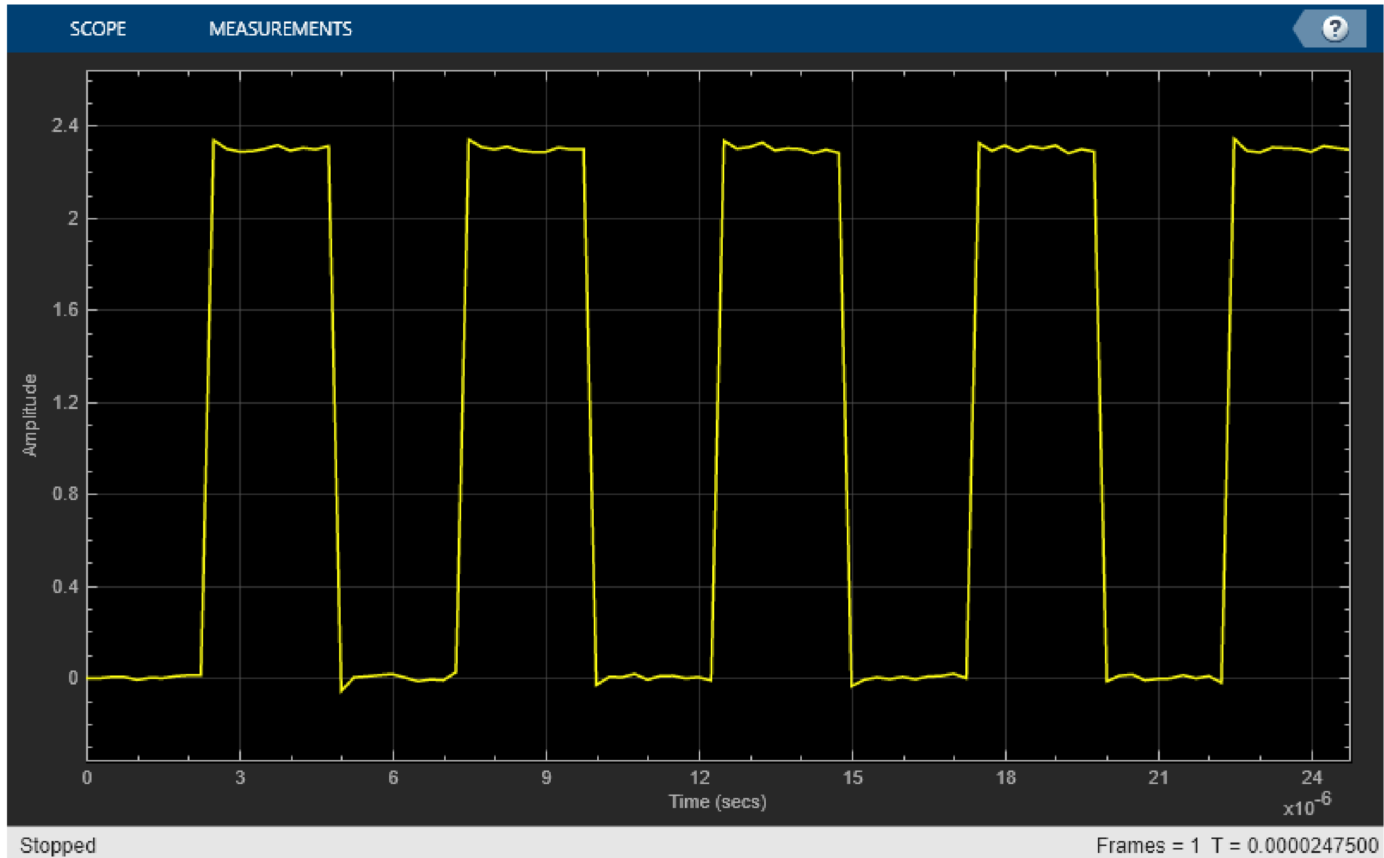
#### Create and Display Clock Input Signal

Load the clock data, `x` and `t`. Find the sample time `ts`.

```
load clockex
ts = t(2)-t(1);
```

Create a `timescope` object and call the object to display the signal. To autoscale the axes and enable changes to property values and input characteristics, call `release`.

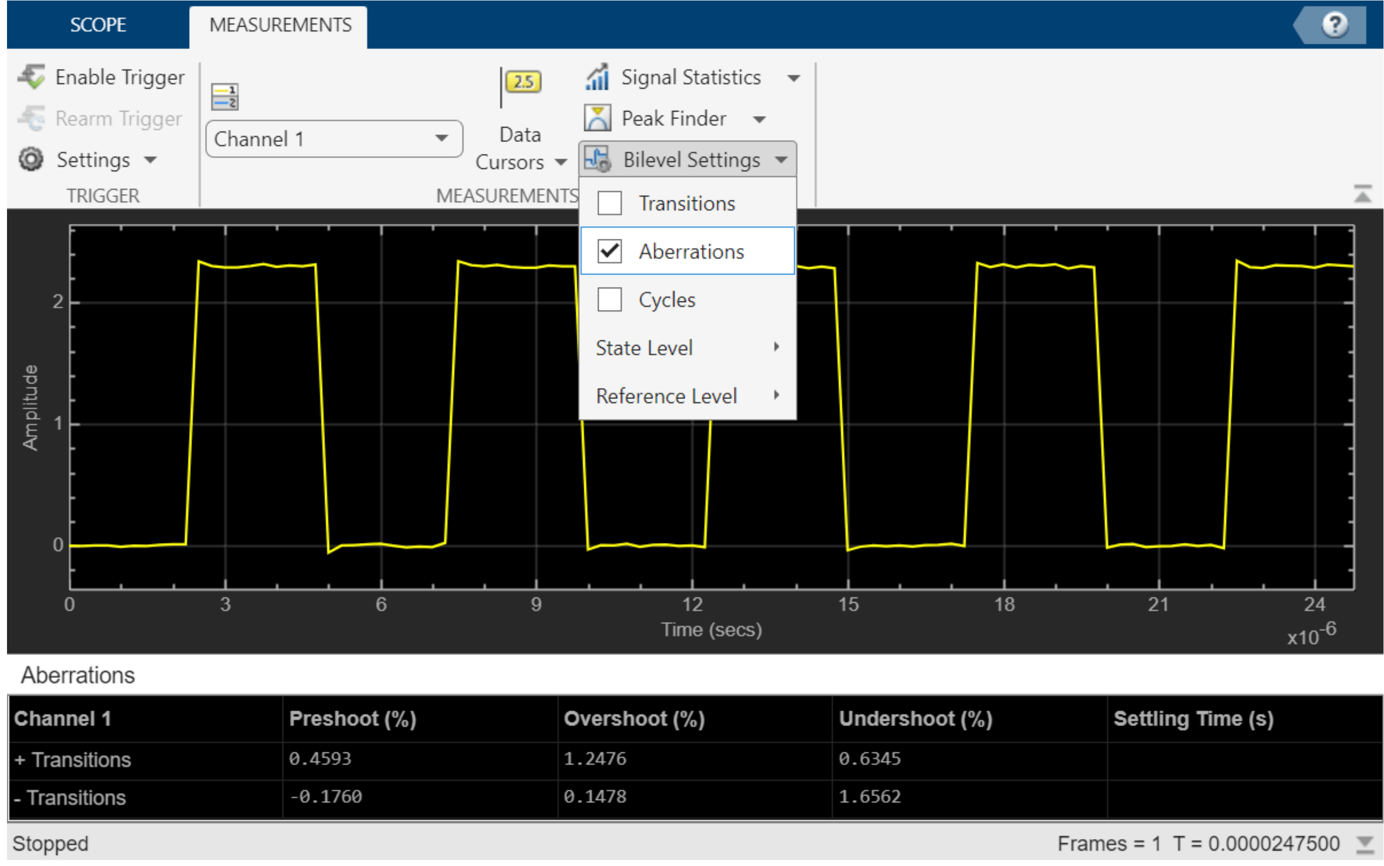
```
scope = timescope(SampleRate=1/ts,TimeSpanSource="auto");
scope(x);
release(scope);
```




### Use Bilevel Measurements Panel to Find Settling Time

On the **Measurements** tab, under **Bilevel Settings,** select **Aberrations**.

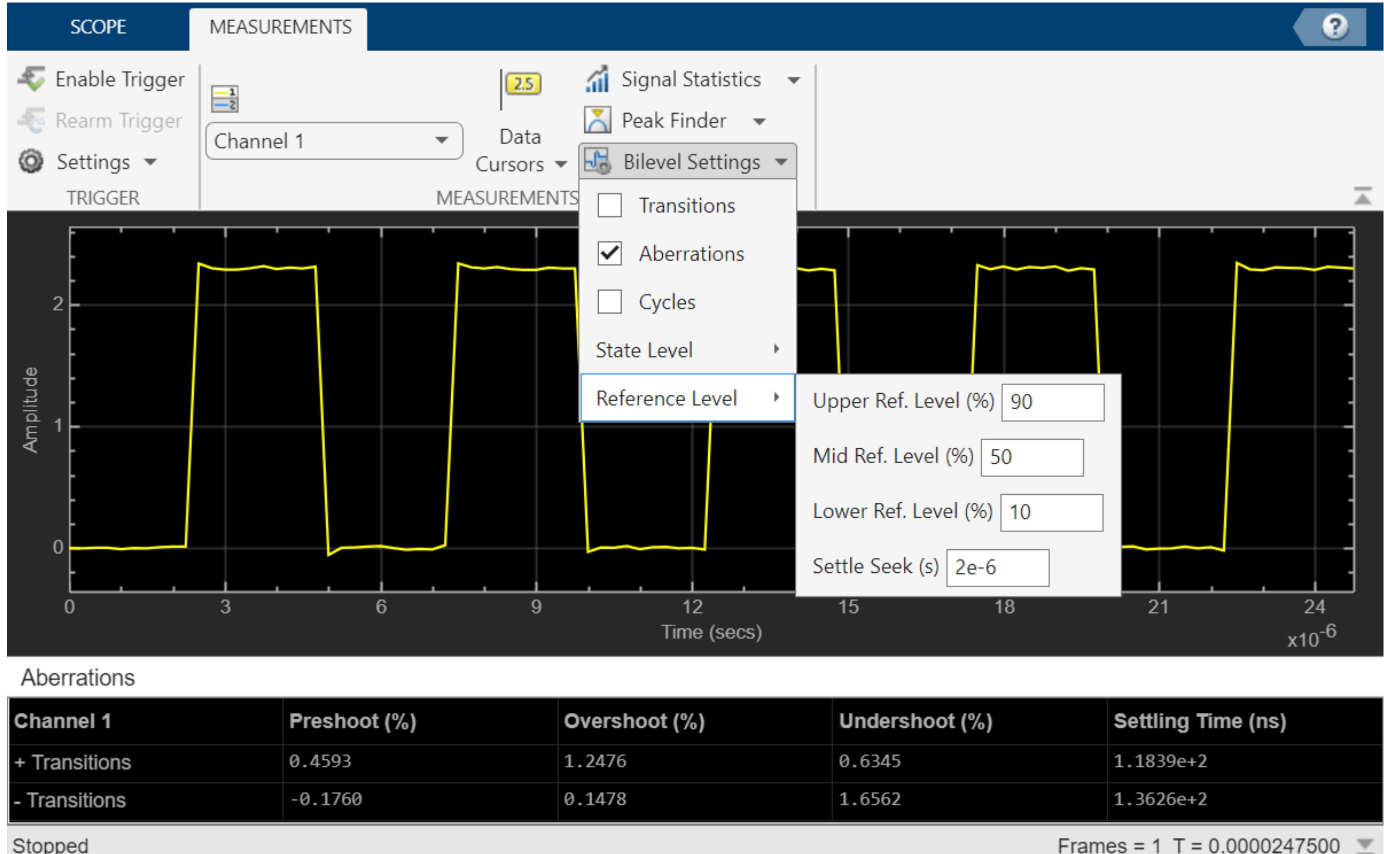
Initially, the Time Scope does not display the **Settling Time(s)** measurement. This absence occurs because the default value of the **Settle Seek** parameter is longer than the entire simulation duration.




To change the value of the **Settle Seek (s)** parameter, click **Bilevel Settings**, and under **Reference Level**, set the settle seek value to `2e-6` and press **Enter**.

Time Scope now displays a rising edge **Settling Time** value of `118.392` ns.

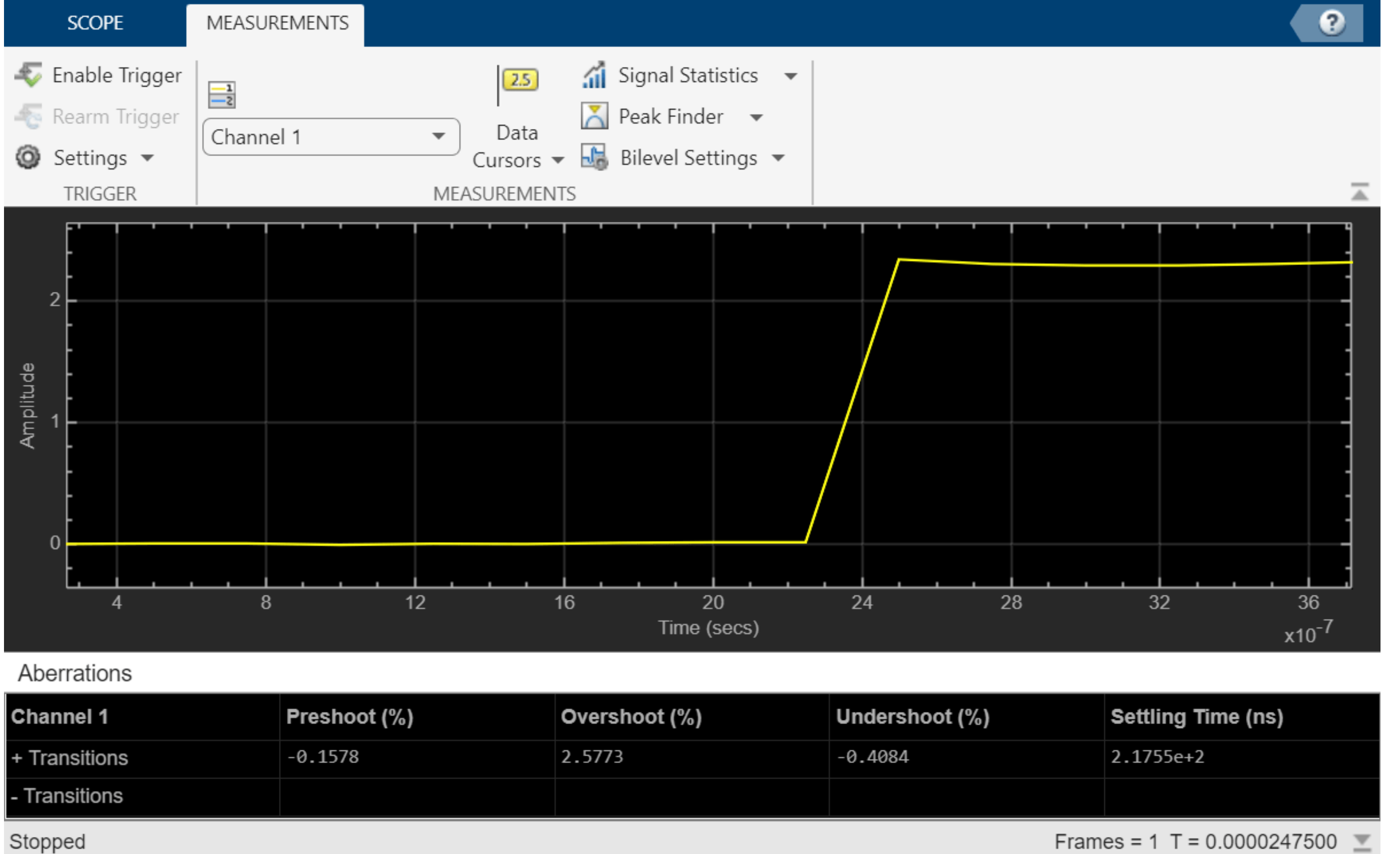
This settling time value is actually the statistical average of the settling times for all five rising edges. To show the settling time for only one rising edge, you can zoom in on that transition.




Hover over the upper right corner of the scope axes and click the zoom button.

Click and drag to zoom in on one of the transitions. Set **Settle Seek (s)** to `2e-7` and press **Enter**.

The Time Scope updates the rising edge **Settling Time** value to reflect the new time window.




### Configure Bilevel Measurements Programmatically in Time Scope MATLAB Object

Create a sine wave and view it in the Time Scope. Programmatically compute the bilevel measurements related to signal transitions, aberrations, and cycles.

#### Initialization

Create the input sine wave using the `sin` function. Create a `timescope` MATLAB® object to display the signal. Set the `TimeSpan` property to 1 second.

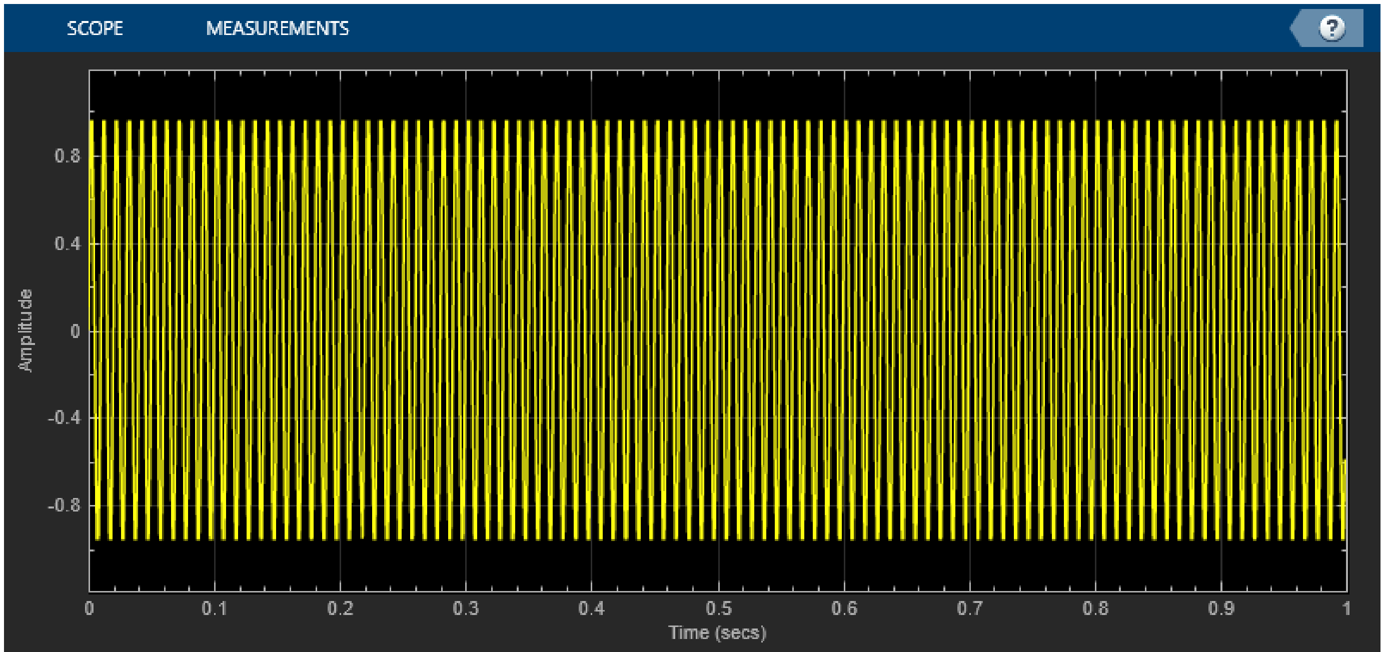
```
f = 100;
fs = 1000;
swv = sin(2.*pi.*f.*(0:1/fs:1-1/fs)).';
scope = timescope(SampleRate=fs,...
    TimeSpanSource="property",...
    TimeSpan=1);
```

#### Transition Measurements

Enable the scope to show transition measurements programmatically by setting the `ShowTransitions` property to `true`. Display the sine wave in the scope.

Transition measurements such as rise time, fall time, and slew rate appear in the **Transitions** pane at the bottom of the scope.

```
scope.BilevelMeasurements.ShowTransitions = true;
scope(swv);
release(scope);
```




Transitions

| Channel 1 | Count | Rise Time (ms) | Fall Time (ms) | Slew Rate (/ms) |
|---|---|---|---|---|
| + Edges | 99.0000 | 1.5792e+0 | | 5.8779e-1 |
| - Edges | 100.0000 | | 1.5792e+0 | -5.8779e-1 |

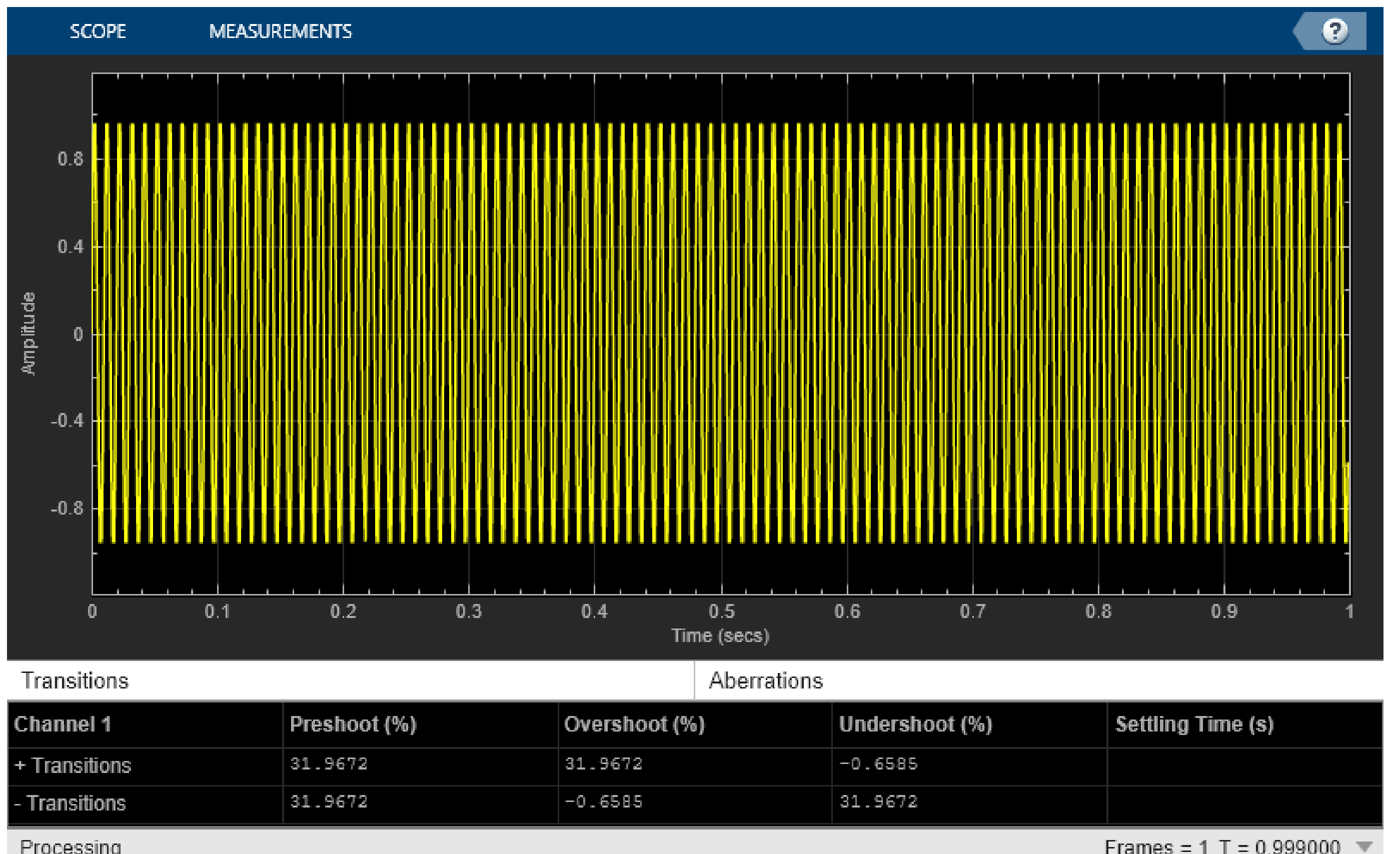
Stopped    Frames = 1  T = 0.999000

### Aberration Measurements

Enable the scope to show aberration measurements programmatically by setting the `ShowAberrations` property to `true`. Display the sine wave in the scope.

Aberration measurements such as preshoot, overshoot, undershoot, and settling time appear in the **Aberrations** pane at the bottom of the scope.

```
scope.BilevelMeasurements.ShowAberrations = true;
scope(swv);
release(scope);
```

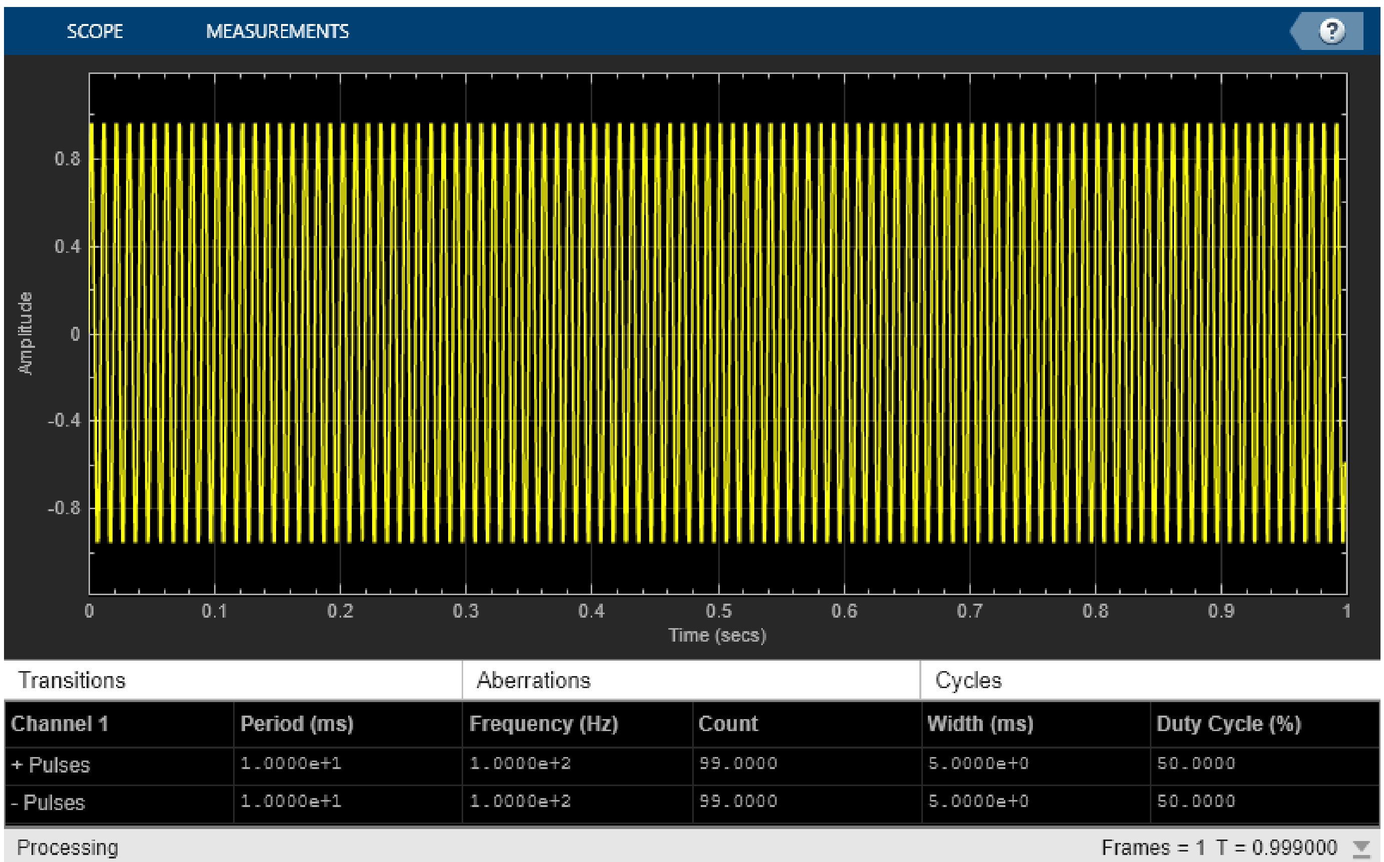



#### Cycle Measurements

Enable the scope to show cycles measurements programmatically by setting the `ShowCycles` property to `true`. Display the sine wave in the scope.

Cycle measurements such as period, frequency, pulse width, and duty cycle appear in the **Cycles** pane at the bottom of the scope.

```
scope.BilevelMeasurements.ShowCycles = true;
scope(swv);
release(scope);
```




#### Configure Signal Statistics Programmatically in Time Scope MATLAB Object

Create a sine wave and view it in the Time Scope. Enable the scope programmatically to compute the signal statistics.

The object supports these signal statistics:

- Maximum
- Minimum
- Mean
- Median
- RMS
- Peak to peak
- Variance
- Standard deviation
- Mean square

#### Initialization

Create the input sine wave using the `sin` function. Create a `timescope` MATLAB® object to display the signal. Set the `TimeSpan` property to 1 second.

```
f = 100;
fs = 1000;
swv = sin(2.*pi.*f.*(0:1/fs:1-1/fs)).';
scope = timescope(SampleRate=fs,...
    TimeSpanSource="property",...
    TimeSpan=1);
```

#### Signal Statistics

Enable the scope to show signal statistics programmatically by setting the `SignalStatistics` > `Enabled` property to `true`.

```
scope.SignalStatistics.Enabled = true;
```

By default, the scope enables the following measurements.

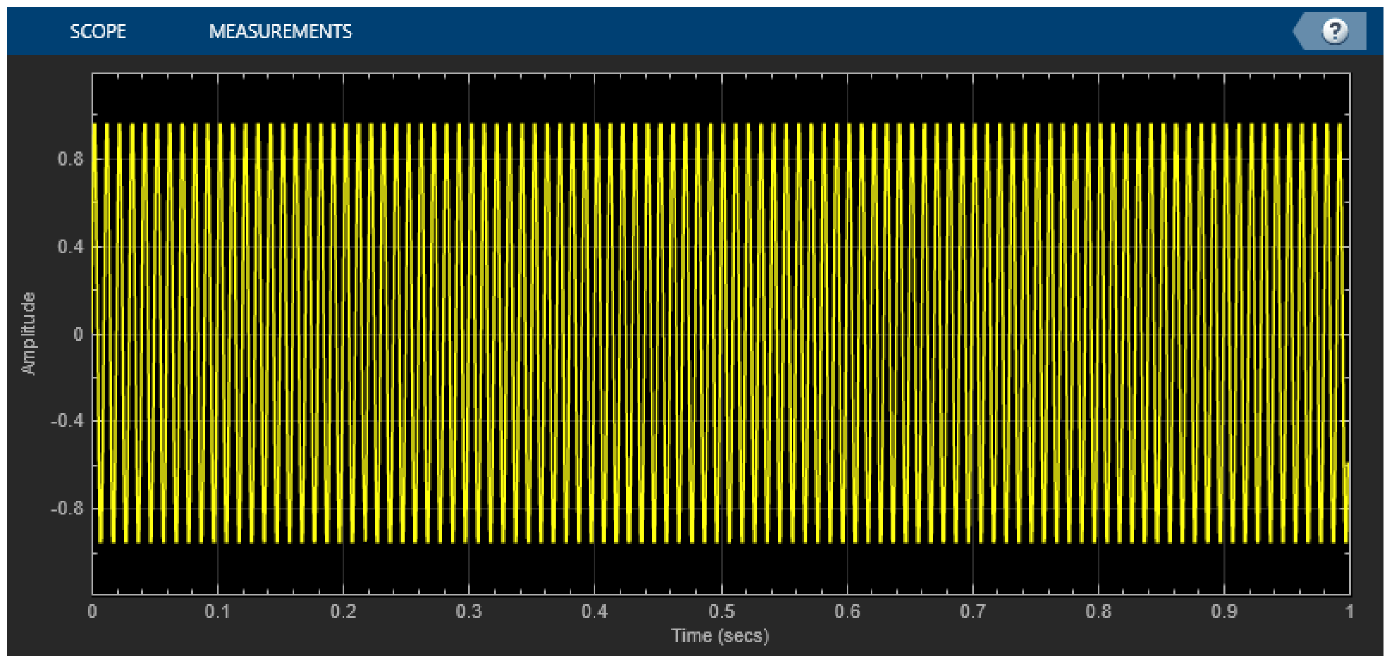
```
scope.SignalStatistics
```

```
ans = 
  SignalStatisticsConfiguration with properties:

                 ShowMax: 1
                 ShowMin: 1
          ShowPeakToPeak: 1
                ShowMean: 1
            ShowVariance: 0
   ShowStandardDeviation: 1
              ShowMedian: 1
                 ShowRMS: 1
          ShowMeanSquare: 0
                 Enabled: 1
```

Display the sine wave in the scope. A Statistics pane appears at the bottom of the scope window displaying the statistics for the portion of the signal that you can see in the scope.

If you use the zoom options on the scope, the statistics automatically adjust to the time range in the display.

```
scope(swv);
release(scope);
```




Statistics

| Channel 1 | Max | Min | Peak to Peak | Mean | Standard De... | Median | RMS |
|---|---|---|---|---|---|---|---|
| Time (ms) | 9.5300e+2 | 9.3700e+2 | | | | | |
| Value | 9.5106e-1 | -9.5106e-1 | 1.9021e+0 | 9.5201e-4 | 7.0717e-1 | 1.2246e-16 | 7.0682e-1 |

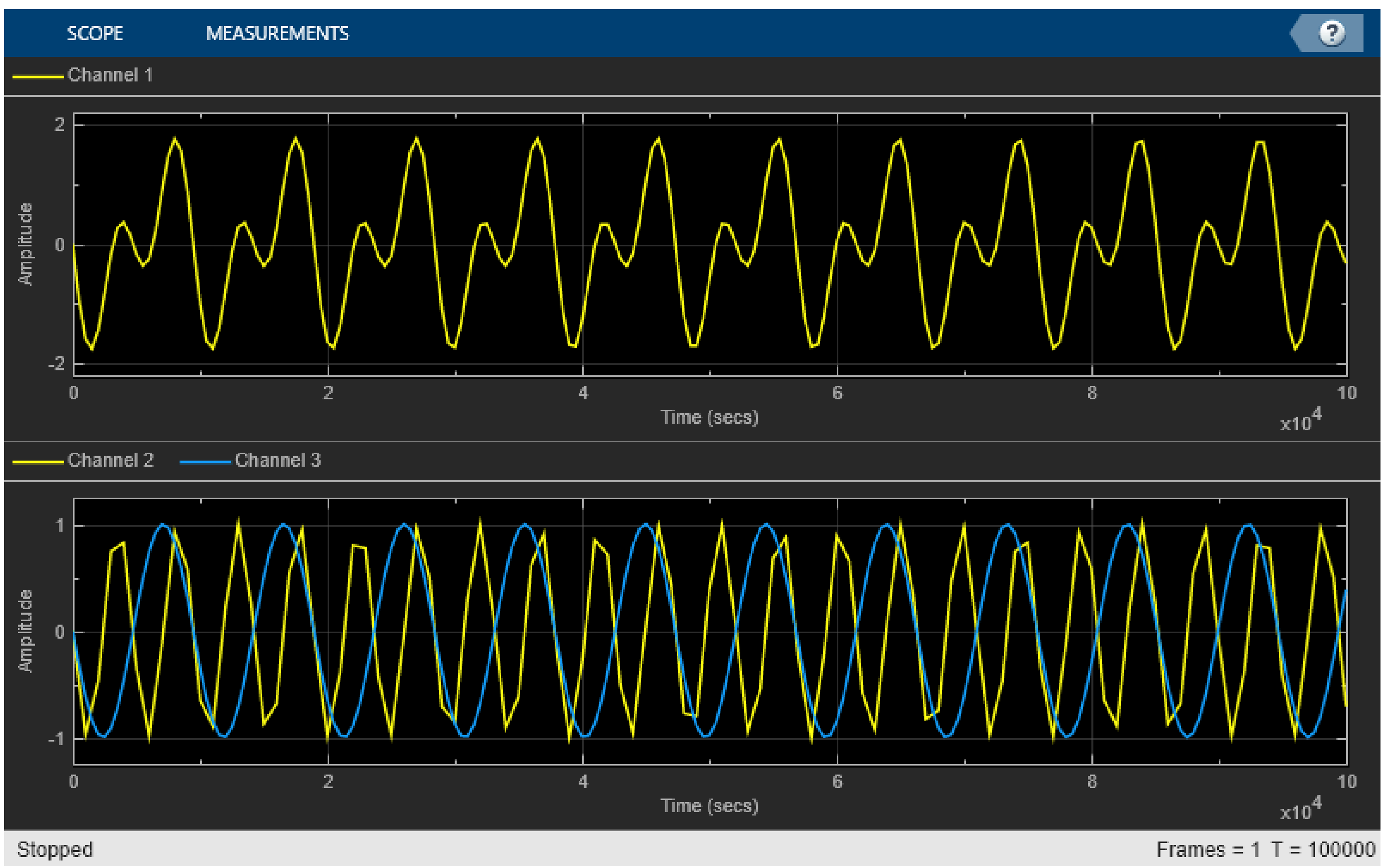
Stopped Frames = 1 T = 0.999000

#### Visualize Multiple Inputs with Different Sample Rates

This example shows how to visualize multiple inputs with different sample rates and plot the signals on multiple axes.

Generate three different sine waves and plot them in the Time Scope.

```
freq = 1/500;
t    = (0:100)'/freq;
t2   = (0:0.5:100)'/freq;
xin1 = sin(1/2*t);
xin2 = sin(1/4*t2);
xin  = sin(1/2*t2)+sin(1/4*t2);

scope = timescope(SampleRate=[freq freq/2 freq],...
    TimeSpanSource="property", ...
    TimeSpan=0.1,...
    LayoutDimensions=[2,1]);
scope(xin,xin1,xin2)

release(scope)
```

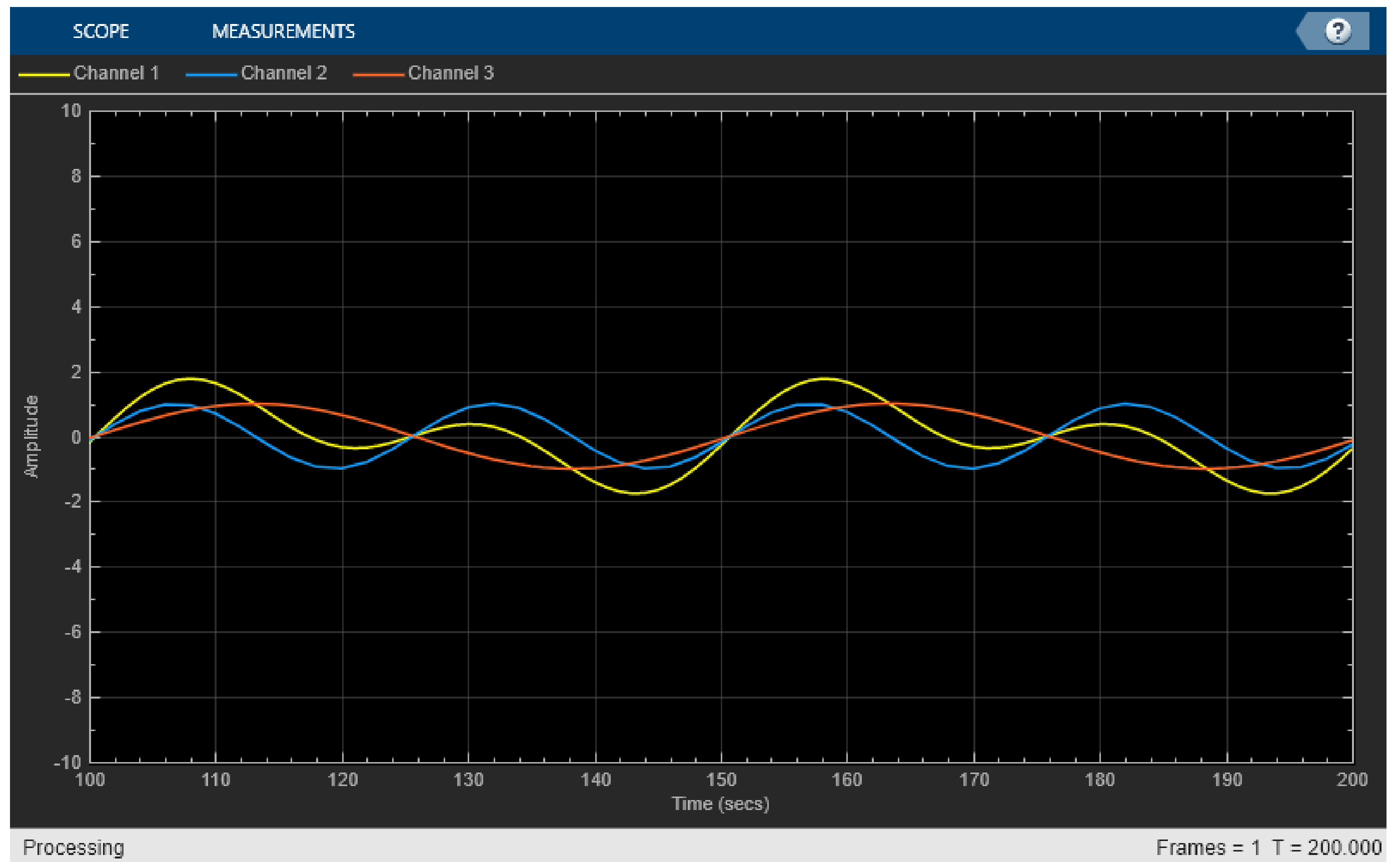



### Use Multiple Axes on Scope

This example show how to add titles, set *y*-axis limits, and modify properties when you have multiple axes on your `timescope` object.

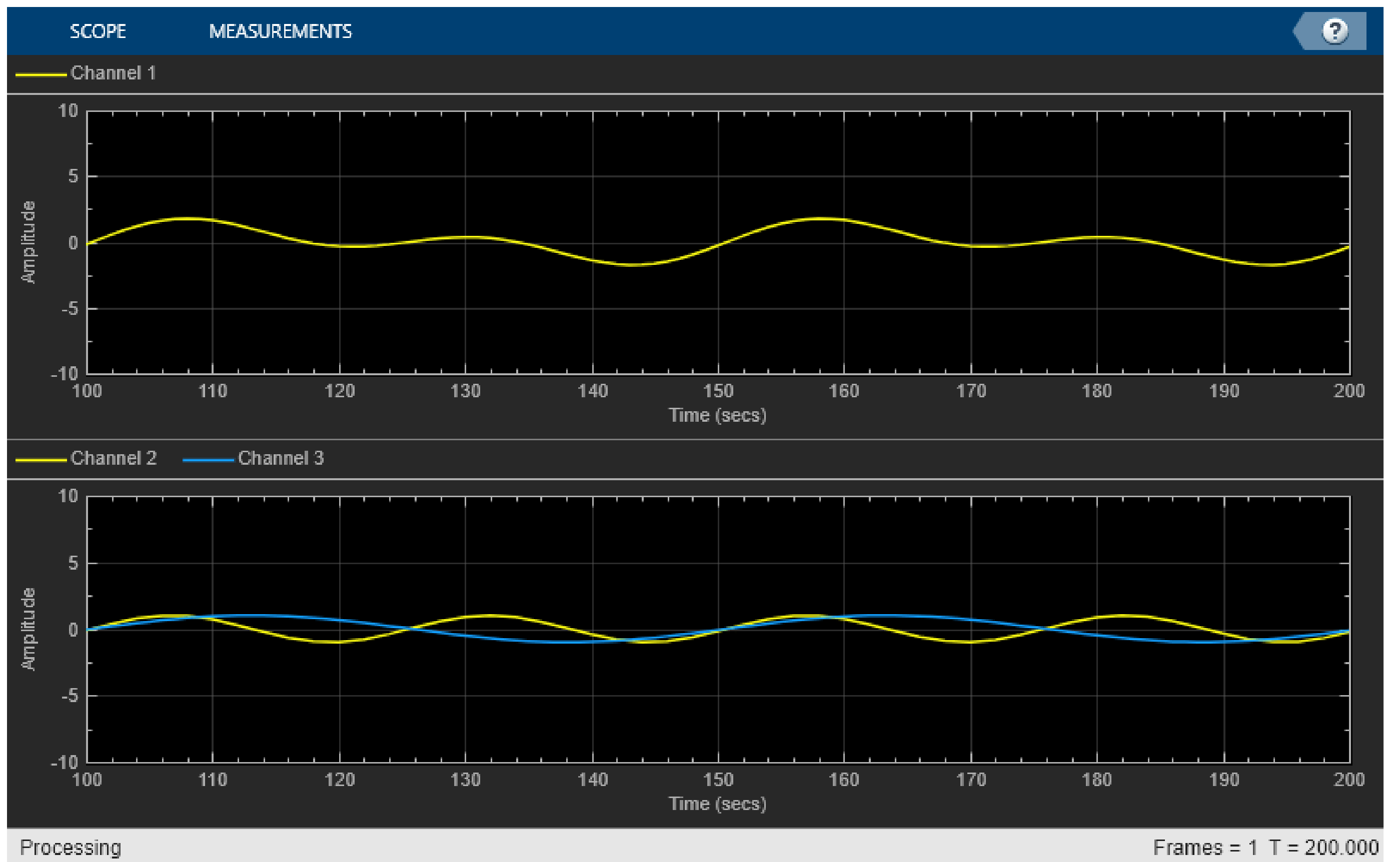
Use the `timescope` object to visualize three sine waves with two different sample rates.

```
freq = 1;
t    = (0:100)'/freq;
t2   = (0:0.5:100)'/freq;
xin1 = sin(1/2*t);
xin2 = sin(1/4*t2);
xin  = sin(1/2*t2)+sin(1/4*t2);

scope = timescope(SampleRate=[freq freq/2 freq],...
     TimeSpanSource="property",...
     TimeSpan=100);
scope(xin, xin1, xin2)
```




Change the layout to add a second axis. The second and third inputs automatically move to the new second axis.

```
scope.LayoutDimensions = [2,1];
```

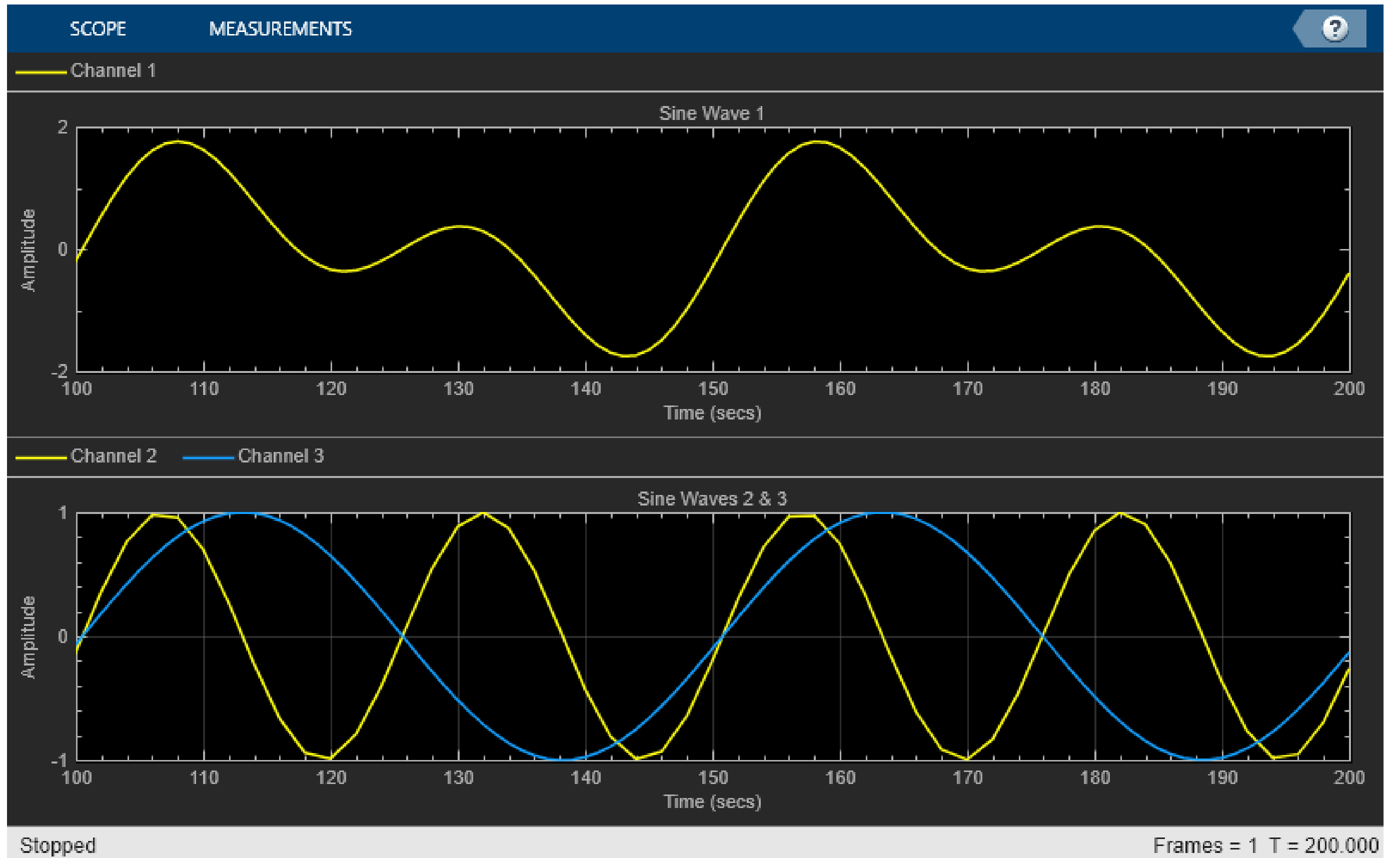



Modify the properties of the first axis.

```
scope.ActiveDisplay = 1;
scope.ShowGrid = false;
scope.Title = "Sine Wave 1";
scope.YLimits = [-2,2];
```

Repeat this process to modify the second axis.

```
scope.ActiveDisplay = 2;
scope.Title = "Sine Waves 2 & 3";
scope.YLimits = [-1,1];
release(scope)
```




#### View Sine Wave Input Signals at Different Sample Rates and Offsets

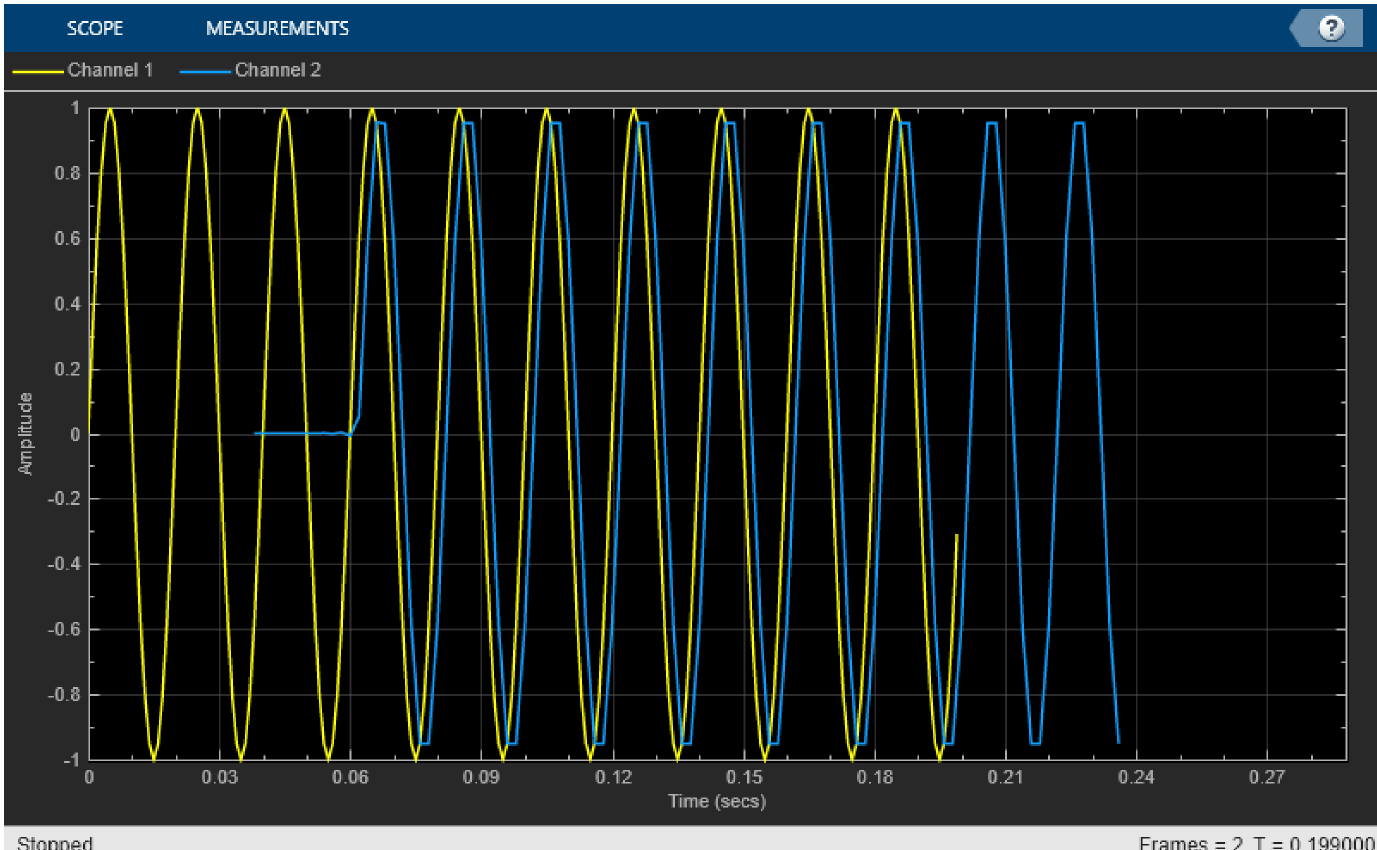
Create a `dsp.SineWave` object. Create a `dsp.FIRDecimator` object to decimate the sine wave by 2. Create a `timescope` object with two input ports.

```
Fs = 1000;  % Sample rate
sine = dsp.SineWave(Frequency=50,...
   SampleRate=Fs,...
   SamplesPerFrame=100);
decimate = dsp.FIRDecimator; % To decimate sine by 2
scope = timescope(SampleRate=[Fs Fs/2],...
   TimeDisplayOffset=[0 38/Fs],...
   TimeSpanSource="Property",...
   TimeSpan=0.25,...
   YLimits=[-1 1],...
   ShowLegend=true);
```

Call the `dsp.SineWave` object to create a sine wave signal. Use the `dsp.FIRDecimator` object to create a second signal that equals the original signal and decimate it by a factor of 2. Display the signals by calling the `timescope` object.

```
for ii = 1:2
     xsine = sine();
     xdec = decimate(xsine);
```

```
    scope(xsine,xdec)
end
release(scope)
```



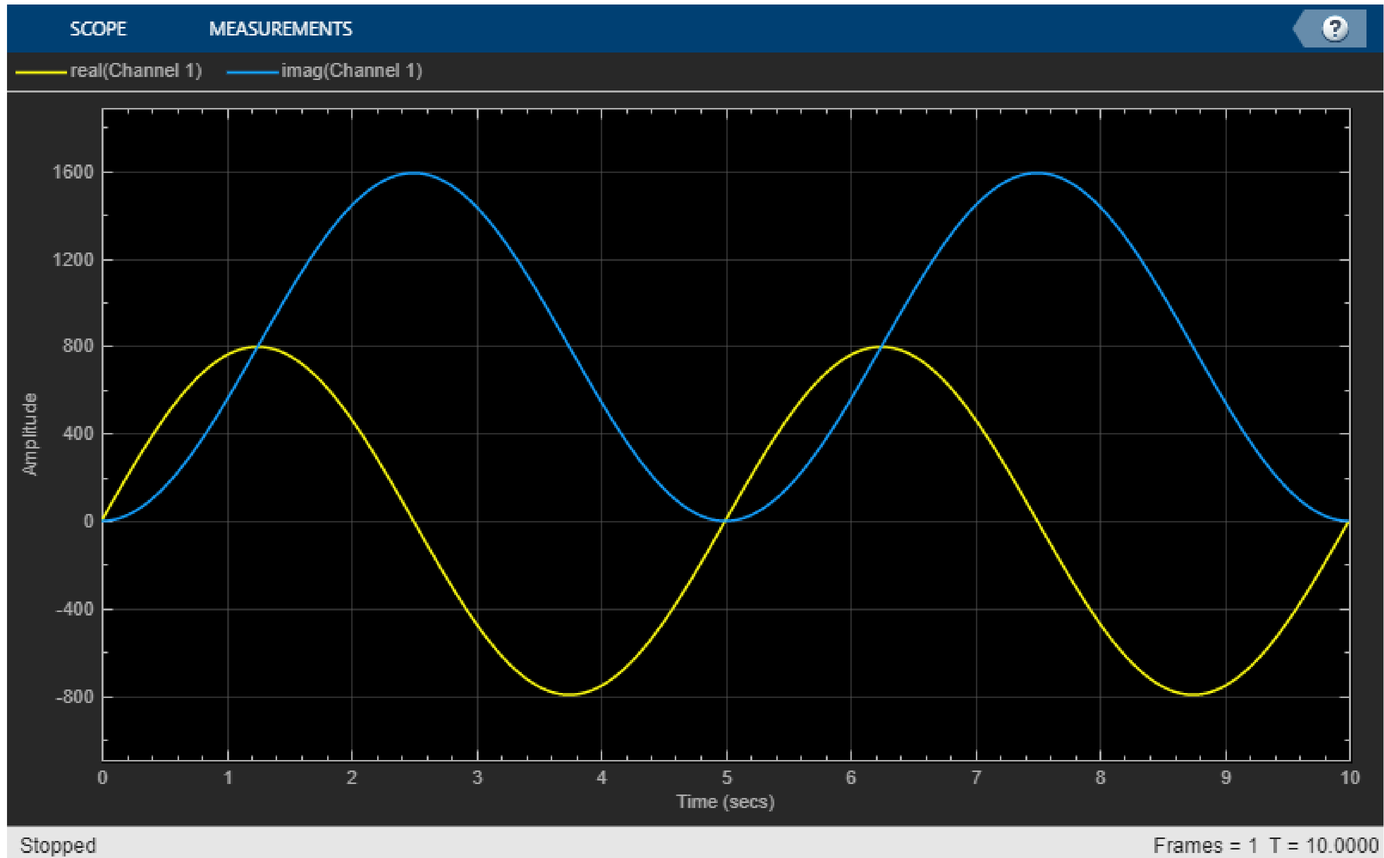

Close the Time Scope window and clear the variables.

```
clear scope Fs sine decimate ii xsine xdec
```

### Display Complex-Valued Input Signal

Create a vector representing a complex-valued sinusoidal signal and a `timescope` object. Call the scope to display the signal.

```
fs = 1000;
t = (0:1/fs:10)';
CxSine = cos(2*pi*0.2*t) + 1i*sin(2*pi*0.2*t);
CxSineSum = cumsum(CxSine);
scope = timescope(SampleRate=fs,...
    TimeSpanSource="auto",ShowLegend=1);
scope(CxSineSum);
release(scope)
```

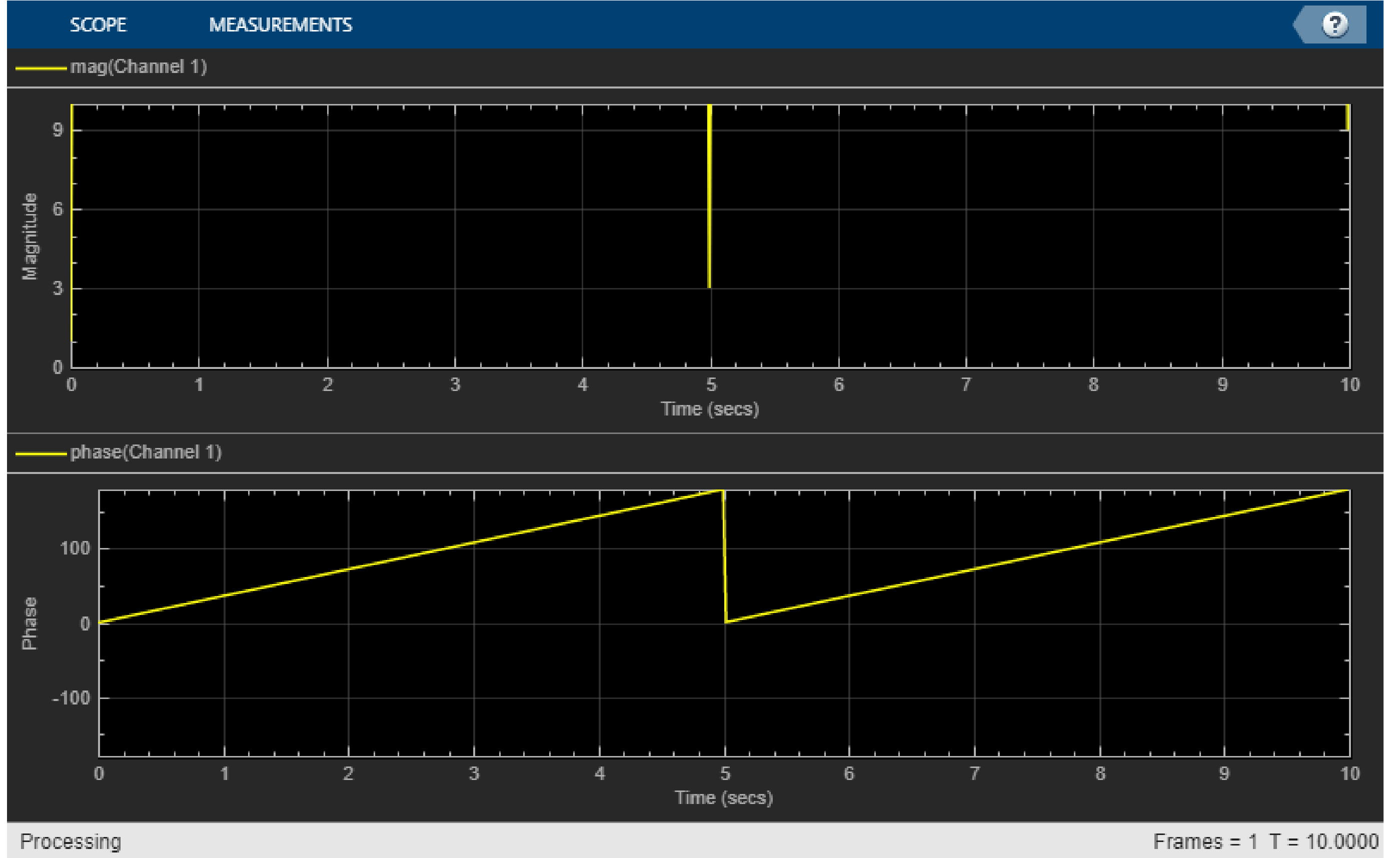



By default, when the input is a complex-valued signal, the Time Scope plots the real and imaginary portions on the same axes. These portions appear as different-colored lines on the same axes within the same active display.

Change the `PlotAsMagnitudePhase` property to `true` and call `release`.

The Time Scope now plots the magnitude and phase of the input signal on two separate axes within the same active display. The top axes display magnitude and the bottom axes display the phase in degrees.

```
scope.PlotAsMagnitudePhase = true;
scope(CxSineSum);
release(scope)
```

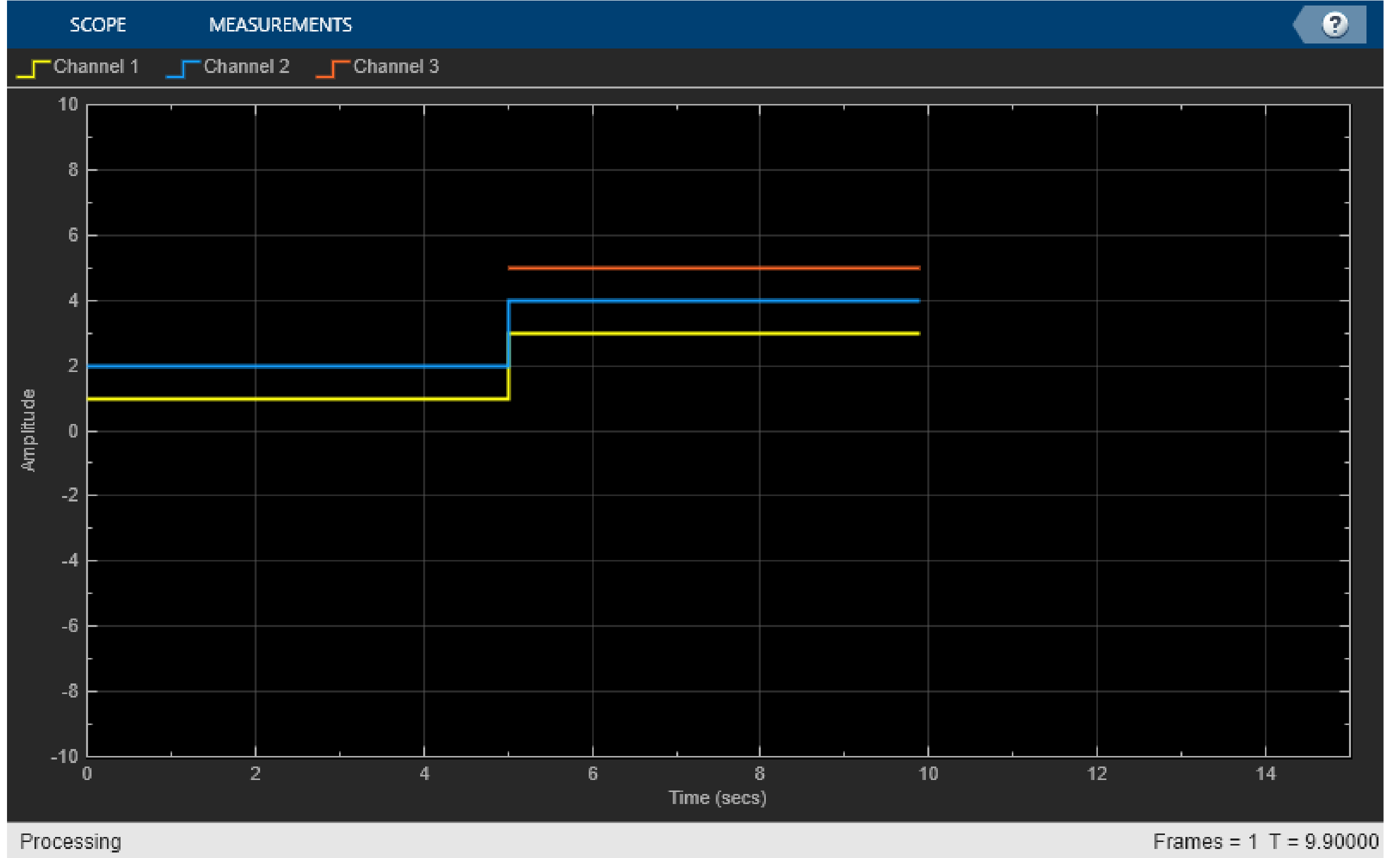



#### Display Input Signal of Changing Size

This example shows how the `timescope` object visualizes inputs that change dimensions halfway through.

Create a vector that represents a two-channel constant signal. Create another vector that represents a three-channel constant signal. Create a `timescope` object and call the scope with two inputs to display the signal.

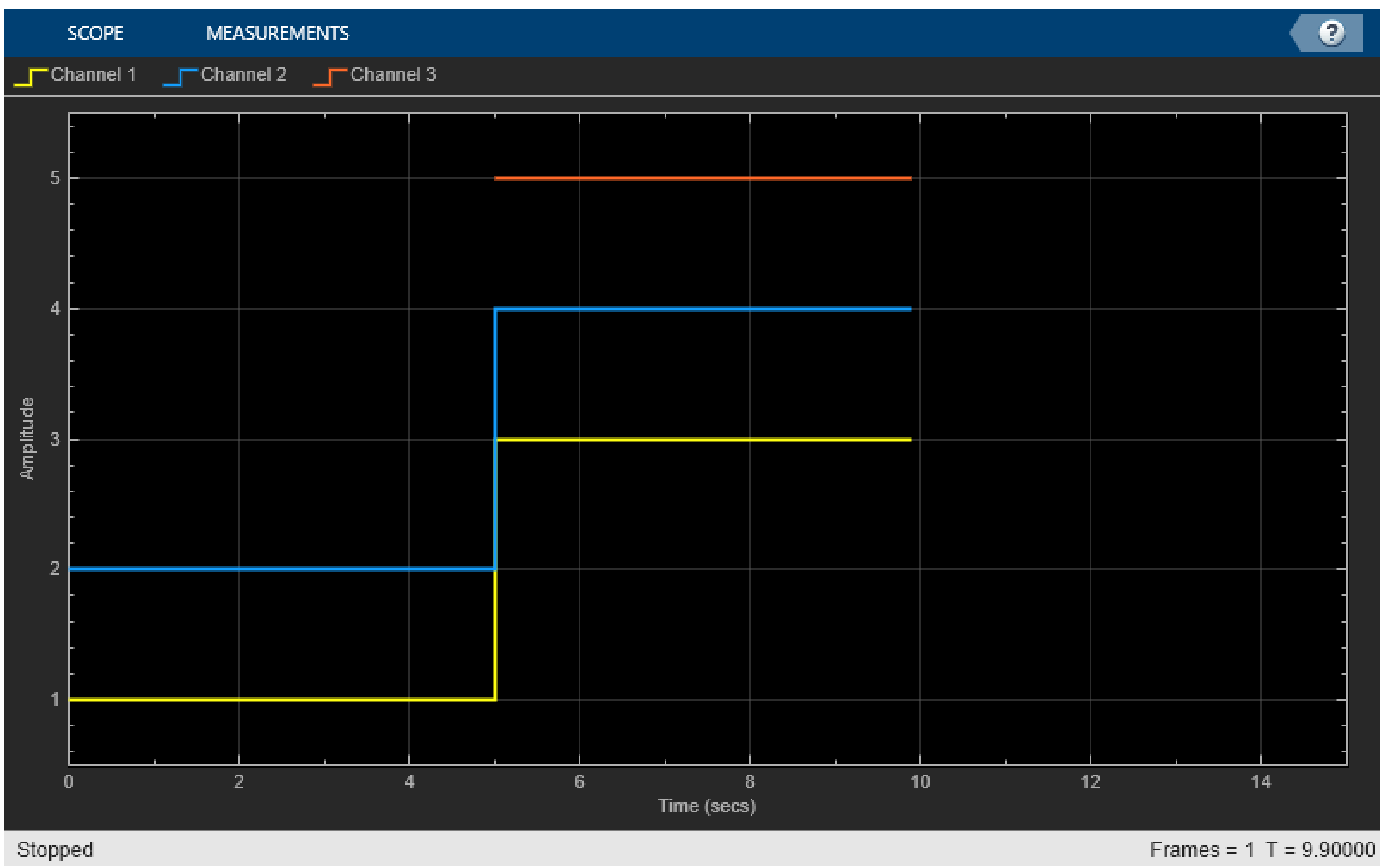
```
fs = 10;
sigdim2 = [ones(5*fs,1) 1+ones(5*fs,1)];                % 2-dim 0-5 s
sigdim3 = [2+ones(5*fs,1) 3+ones(5*fs,1) 4+ones(5*fs,1)];  % 3-dim 5-10 s
scope = timescope(SampleRate=fs,TimeSpanSource="property");
scope.PlotType = "stairs";
scope.TimeSpanOverrunAction = "scroll";
scope.TimeDisplayOffset = [0 5];
scope([sigdim2; sigdim3(:,1:2)], sigdim3(:,3));
```




The size of the input signal to the Time Scope changes as the simulation progresses. When the simulation time is less than 5 seconds, the Time Scope plots only the two-channel signal `sigdim2`. After 5 seconds, the Time Scope also plots the three-channel signal `sigdim3`.

Run the `release` method to enable changes to property values and input characteristics. The scope automatically scales the axes.

```
release(scope)
```




### Find Heart Rate Using Peak Finder Panel with ECG Input Signal

Use Peak Finder pane in the Time Scope to measure heart rate.

### Create and Display ECG Signal

Use the custom `ecg` function to generate an electrocardiogram (ECG) signal.

```
type ecg.m
```

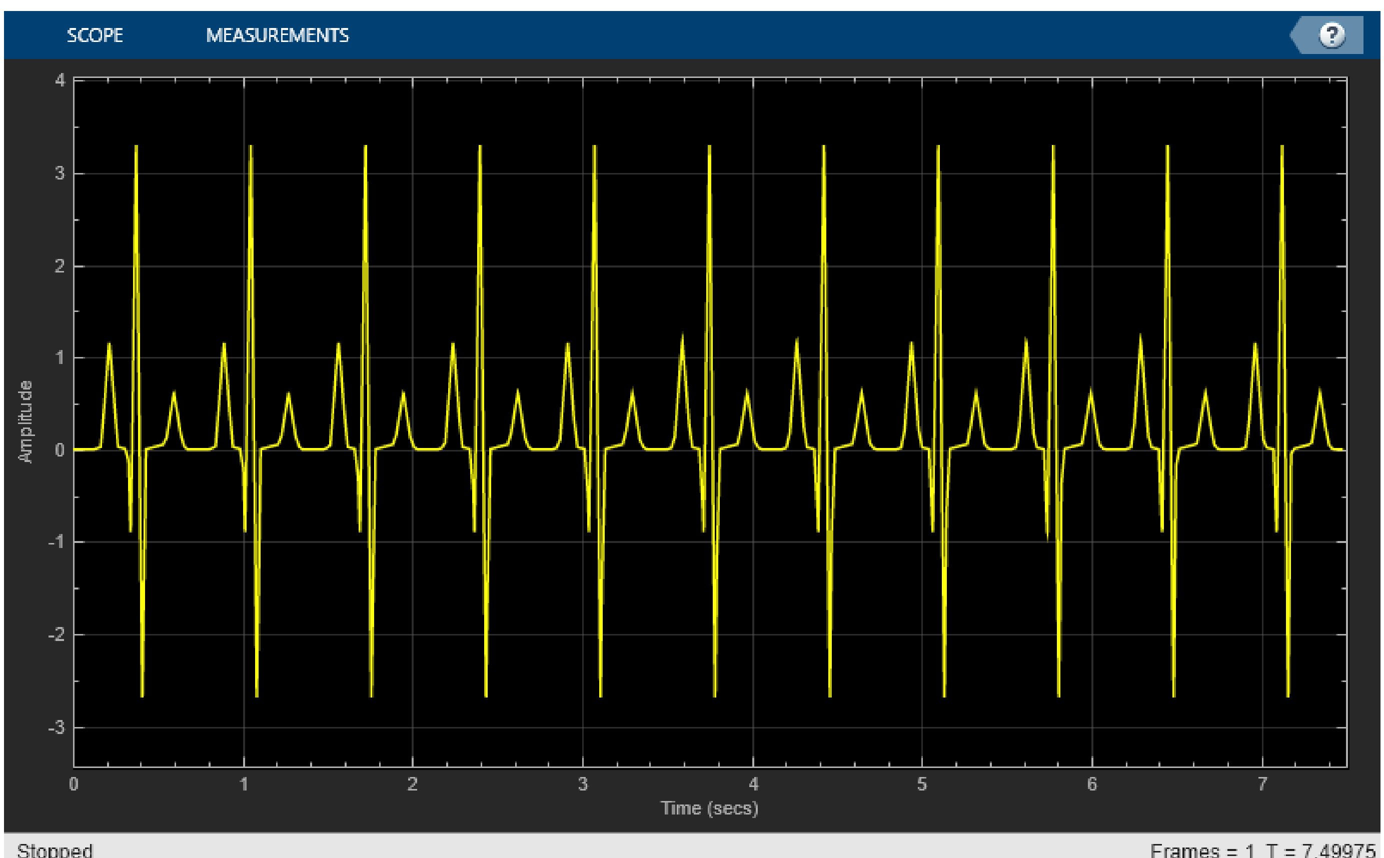
```
function x = ecg(L)
a0 = [0,  1, 40,  1,   0, -34, 118, -99,   0,   2,  21,   2,   0,   0,   0];
d0 = [0, 27, 59, 91, 131, 141, 163, 185, 195, 275, 307, 339, 357, 390, 440];
a = a0 / max(a0);
d = round(d0 * L / d0(15));
d(15) = L;
for i = 1:14
    m = d(i) : d(i+1) - 1;
    slope = (a(i+1) - a(i)) / (d(i+1) - d(i));
    x(m+1) = a(i) + slope * (m - d(i));
end
```

```
x1 = 3.5*ecg(2700).';
y1 = sgolayfilt(kron(ones(1,13),x1),0,21);
n = (1:30000)';
```

```
del = round(2700*rand(1));
mhb = y1(n + del);
ts = 0.00025;
```

Create a `timescope` object and call the object to display the signal. To autoscale the axes and enable changes to property values and input characteristics, call `release`.

```
scope = timescope(SampleRate=1/ts);
scope(mhb);
release(scope)
```




### Find Heart Rate

Use the Peak Finder measurements to measure the time between heartbeats.

In the **Measurements** tab, select **Peak Finder** to enable the peak finder measurements.

Click the **Peak Finder** arrow and set the **Num Peaks** property to `10` and hit `enter`.

In the **Peaks** pane at the bottom of the window, the Time Scope displays a list of ten peak amplitude values and the times at which they occur.

The list of peak values shows a constant time difference of 0.675 seconds between each heartbeat. Based on this equation, the heart rate of this ECG signal is about 89 beats per minute.

$$\frac{60\ \mathrm{s/min}}{0.675\ \mathrm{s/beat}} = 88.89\ \mathrm{bpm}$$

Close the Time Scope window and remove the variables you created from the workspace.

```
clear scope x1 y1 n del mhb ts
```

## Tips

- To close the scope window and clear its associated data, use the MATLAB `clear` function.
- To hide or show the scope window, use the `hide` and `show` functions.
- Use the MATLAB `mcc` function to compile code containing a scope. You cannot open scope configuration dialogs if you have more than one compiled component in your application.

# Version History

**Introduced in R2020a**

### R2022b: Channel names support array of strings

Starting in R2022b, you can specify the `ChannelNames` property of the `timescope` object as an array of strings.

```
ts = timescope(SampleRate=Fs, ChannelNames=["Input", "Lowpass Output"]);
```

## See Also

**Topics**
"Configure Time Scope MATLAB Object"

# generateScript

Generate MATLAB script to create scope with current settings

## Syntax

```
generateScript(scope)
```

## Description

`generateScript(scope)` generates a MATLAB script that can re-create a `timescope` object with the current settings in the scope.

## Examples

### Generate Script from `timescope`

Generate MATLAB script after making changes to the `timescope` object in the scope window.

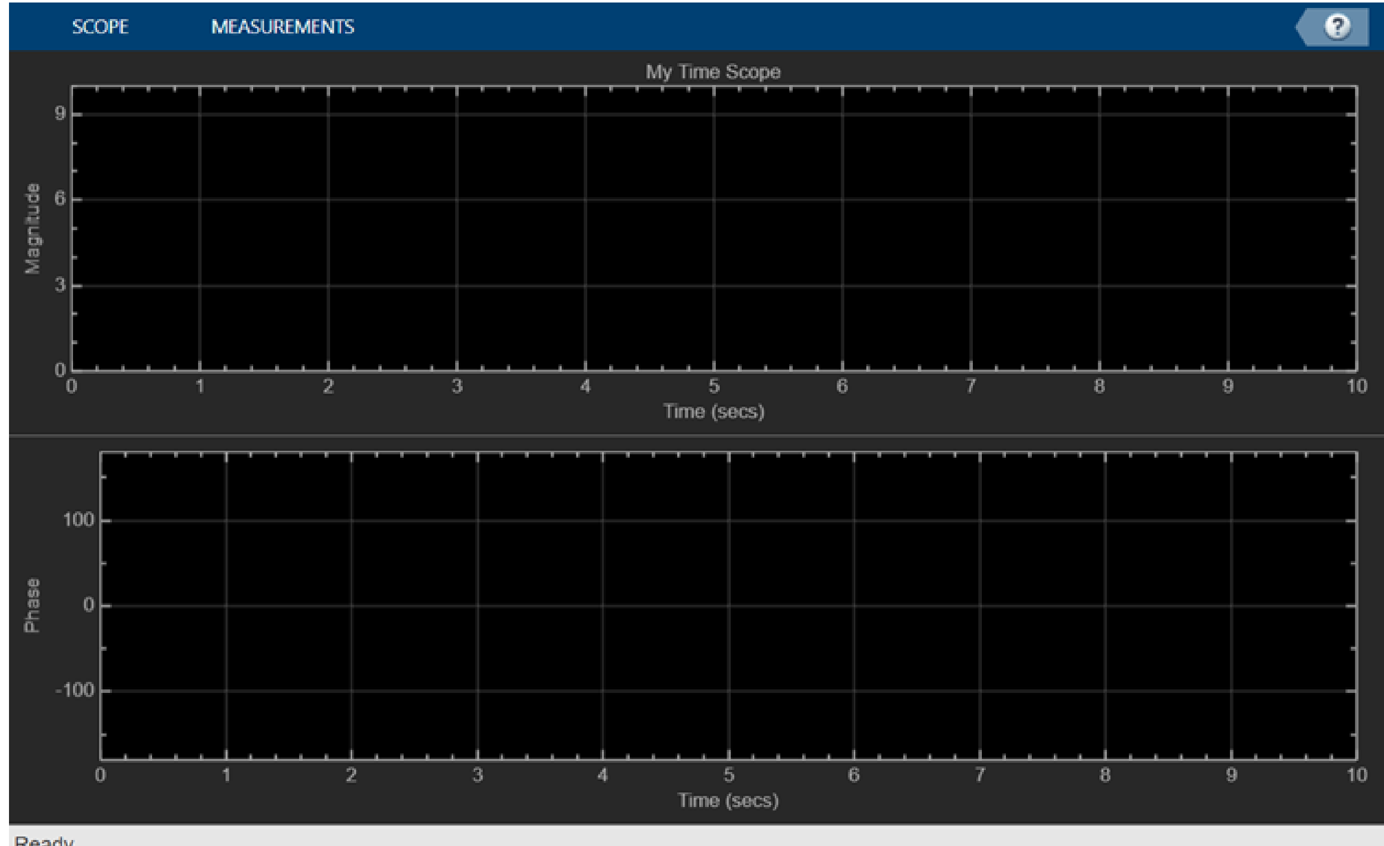
---

**Note** The script only generates commands for settings that are available from the command line, applicable to the current visualization, and changed from the default value.

---

1. Create a `timescope` object.

   ```
   scope = timescope;
   show(scope)
   ```
2. Set options in the Time Scope. For this example, on the **Scope** tab, click **Settings**. Under **Display and Labels**, select **Show Legend** and **Magnitude Phase Plot**. Set the **Title** as well.




3 Generate a script to recreate the `timescope` with the same modified settings. Either select **Generate Script** from the **Scope** tab, or enter:

```
generateScript(scope);
```

A new editor window opens with code to regenerate the same scope.

```
% Creation Code for 'timescope'.
% Generated by Time Scope on 8-Nov-2019 13:51:54 -0500.

timeScope = timescope('Position',[2286 355 800 500], ...
    'Title','My Time Scope', ...
    'ShowLegend',true, ...
    'PlotAsMagnitudePhase',true);
```

## Input Arguments

### scope — object

`timescope` object

Object whose settings you want to recreate with a script.

# Version History

**Introduced in R2020a**

## See Also

**Functions**
`hide` | `show` | `isVisible`

**Objects**
`timescope`

# hide

Hide scope window

## Syntax

`hide(scope)`

## Description

`hide(scope)` hides the scope window.

## Examples

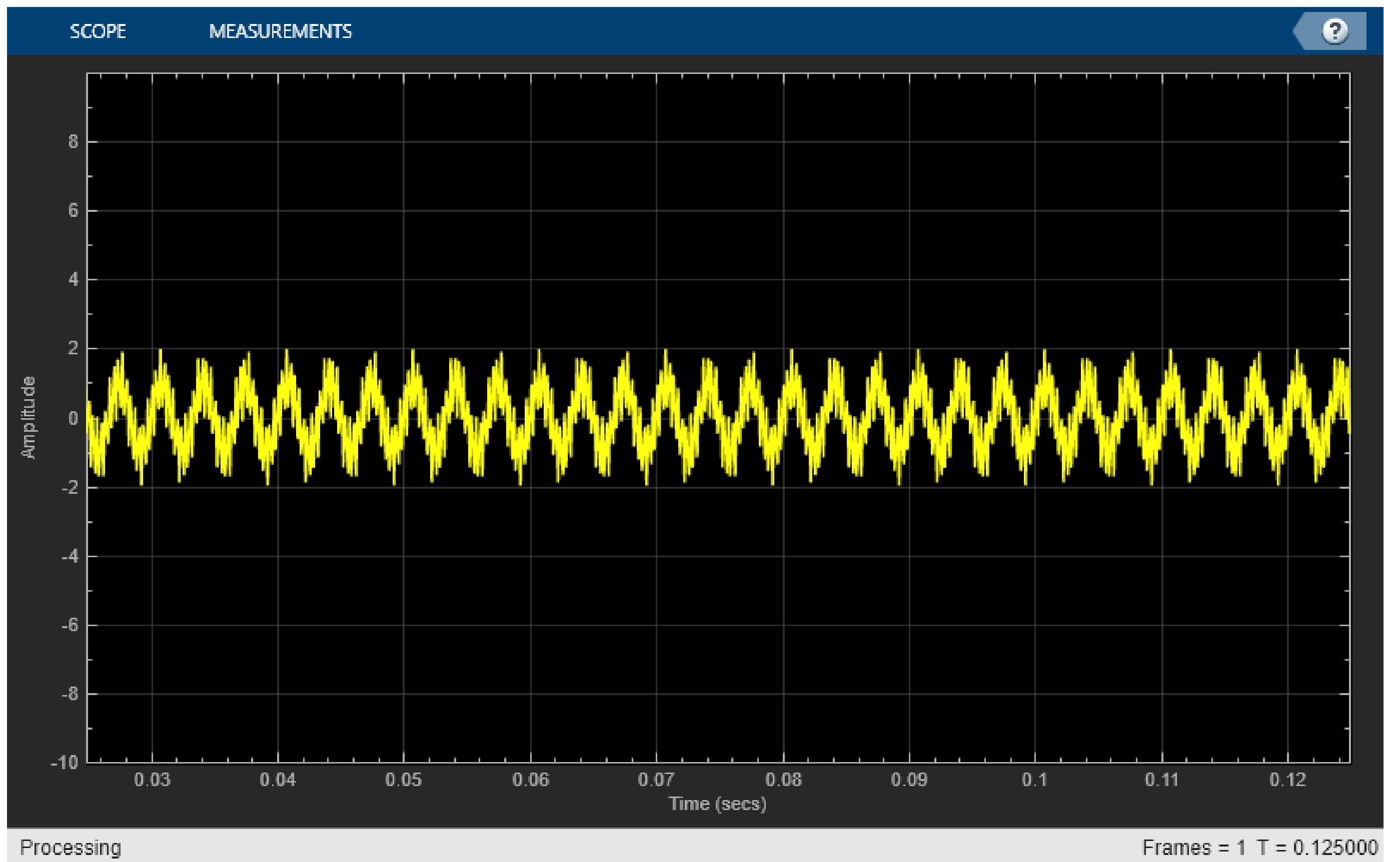
### View Sine Wave on Time Scope

Create a sinusoidal signal with two tones, one at 0.3 kHz and the other at 3 kHz.

```
t = (0:1000)'/8e3;
xin = sin(2*pi*0.3e3*t)+sin(2*pi*3e3*t);
```

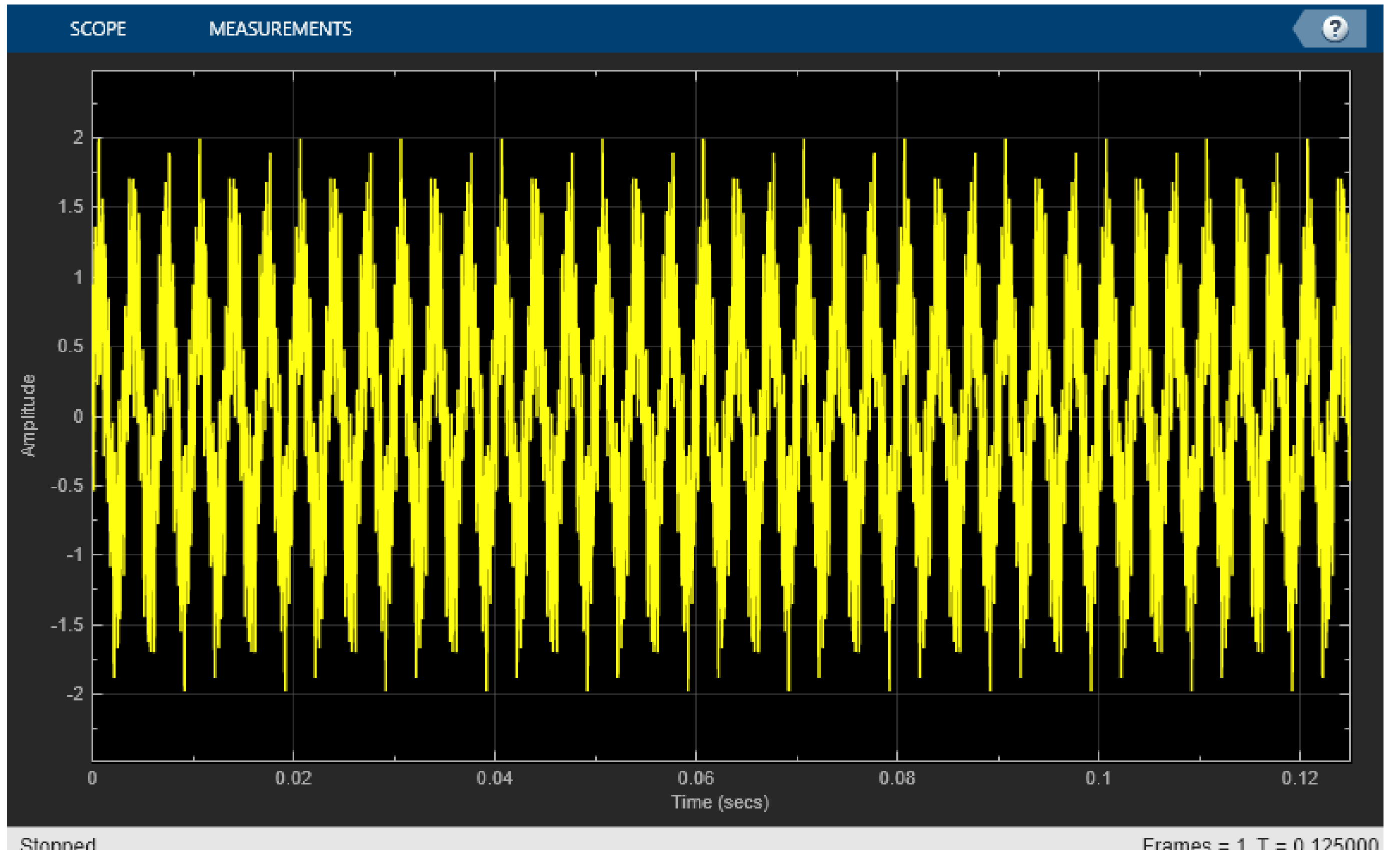
Create a `timescope` object and view the sinusoidal signal by calling the time scope object `scope`.

```
scope = timescope(SampleRate=8e3,...
    TimeSpanSource="property",...
    TimeSpan=0.1);
scope(xin)
```




Run `release` to allow changes to property values and input characteristics. The scope automatically scales the axes.

```
release(scope);
```

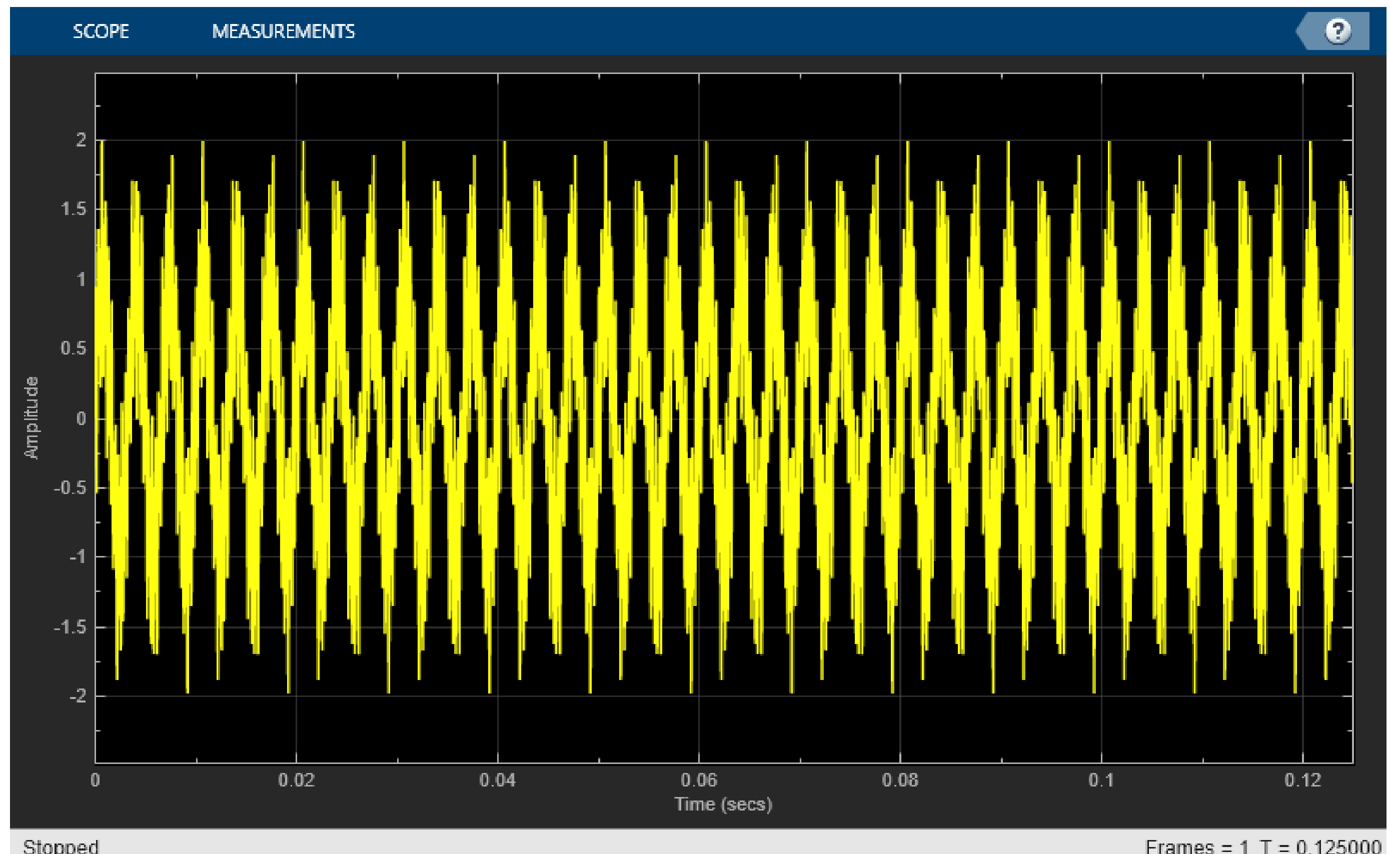



Hide the scope window.

```
if(isVisible(scope))
    hide(scope)
end
```

Show the scope window.

```
if(~isVisible(scope))
    show(scope)
end
```




## Input Arguments

**scope — Scope object**
timescope object

Scope object whose window you want to hide, specified as a `timescope` object.

Example: `myScope = timescope; hide(myScope)`

# Version History

**Introduced in R2020a**

## See Also

**Functions**
`show` | `isVisible` | `generateScript`

**Objects**
`timescope`

# isVisible

Determine visibility of scope

## Syntax

```
visibility = isVisible(scope)
```

## Description

`visibility = isVisible(scope)` returns the visibility of the scope as logical, with `1` (`true`) for visible.

## Examples

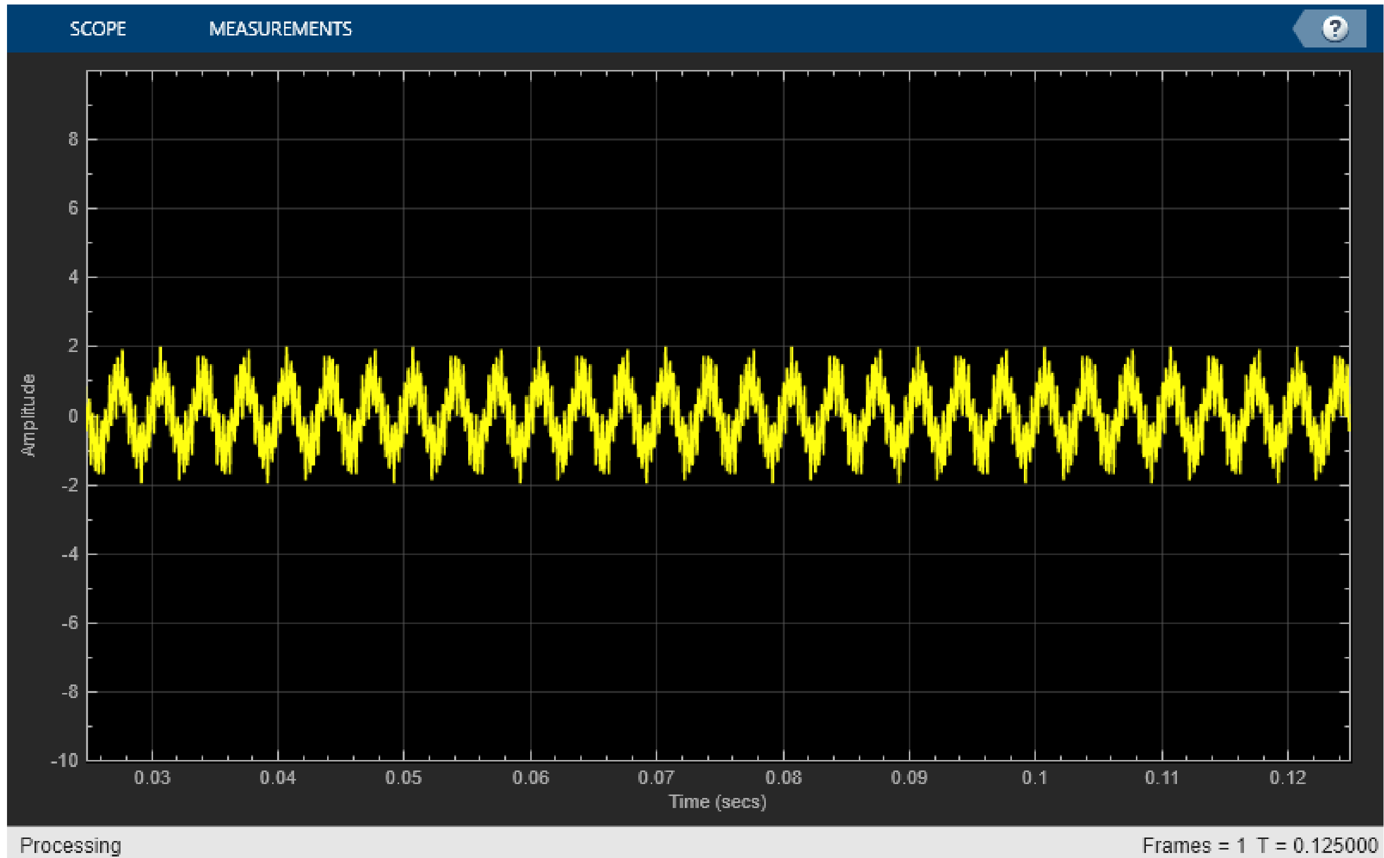
### View Sine Wave on Time Scope

Create a sinusoidal signal with two tones, one at 0.3 kHz and the other at 3 kHz.

```
t = (0:1000)'/8e3;
xin = sin(2*pi*0.3e3*t)+sin(2*pi*3e3*t);
```

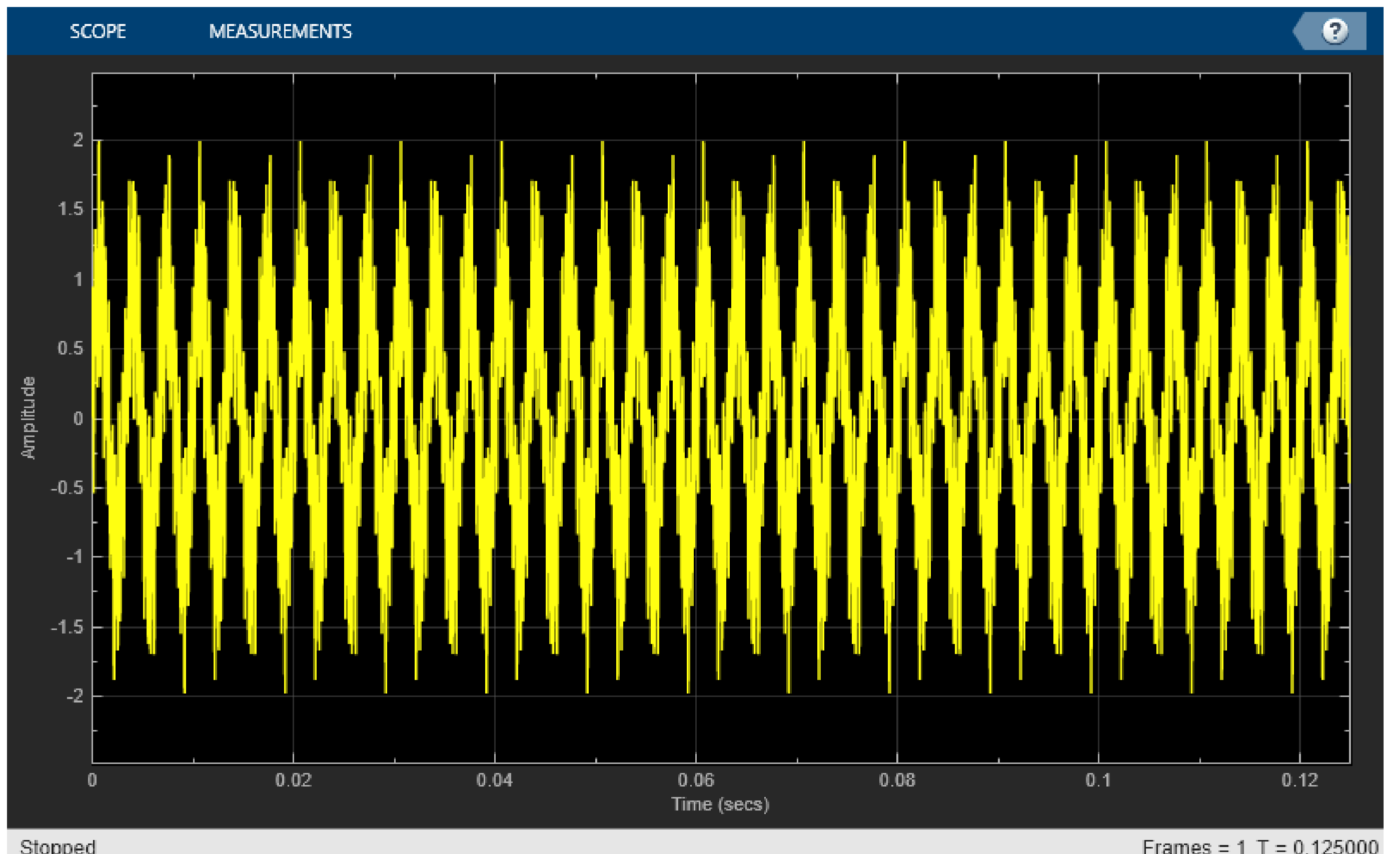
Create a `timescope` object and view the sinusoidal signal by calling the time scope object `scope`.

```
scope = timescope(SampleRate=8e3,...
    TimeSpanSource="property",...
    TimeSpan=0.1);
scope(xin)
```




Run `release` to allow changes to property values and input characteristics. The scope automatically scales the axes.

```
release(scope);
```

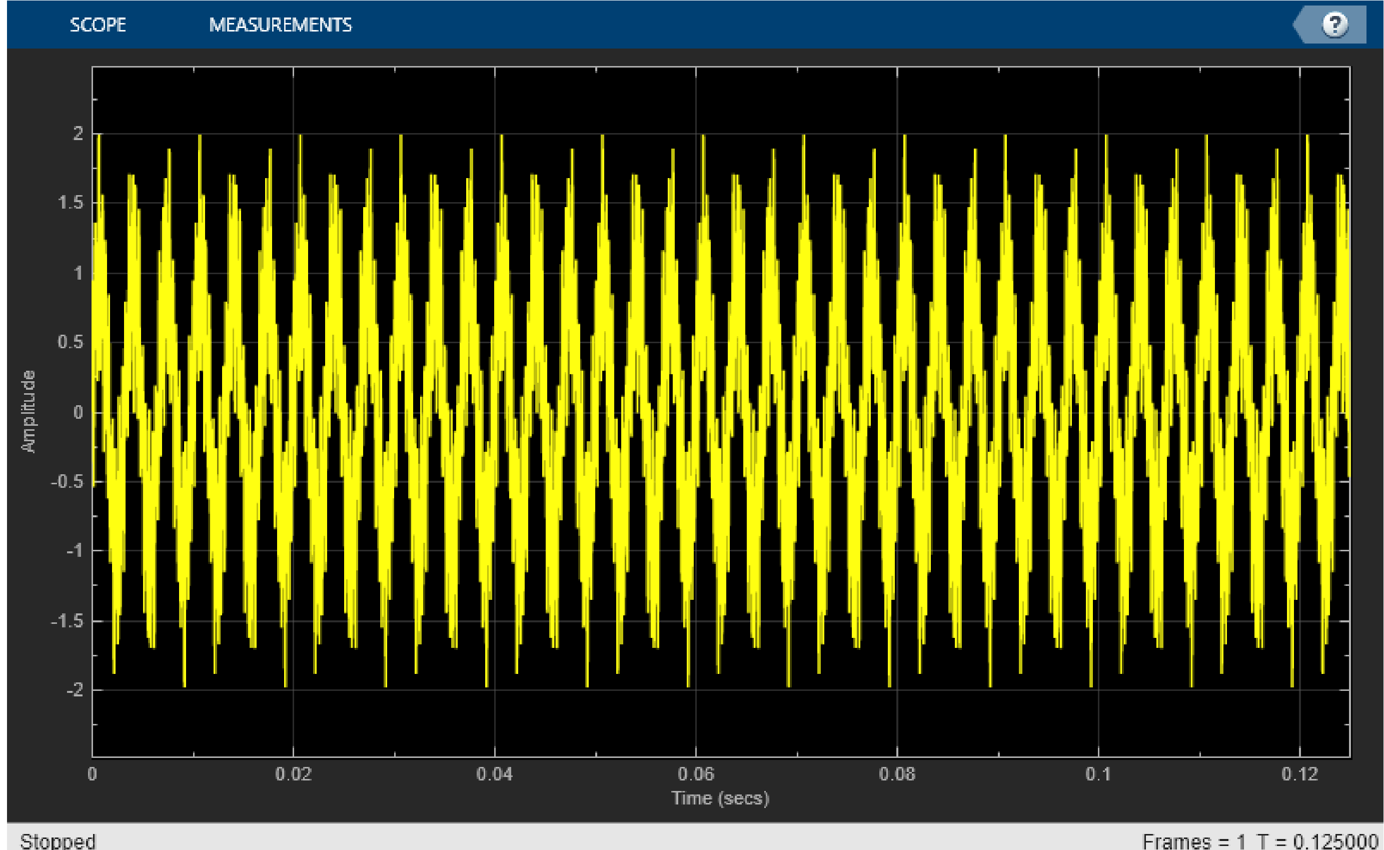



Hide the scope window.

```
if(isVisible(scope))
    hide(scope)
end
```

Show the scope window.

```
if(~isVisible(scope))
    show(scope)
end
```




## Input Arguments

**`scope` — Scope object**
`timescope` object

Scope object whose visibility you want to query.

Example: `myScope = timescope; visibility = isVisible(myScope)`

## Output Arguments

**`visibility` — Scope visibility**
`1` | `0`

If the scope window is open, the `isVisible` function returns `1` (`true`). Otherwise, the function returns `0` (`false`).

# Version History

**Introduced in R2020a**

## See Also

**Functions**
`hide` | `show` | `generateScript`

**Objects**
`timescope`

# show

Display scope window

## Syntax

`show(scope)`

## Description

`show(scope)` shows the scope window.

## Examples

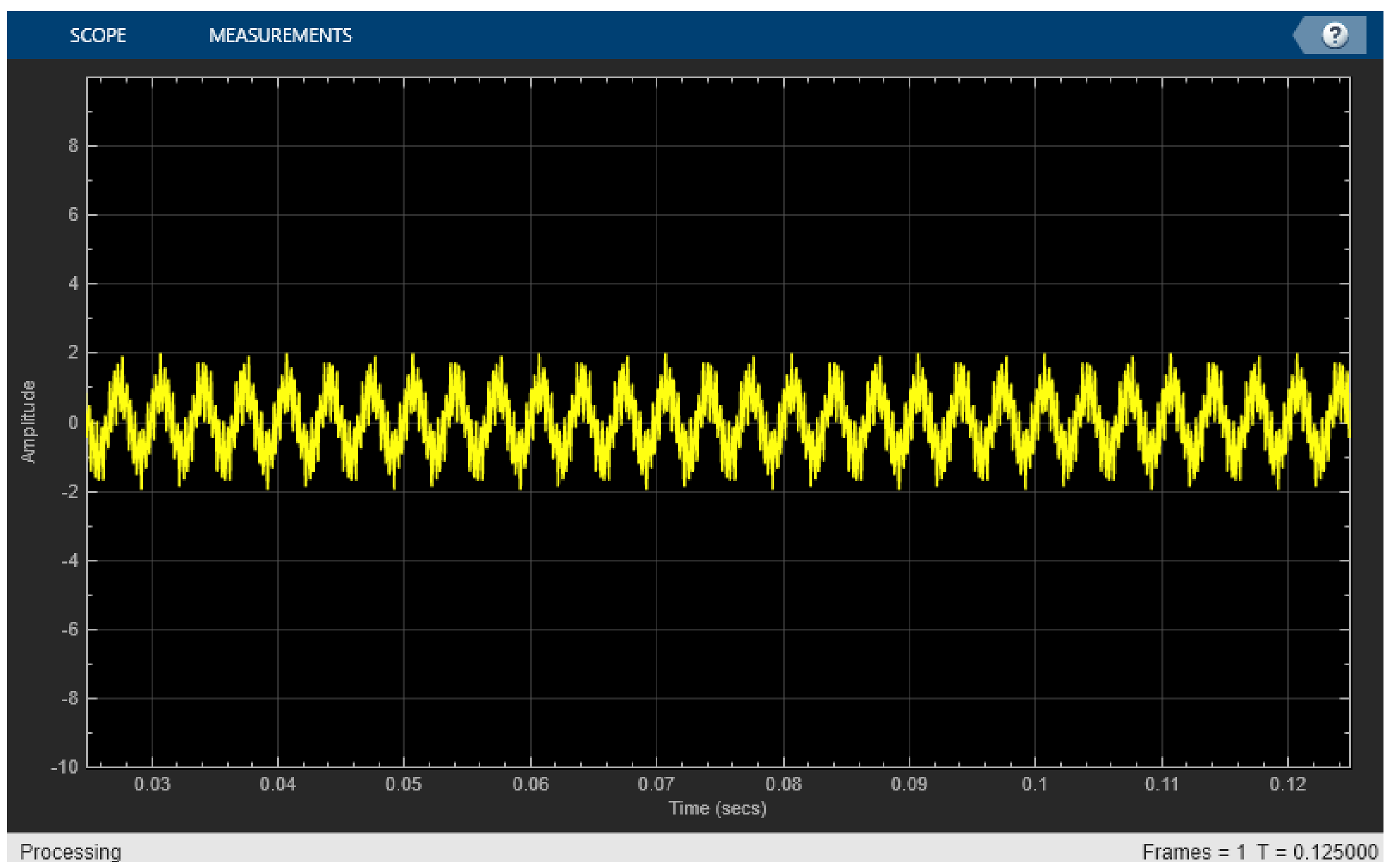
### View Sine Wave on Time Scope

Create a sinusoidal signal with two tones, one at 0.3 kHz and the other at 3 kHz.

```
t = (0:1000)'/8e3;
xin = sin(2*pi*0.3e3*t)+sin(2*pi*3e3*t);
```

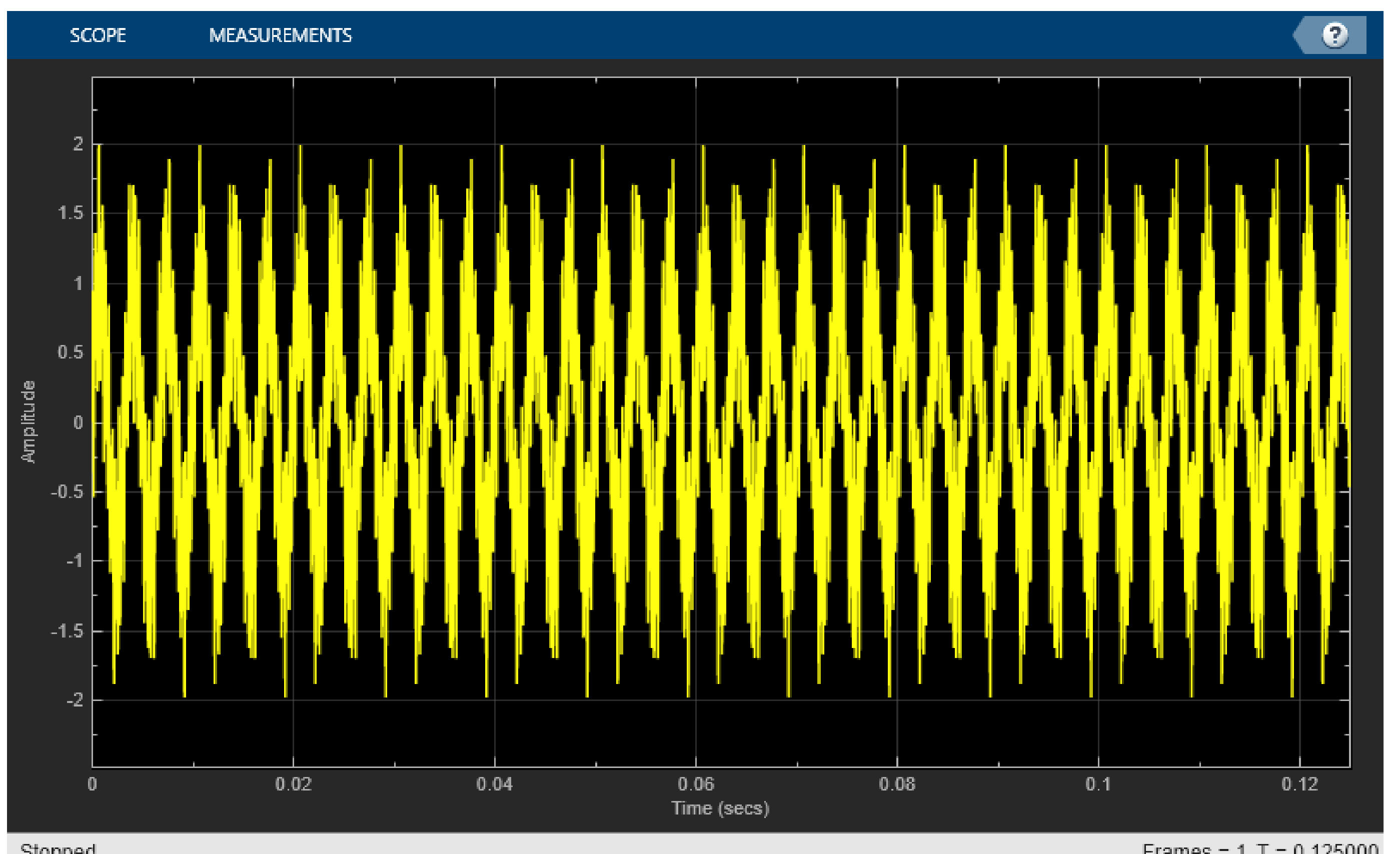
Create a `timescope` object and view the sinusoidal signal by calling the time scope object `scope`.

```
scope = timescope(SampleRate=8e3,...
    TimeSpanSource="property",...
    TimeSpan=0.1);
scope(xin)
```




Run `release` to allow changes to property values and input characteristics. The scope automatically scales the axes.

```
release(scope);
```

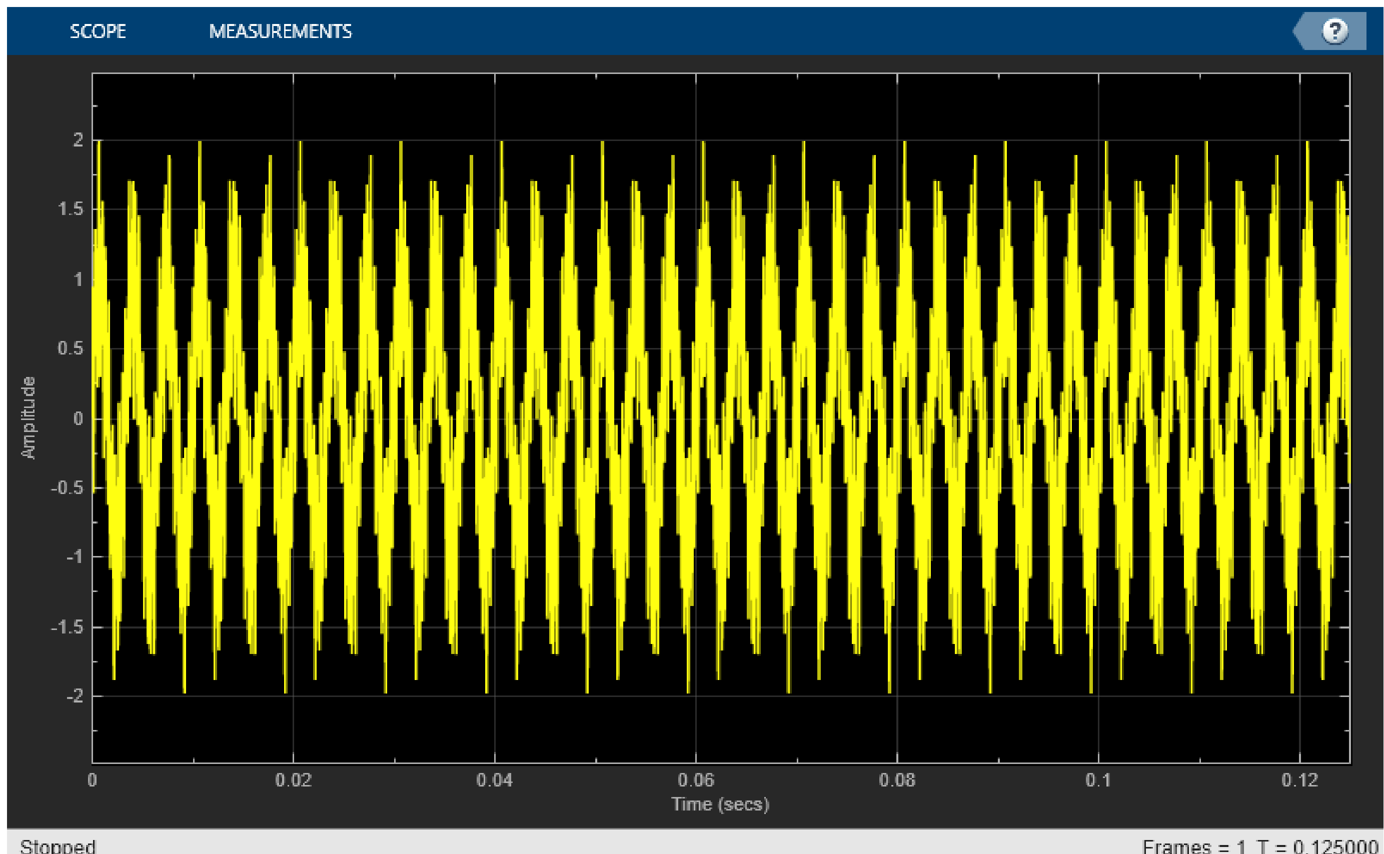



Hide the scope window.

```
if(isVisible(scope))
    hide(scope)
end
```

Show the scope window.

```
if(~isVisible(scope))
    show(scope)
end
```




## Input Arguments

**scope — Scope object**
`timescope` object

Scope object whose window you want to show, specified as a `timescope` object.

Example: `myScope = timescope; show(myScope)`

# Version History

**Introduced in R2020a**

## See Also

**Functions**
`hide` | `isVisible` | `generateScript`

**Objects**
`timescope`

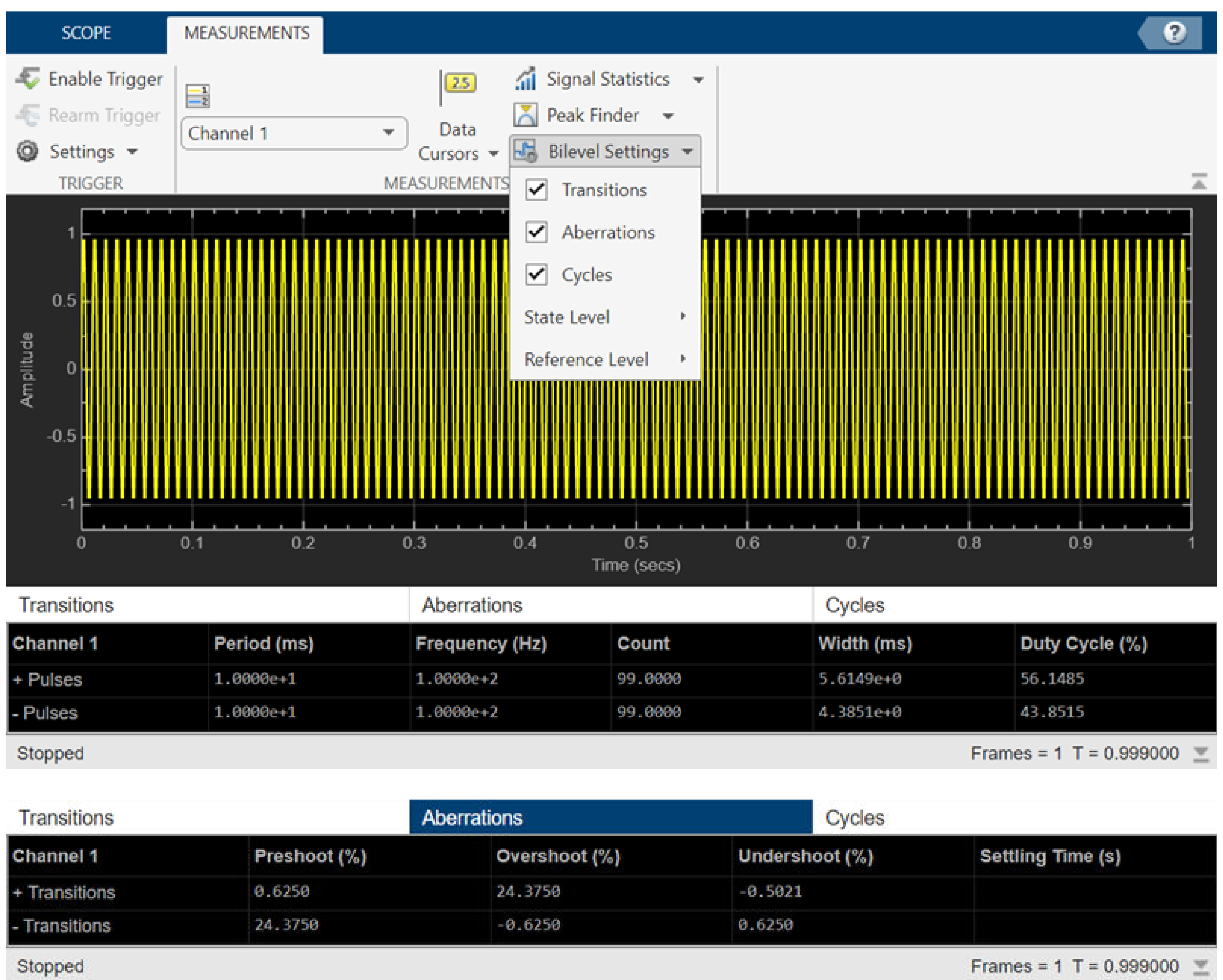
# BilevelMeasurementsConfiguration

Measure transitions, aberrations, and cycles of bilevel signals

## Description

Use the `BilevelMeasurementsConfiguration` object to measure transitions, aberrations, and cycles of bilevel signals. You can also specify the bilevel settings such as high-state level, low-state level, state-level tolerance, upper-reference level, mid-reference level, and lower-reference level.

You can control bilevel measurements from the toolstrip or from the command line. To modify bilevel measurements from the toolstrip, in the **Measurements** tab, click **Bilevel Settings** and select the measurements you want to display. A panel appears at the bottom of the Time Scope window showing all the measurements you enabled.



| Transitions | | Aberrations | | Cycles | |
|---|---|---|---|---|---|
| Channel 1 | Period (ms) | Frequency (Hz) | Count | Width (ms) | Duty Cycle (%) |
| + Pulses | 1.0000e+1 | 1.0000e+2 | 99.0000 | 5.6149e+0 | 56.1485 |
| - Pulses | 1.0000e+1 | 1.0000e+2 | 99.0000 | 4.3851e+0 | 43.8515 |

Stopped    Frames = 1  T = 0.999000

# Creation

## Syntax

`bilevelMeas = BilevelMeasurementsConfiguration()`

### Description

`bilevelMeas = BilevelMeasurementsConfiguration()` creates a bilevel measurements configuration object.

## Properties

All properties are tunable.

**`AutoStateLevel` — Automatic detection of high- and low-state levels**
`true` (default) | `false`

Automatic detection of high- and low-state levels, specified as `true` or `false`. Set this property to `true` so that the scope automatically detects high- and low-state levels in the bilevel waveform. When you set this property to `false`, you can specify values for the high- and low- state levels manually using the `HighStateLevel` and `LowStateLevel` properties.

**Scope Window Use**

On the **Measurements** tab, in the **Measurements** section, click **Bilevel Settings**. Under **State Level**, and select **Auto State Level**.

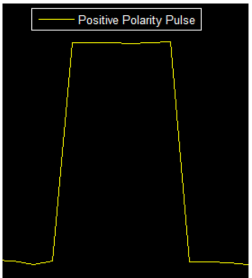
Data Types: `logical`

**`HighStateLevel` — High-state level**
`2.3` (default) | nonnegative scalar

High-state level, specified as a nonnegative scalar. The high-state level denotes a positive polarity.

If the initial transition of a pulse is positive-going, the pulse has positive polarity. The terminating state of a positive-polarity (positive-going) pulse is more positive than the originating state.

This figure shows a positive-polarity pulse.




#### Dependency

To enable this property, set `AutoStateLevel` to `false`.

#### Scope Window Use

On the **Measurements** tab, in the **Measurements** section, click **Bilevel Settings**. Under **State Level**, clear **Auto State Level** and specify a nonnegative scalar in the **High** box.

Data Types: `double`

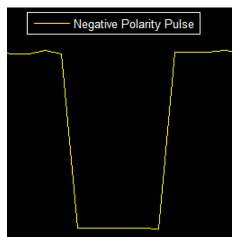
### `LowStateLevel` — Low-state level

`0` (default) | nonnegative scalar

High-state level, specified as a nonnegative scalar. The low-state level denotes a negative polarity.

If the initial transition of a pulse is negative-going, the pulse has negative polarity. The terminating state of a negative-polarity (negative-going) pulse is more negative than the originating state.

This figure shows a negative-polarity pulse.




#### Dependency

To enable this property, set `AutoStateLevel` to `false`.

#### Scope Window Use

On the **Measurements** tab, in the **Measurements** section, click **Bilevel Settings**. Under **State Level**, clear **Auto State Level** and specify a nonnegative scalar in the **Low** box.

Data Types: `double`

### `StateLevelTolerance` — Tolerance level of state

2 (default) | positive scalar in the range (0 100)

Tolerance level of the state, specified as a positive scalar in the range (0 100).

This value determines how much a signal can deviate from the low- or high-state level before it is considered to be outside that state. Specify this value as a percentage of the difference between the high- and low-state levels. For more details, see “State-Level Tolerances” on page 2-1689.

#### Scope Window Use

On the **Measurements** tab, in the **Measurements** section, click **Bilevel Settings**. Under **State Level**, specify a positive scalar less than 100 in the **State Level Tol. (%)** box.

Data Types: `double`

### `UpperReferenceLevel` — Upper-reference level

`90` (default) | positive scalar in the range (0 100)

Upper-reference level, specified as a positive scalar in the range (0 100). The scope uses the upper-reference level to compute the start of a fall time or the end of a rise time. Specify this value as a percentage of the difference between the high- and low-state levels.

If $S_1$ is the low-state level, $S_2$ is the high-state level, and $U$ is the upper-reference level, the waveform value corresponding to the upper-reference level is

$$S_1 + \frac{U}{100}(S_2 - S_1)\,.$$

#### Scope Window Use

On the **Measurements** tab, in the **Measurements** section, click **Bilevel Settings**. Under **Reference Level**, specify a positive scalar less than 100 in the **Upper Ref. Level (%)** box.

Data Types: `double`

### `MidReferenceLevel` — Mid-reference level

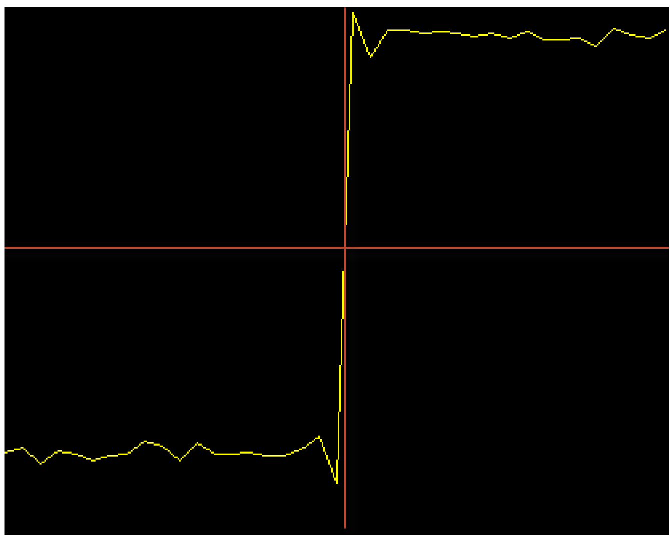
`50` (default) | positive scalar in the range (0 100)

Mid-reference level, specified as a positive scalar in the range (0 100). The scope uses the mid-reference level to determine when a transition occurs. Specify this value as a percentage of the difference between the high- and low-state levels.

The mid-reference level in a bilevel waveform with low-state level $S_1$ and high-state level $S_2$ is

$$S_1 + \frac{1}{2}(S_2 - S_1)$$

This figure shows the mid-reference level as a horizontal line, and shows its corresponding mid-reference level instant as a vertical line.



#### Scope Window Use

On the **Measurements** tab, in the **Measurements** section, click **Bilevel Settings**. Under **Reference Level**, specify a positive scalar less than 100 in the **Mid Ref. Level (%)** box.

Data Types: `double`

### `LowerReferenceLevel` — Lower-reference level

`10` (default) | positive scalar in the range (0 100)

Lower-reference level, specified as a positive scalar in the range (0 100). The scope uses the lower-reference level to compute the end of a fall time or the start of a rise time. Specify this value as a percentage of the difference between the high- and low-state levels.

If $S_1$ is the low-state level, $S_2$ is the high-state level, and $L$ is the lower-reference level, the waveform value corresponding to the lower-reference level is

$$S_1 + \frac{L}{100}(S_2 - S_1)\,.$$

#### Scope Window Use

On the **Measurements** tab, in the **Measurements** section, click **Bilevel Settings**. Under **Reference Level**, specify a positive scalar less than 100 in the **Lower Ref. Level (%)** box.

Data Types: `double`

### `SettleSeek` — Time duration over which to search for a settling time

`0.02` (default) | positive scalar

Time duration over which the scope searches for a settling time, specified as a positive scalar in seconds.

#### Scope Window Use

On the **Measurements** tab, in the **Measurements** section, click **Bilevel Settings**. Under **Reference Level**, specify a positive scalar in the **Settle Seek (s)** box.

Data Types: `double`

**`ShowTransitions` — Enable transition measurements**
`false` (default) | `true`

Enable transition measurements, specified as `true` or `false`. For more information on the transition measurements that the scope displays, see "Transitions Pane".

**Scope Window Use**

On the **Measurements** tab, in the **Measurements** section, click **Bilevel Settings** and select **Transitions**. A **Transitions** pane opens at the bottom of the Time Scope window to show the transition measurements.

Data Types: `logical`

**`ShowAberrations` — Enable aberration measurements**
`false` (default) | `true`

Enable aberration measurements, specified as `true` or `false`. Aberration measurements include distortion and damping measurements such as preshoot, overshoot, and undershoot. For more information on the aberration measurements that the scope displays, see "Overshoots / Undershoots Pane".

**Scope Window Use**

On the **Measurements** tab, in the **Measurements** section, click **Bilevel Settings** and select **Aberrations**. An **Aberrations** pane opens at the bottom of the Time Scope window to show the aberration measurements.

Data Types: `logical`

**`ShowCycles` — Enable cycle measurements**
`false` (default) | `true`

Enable cycle measurements, specified as `true` or `false`. These measurements are related to repetitions or trends in the displayed portion of the input signal. For more information on the cycle measurements, see "Cycles Pane".

**Scope Window Use**

On the **Measurements** tab, in the **Measurements** section, click **Bilevel Settings** and select **Cycles**. A **Cycles** pane opens at the bottom of the Time Scope window to show the cycle measurements.

Data Types: `logical`

## Examples

### Configure Bilevel Measurements Programmatically in Time Scope MATLAB Object

Create a sine wave and view it in the Time Scope. Programmatically compute the bilevel measurements related to signal transitions, aberrations, and cycles.

#### Initialization

Create the input sine wave using the `sin` function. Create a `timescope` MATLAB® object to display the signal. Set the `TimeSpan` property to 1 second.

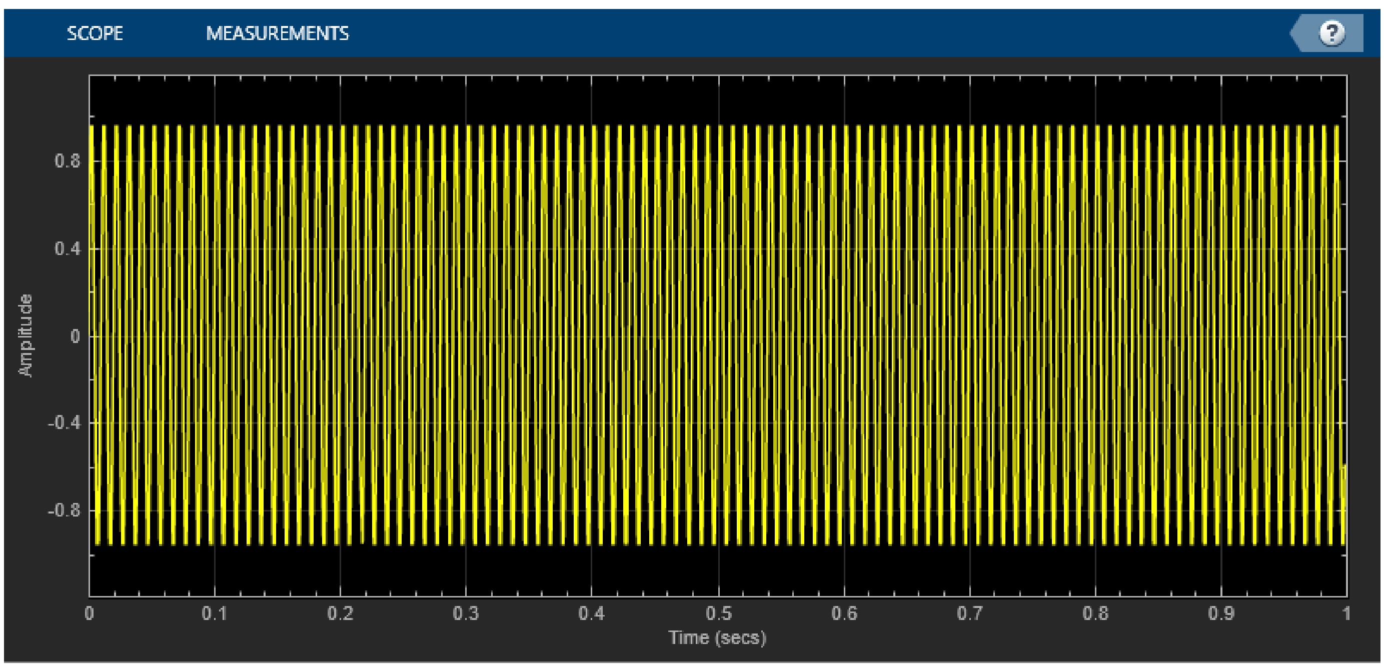
```
f = 100;
fs = 1000;
swv = sin(2.*pi.*f.*(0:1/fs:1-1/fs)).';
scope = timescope(SampleRate=fs,...
    TimeSpanSource="property",...
    TimeSpan=1);
```

#### Transition Measurements

Enable the scope to show transition measurements programmatically by setting the `ShowTransitions` property to `true`. Display the sine wave in the scope.

Transition measurements such as rise time, fall time, and slew rate appear in the **Transitions** pane at the bottom of the scope.

```
scope.BilevelMeasurements.ShowTransitions = true;
scope(swv);
release(scope);
```




Transitions

| Channel 1 | Count | Rise Time (ms) | Fall Time (ms) | Slew Rate (/ms) |
|---|---|---|---|---|
| + Edges | 99.0000 | 1.5792e+0 | | 5.8779e-1 |
| - Edges | 100.0000 | | 1.5792e+0 | -5.8779e-1 |

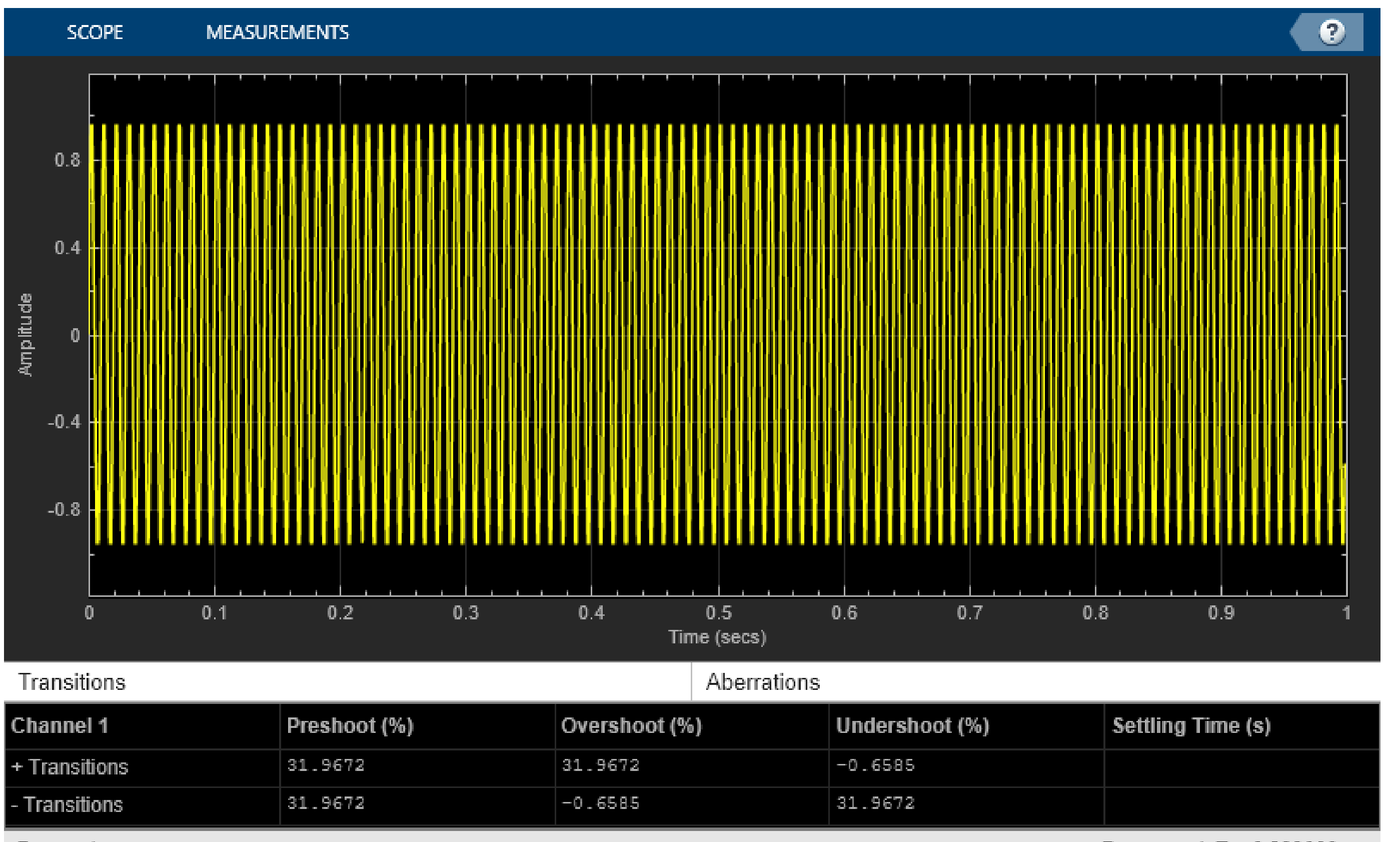
Stopped    Frames = 1  T = 0.999000

#### Aberration Measurements

Enable the scope to show aberration measurements programmatically by setting the `ShowAberrations` property to `true`. Display the sine wave in the scope.

Aberration measurements such as preshoot, overshoot, undershoot, and settling time appear in the **Aberrations** pane at the bottom of the scope.

```
scope.BilevelMeasurements.ShowAberrations = true;
scope(swv);
release(scope);
```

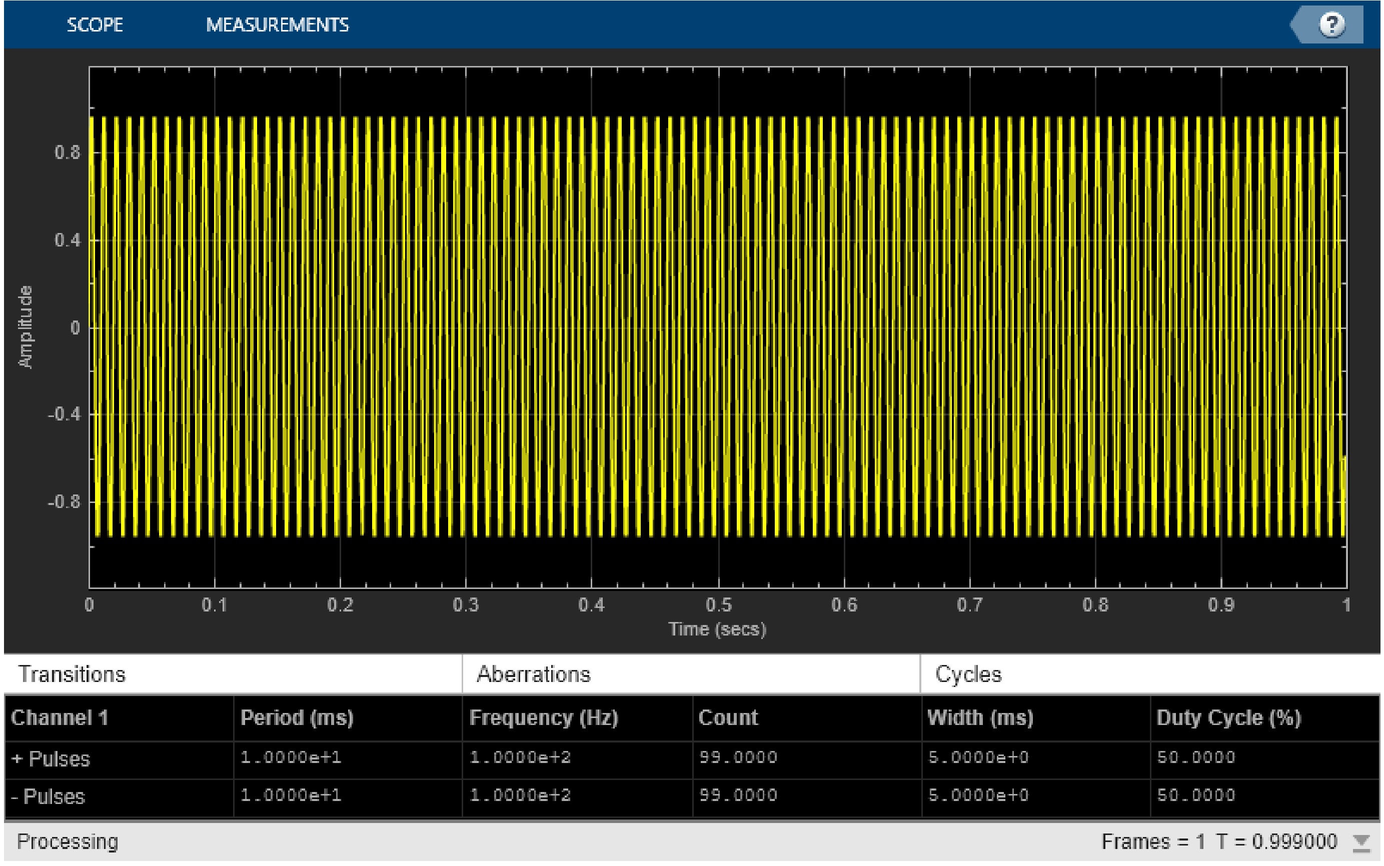



### Cycle Measurements

Enable the scope to show cycles measurements programmatically by setting the `ShowCycles` property to `true`. Display the sine wave in the scope.

Cycle measurements such as period, frequency, pulse width, and duty cycle appear in the **Cycles** pane at the bottom of the scope.

```
scope.BilevelMeasurements.ShowCycles = true;
scope(swv);
release(scope);
```




| Channel 1 | Period (ms) | Frequency (Hz) | Count | Width (ms) | Duty Cycle (%) |
|---|---|---|---|---|---|
| + Pulses | 1.0000e+1 | 1.0000e+2 | 99.0000 | 5.0000e+0 | 50.0000 |
| - Pulses | 1.0000e+1 | 1.0000e+2 | 99.0000 | 5.0000e+0 | 50.0000 |

## More About

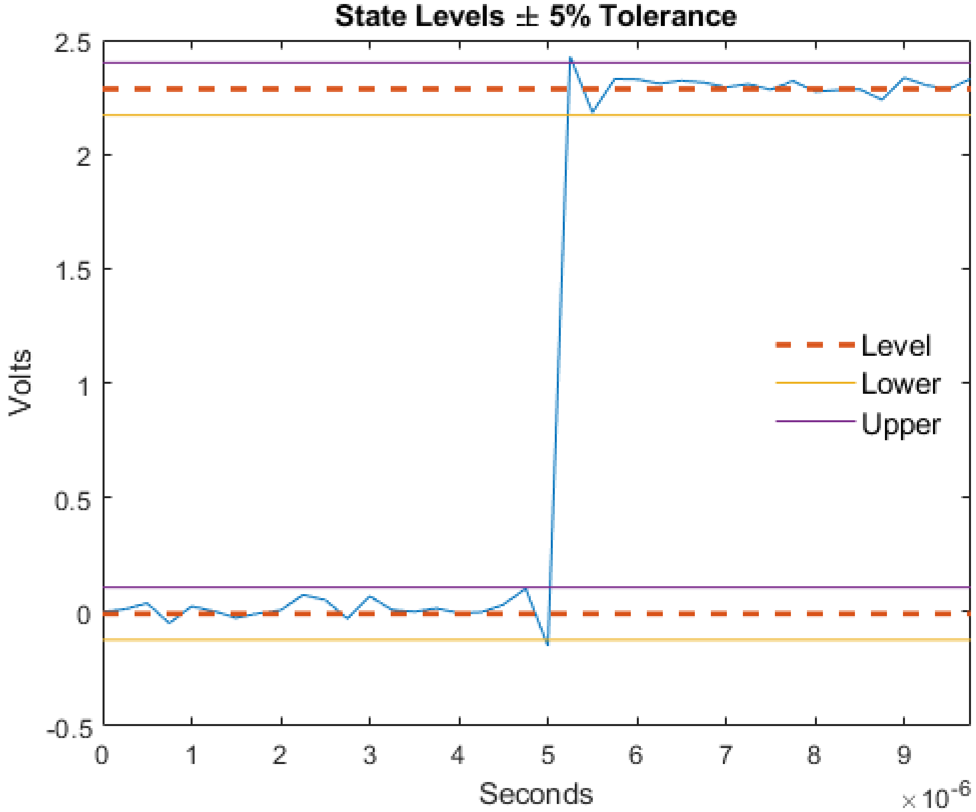
### State-Level Tolerances

You can specify lower- and upper-state boundaries for each state level. Define the boundaries as the state level plus or minus a scalar multiple of the difference between the high state and the low state. To provide a useful tolerance region, specify the scalar as a small number such as 2/100 or 3/100. In general, the $\alpha\%$ region for the low state is defined as

$$S_1 \pm \frac{\alpha}{100}(S_2 - S_1),$$

where $S_1$ is the low-state level and $S_2$ is the high-state level. Replace the first term in the equation with $S_2$ to obtain the $\alpha\%$ tolerance region for the high state.

This figure shows lower and upper 5% state boundaries (tolerance regions) for a positive-polarity bilevel waveform. The thick dashed lines indicate the estimated state levels.




## Version History

**Introduced in R2022a**

## See Also

`timescope`

**Topics**

"Configure Time Scope MATLAB Object"

# SignalStatisticsConfiguration

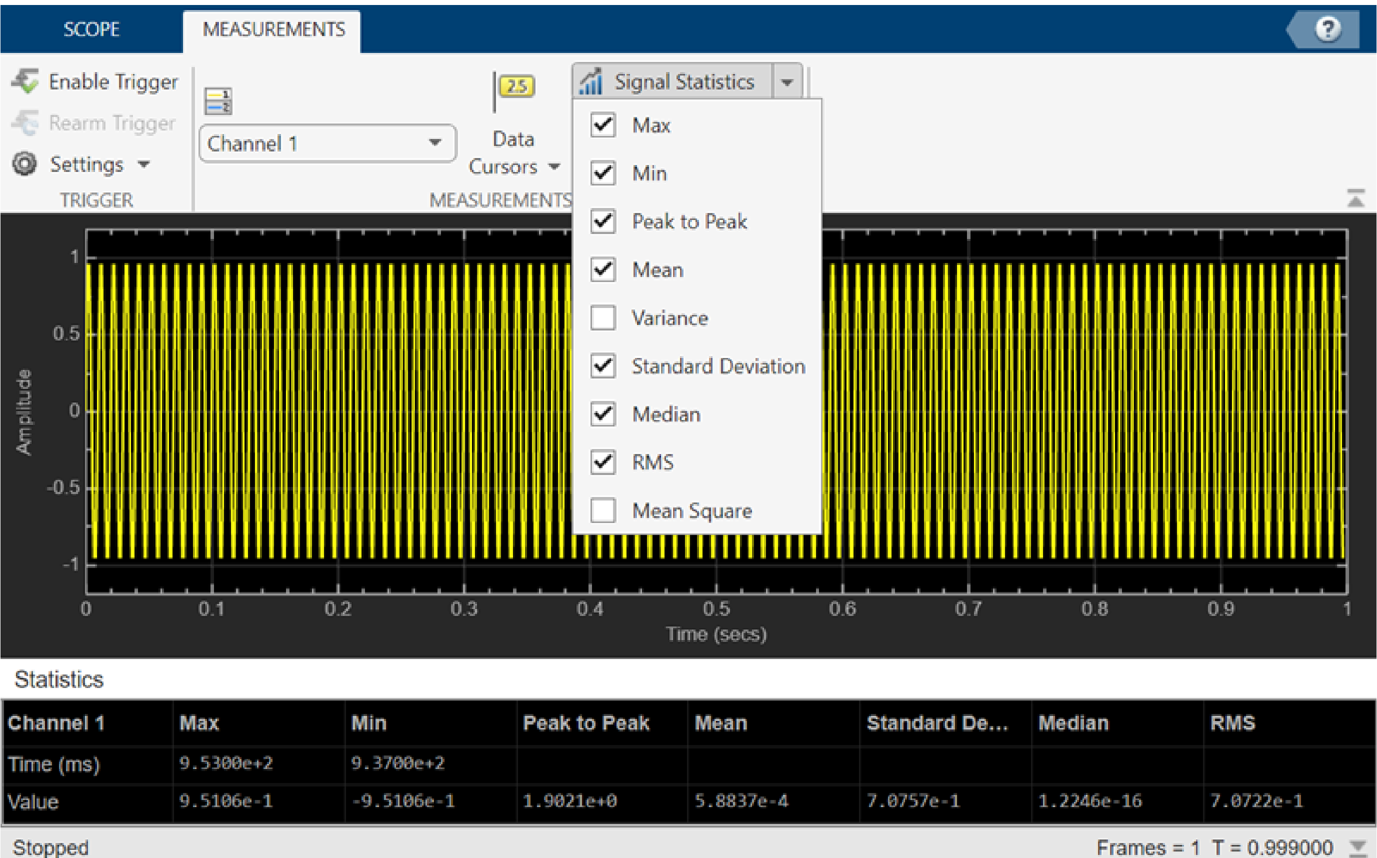
Compute and display signal statistics

## Description

Use the `SignalStatisticsConfiguration` object to measure signal statistics such as maximum, minimum, peak-to-peak value, mean, variance, standard deviation, median, RMS, and mean square.

You can enable the scope to compute and display signal statistics from the toolstrip or from the command line. To enable from the scope interface, click the **Measurements** tab, and then click **Signal Statistics**. A statistics panel appears at the bottom of the scope window. To enable specific statistics, click the **Signal Statistics** drop-down list and select a statistic from the options. The **Statistics** panel shows those statistics.

**Time Scope**



# Creation

## Syntax

`signalStats = SignalStatisticsConfiguration()`

### Description

`signalStats = SignalStatisticsConfiguration()` creates a signal statistics configuration object `signalStats`.

# Properties

All properties are tunable.

**`ShowMax` — Compute and display maximum**
`true` (default) | `false`

Compute and display the maximum value, specified as `true` or `false`. The scope computes and displays the maximum value of the portion of the input signal that is currently on display in the scope.

**Scope Window Use**

On the **Measurements** tab, select **Signal Statistics** and then click **Signal Statistics** to select **Max**.

Data Types: `logical`

**`ShowMin` — Compute and display minimum**
`true` (default) | `false`

Compute and display the minimum value, specified as `true` or `false`. The scope computes and displays the minimum value of the portion of the input signal that is currently on display in the scope.

**Scope Window Use**

On the **Measurements** tab, select **Signal Statistics** and then click **Signal Statistics** to select **Min**.

Data Types: `logical`

**`ShowPeakToPeak` — Compute and display peak-to-peak values**
`true` (default) | `false`

Compute and display the peak-to-peak values, specified as `true` or `false`. The scope computes and displays the peak-to-peak values from the portion of the input signal that is currently on display in the scope.

**Scope Window Use**

On the **Measurements** tab, select **Signal Statistics** and then click **Signal Statistics** to select **Peak to Peak**.

Data Types: `logical`

**`ShowMean` — Compute and display mean**
`true` (default) | `false`

Compute and display the mean value, specified as `true` or `false`. The scope computes and displays the mean value of the portion of the input signal that is currently on display in the scope.

**Scope Window Use**

On the **Measurements** tab, select **Signal Statistics** and then click **Signal Statistics** to select **Mean**.

Data Types: `logical`

### `ShowVariance` — Compute and display variance

`false` (default) | `true`

Compute and display the variance, specified as `true` or `false`. The scope computes and displays the variance of the portion of the input signal that is currently on display in the scope.

**Scope Window Use**

On the **Measurements** tab, select **Signal Statistics** and then click **Signal Statistics** to select **Variance**.

Data Types: `logical`

### `ShowStandardDeviation` — Compute and display standard deviation

`true` (default) | `false`

Compute and display the standard deviation, specified as `true` or `false`. The scope computes and displays the standard deviation of the portion of the input signal that is currently on display in the scope.

**Scope Window Use**

On the **Measurements** tab, select **Signal Statistics** and then click **Signal Statistics** to select **Standard Deviation**.

Data Types: `logical`

### `ShowMedian` — Compute and display median

`true` (default) | `false`

Compute and display the median, specified as `true` or `false`. The scope computes and displays the median of the portion of the input signal that is currently on display in the scope.

**Scope Window Use**

On the **Measurements** tab, select **Signal Statistics** and then click **Signal Statistics** to select **Median**.

Data Types: `logical`

### `ShowRMS` — Compute and display RMS

`true` (default) | `false`

Compute and display the RMS, specified as `true` or `false`. The scope computes and displays the RMS of the portion of the input signal that is currently on display in the scope.

**Scope Window Use**

On the **Measurements** tab, select **Signal Statistics** and then click **Signal Statistics** to select **RMS**.

Data Types: `logical`

#### `ShowMeanSquare` — Compute and display mean square
`false` (default) | `true`

Compute and display the mean square, specified as `true` or `false`. The scope computes and displays the mean square of the portion of the input signal that is currently on display in the scope.

##### Scope Window Use

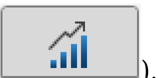
On the **Measurements** tab, select **Signal Statistics** and then click **Signal Statistics** to select **Mean Square**.

Data Types: `logical`

#### `Enabled` — Enable signal statistics measurements
`false` (default) | `true`

Enable signal statistics measurements, specified as `true` or `false`. Set this property to `true` to enable signal statistics measurements.

##### Scope Window Use

On the **Measurements** tab, select **Signal Statistics**().

Data Types: `logical`

## Examples

### Configure Signal Statistics Programmatically in Time Scope MATLAB Object

Create a sine wave and view it in the Time Scope. Enable the scope programmatically to compute the signal statistics.

The object supports these signal statistics:

- Maximum
- Minimum
- Mean
- Median
- RMS
- Peak to peak
- Variance
- Standard deviation
- Mean square

#### Initialization

Create the input sine wave using the `sin` function. Create a `timescope` MATLAB® object to display the signal. Set the `TimeSpan` property to 1 second.

```
f = 100;
fs = 1000;
swv = sin(2.*pi.*f.*(0:1/fs:1-1/fs)).';
scope = timescope(SampleRate=fs,...
    TimeSpanSource="property",...
    TimeSpan=1);
```

#### Signal Statistics

Enable the scope to show signal statistics programmatically by setting the `SignalStatistics` > `Enabled` property to `true`.

```
scope.SignalStatistics.Enabled = true;
```

By default, the scope enables the following measurements.

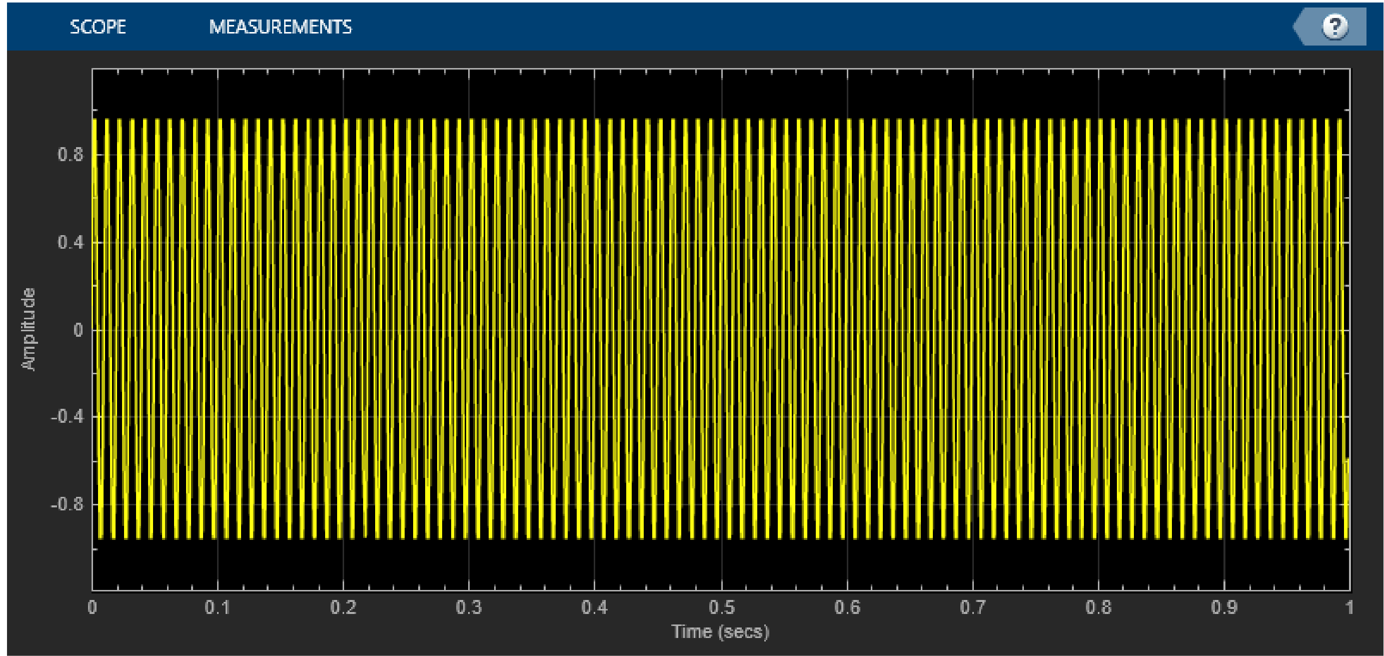
```
scope.SignalStatistics
```

```
ans = 
  SignalStatisticsConfiguration with properties:

                 ShowMax: 1
                 ShowMin: 1
          ShowPeakToPeak: 1
                ShowMean: 1
            ShowVariance: 0
   ShowStandardDeviation: 1
              ShowMedian: 1
                 ShowRMS: 1
          ShowMeanSquare: 0
                 Enabled: 1
```

Display the sine wave in the scope. A Statistics pane appears at the bottom of the scope window displaying the statistics for the portion of the signal that you can see in the scope.

If you use the zoom options on the scope, the statistics automatically adjust to the time range in the display.

```
scope(swv);
release(scope);
```




Statistics

| Channel 1 | Max | Min | Peak to Peak | Mean | Standard De... | Median | RMS |
|---|---|---|---|---|---|---|---|
| Time (ms) | 9.5300e+2 | 9.3700e+2 | | | | | |
| Value | 9.5106e-1 | -9.5106e-1 | 1.9021e+0 | 9.5201e-4 | 7.0717e-1 | 1.2246e-16 | 7.0682e-1 |

Stopped Frames = 1 T = 0.999000

## Version History

**Introduced in R2022a**

## See Also

`timescope`

### Topics

"Configure Time Scope MATLAB Object"

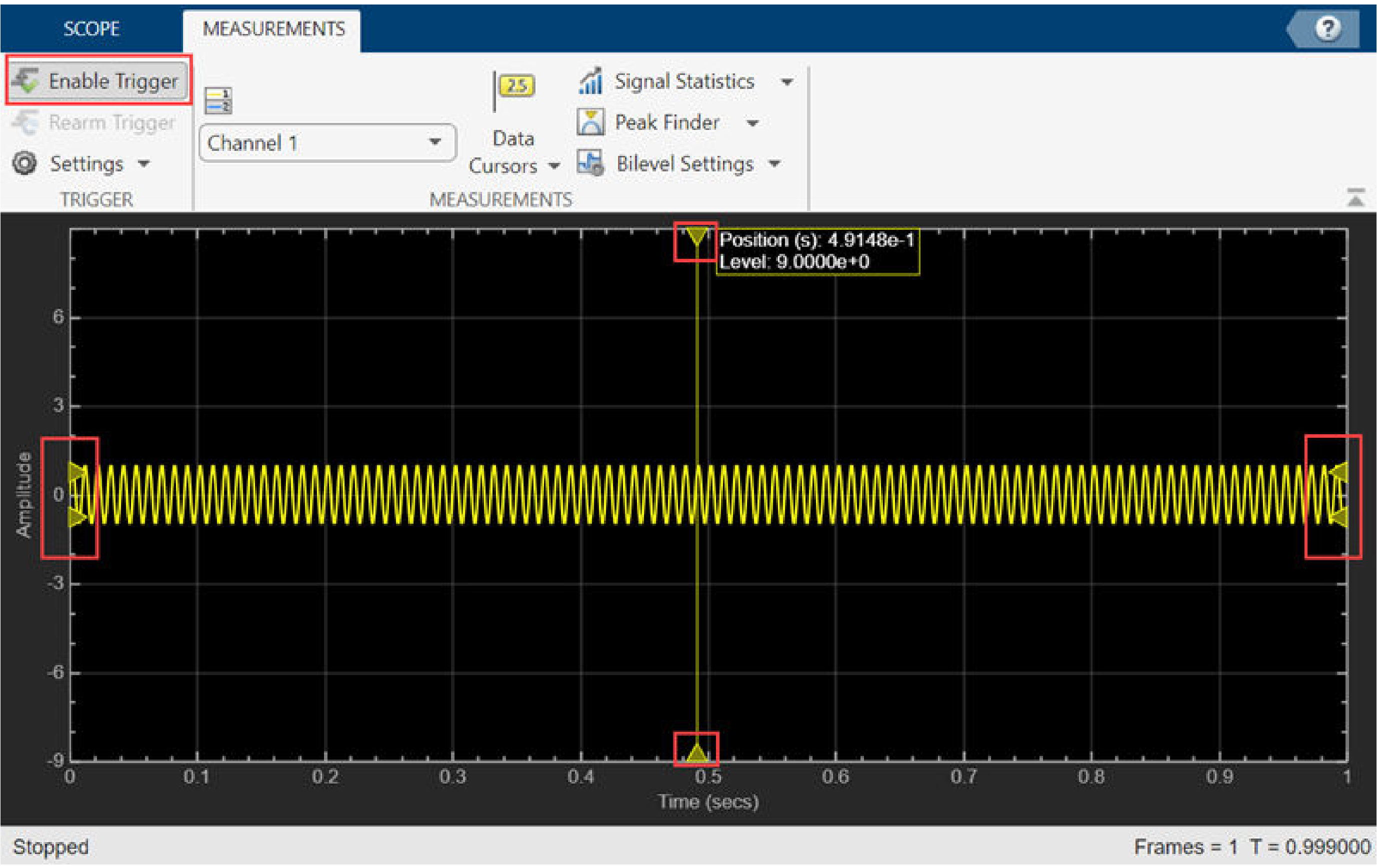
# TriggerConfiguration

Trigger measurements properties for scope

## Description

Use the `TriggerConfiguration` object to define a trigger event to identify the simulation time of specified input signal characteristics. You can use trigger events to stabilize periodic signals such as a sine wave or capture nonperiodic signals such as a pulse that occurs intermittently.

You can enable the trigger events either from the Time Scope toolstrip or from the command line. To enable a trigger event from the toolstrip, open the **Measurements** tab and click **Enable Trigger**.




## Creation

### Syntax

```
trigger = TriggerConfiguration()
```

#### Description

`trigger = TriggerConfiguration()` creates a trigger configuration object `trigger`.

## Properties

All properties are tunable.

For more information on these triggers and the associated parameters, see “Source/Type and Levels/Timing Panes”.

**Mode — Display update mode**
"auto" (default) | "normal" | "once"

Display update mode, specified as one of these:

- "auto" –– Display data from the last trigger event. If no event occurs after one time span, display the last available data.
- "normal" –– Display data from the last trigger event. If no event occurs, the display remains blank.
- "once" –– Display data from the last trigger event and freeze the display. If no event occurs, the display remains blank. Click the **Rearm** button ( ) to look for the next trigger event.

##### Scope Window Use

On the **Measurements** tab, in the **Trigger** section, click **Settings** and set **Mode** to one of the available options.

Data Types: char | string

**Type — Type of trigger**
"edge" (default) | "pulse-width" | "transition" | "runt" | "window" | "timeout"

Type of trigger, specified as one of the following:

- "edge" –– Trigger when the signal crosses a threshold.
- "pulse-width" –– Trigger when the signal crosses a low threshold and a high threshold twice within a specified time.
- "transition" –– Trigger on the rising or falling edge of a signal that crosses the high and low levels within a specified time range.
- "runt" –– Trigger when a signal crosses a low threshold or a high threshold twice within a specified time.
- "window" –– Trigger when a signal stays within or outside a region defined by the high and low thresholds for a specified time.
- "timeout" –– Trigger when a signal stays above or below a threshold longer than a specified time.

##### Scope Window Use

On the **Measurements** tab, in the **Trigger** section, click **Settings** and set **Type** to one of the available options.

Data Types: `char` | `string`

**`Polarity` — Trigger polarity**
`"rising"` (default) | `"falling"` | `"either"` | `"positive"` | `"negative"` | `"rise-time"` | `"fall-time"` | `"inside"` | `"outside"`

Trigger polarity, specified as one of the following:

- `"rising"`, `"falling"`, or `"either"` -– When `Type` is set to `"edge"` or `"timeout"`.
- `"positive"`, `"negative"`, or `"either"` -– When `Type` is set to `"pulse-width"` or `"runt"`.
- `"rise-time"`, `"fall-time"`, or `"either"` -– When `Type` is set to `"transition"`.
- `"inside"`, `"outside"`, or `"either"` -– When `Type` is set to `"window"`.

**Scope Window Use**

On the **Measurements** tab, in the **Trigger** section, click **Settings** and set **Polarity** to one of the available options.

Data Types: `char` | `string`

**`AutoLevel` — Automatic thresholding**
`true` (default) | `false`

Automatic thresholding of edge-triggered signal, specified as `true` or `false`. When you set this property to false, specify the threshold manually using the `Level` property.

**Scope Window Use**

On the **Measurements** tab, in the **Trigger** section, click **Settings**. Under **Level Settings**, select **Auto Level**.

Data Types: `logical`

**`Position` — Horizontal position of trigger**
`50` (default) | positive scalar in the range (0 100]

Horizontal position of the trigger on the screen, specified as a positive scalar in the range (0 100].

**Scope Window Use**

On the **Measurements** tab, in the **Trigger** section, click **Settings** and specify a positive scalar less than or equal to 100 in the **Position (%)** box.

Data Types: `double`

**`Level` — Threshold of edge-triggered signal**
`0` (default) | real scalar

Threshold of an edge-triggered signal, specified as a finite real scalar.

**Dependency**

To enable this property, set `AutoLevel` to `false` and `Type` to `"edge"` or `"timeout"`.

**Scope Window Use**

On the **Measurements** tab, in the **Trigger** section, click **Settings**. Under **Level Settings**, clear **Auto Level** and specify a real scalar in the **Level** box.

To enable this property, set **Type** to `Edge` or `Timeout`.

Data Types: `double`

#### `Hysteresis` — Noise reject value
`0` (default) | real scalar

Noise reject value, specified as a finite real scalar. For more information on hysteresis, see "Hysteresis of Trigger Signals".

##### Dependency

To enable this property, set `AutoLevel` to `false` and `Type` to `"edge"` or `"timeout"`.

##### Scope Window Use

On the **Measurements** tab, in the **Trigger** section, click **Settings**. Under **Level Settings**, clear **Auto Level** and specify a real scalar in the **Hysteresis** box.

To enable this property, set **Type** to `Edge` or `Timeout`.

Data Types: `double`

#### `LowLevel` — Lower trigger level of window-triggered signal
`0.2` (default) | real scalar

Lower trigger level of window-triggered signal, specified as a finite real scalar.

##### Dependency

To enable this property, set `AutoLevel` to `false` and `Type` to `"pulse-width"`, `"transition"`, `"runt"`, or `"window"`.

##### Scope Window Use

On the **Measurements** tab, in the **Trigger** section, click **Settings**. Under **Level Settings**, clear **Auto Level** and specify a real scalar in the **Low** box.

To enable this property, set **Type** to `Pulse Width`, `Transition`, `Runt`, or `Window`.

Data Types: `double`

#### `HighLevel` — Higher trigger level of window-triggered signal
`2.3` (default) | real scalar

Higher trigger level of window-triggered signal, specified as a finite real scalar.

##### Dependency

To enable this property, set `AutoLevel` to `false` and `Type` to `"pulse-width"`, `"transition"`, `"runt"`, or `"window"`.

##### Scope Window Use

On the **Measurements** tab, in the **Trigger** section, click **Settings**. Under **Level Settings**, clear **Auto Level** and specify a real scalar in the **High** box.

To enable this property, set **Type** to `Pulse Width`, `Transition`, `Runt`, or `Window`.

Data Types: `double`

### `MinPulseWidth` — Minimum pulse width for pulse or runt-triggered signal
`0` (default) | nonnegative scalar

Minimum pulse width for a pulse or runt-triggered signal, specified as a nonnegative scalar.

#### Dependency

To enable this property, set `Type` to `"pulse-width"` or `"runt"`.

#### Scope Window Use

On the **Measurements** tab, in the **Trigger** section, click **Settings**. Under **Level Settings**, specify a nonnegative scalar in the **Min Width (s)** box.

To enable this property, set **Type** to `Pulse Width` or `Runt`.

Data Types: `double`

### `MaxPulseWidth` — Maximum pulse width for pulse or runt-triggered signal
`Inf` (default) | nonnegative scalar

Maximum pulse width for a pulse or runt-triggered signal, specified as a nonnegative scalar.

#### Dependency

To enable this property, set `Type` to `"pulse-width"` or `"runt"`.

#### Scope Window Use

On the **Measurements** tab, in the **Trigger** section, click **Settings**. Under **Level Settings**, specify a nonnegative scalar in the **Max Width (s)** box.

To enable this property, set **Type** to `Pulse Width` or `Runt`.

Data Types: `double`

### `MinDuration` — Minimum duration for transition or window-triggered signal
`0` (default) | nonnegative scalar

Minimum duration for a transition or window-triggered signal, specified as a nonnegative scalar.

#### Dependency

To enable this property, set `Type` to `"transition"` or `"window"`.

#### Scope Window Use

On the **Measurements** tab, in the **Trigger** section, click **Settings**. Under **Level Settings**, specify a nonnegative scalar in the **Min Time (s)** box.

To enable this property, set **Type** to `Transition` or `Window`.

Data Types: `double`

### `MaxDuration` — Maximum duration for transition or window-triggered signal
`Inf` (default) | nonnegative scalar

Maximum time duration for a transition or window-triggered signal, specified as a nonnegative scalar.

#### Dependency

To enable this property, set `Type` to `"transition"` or `"window"`.

#### Scope Window Use

On the **Measurements** tab, in the **Trigger** section, click **Settings**. Under **Level Settings**, specify a nonnegative scalar in the **Max Time (s)** box.

To enable this property, set **Type** to `Transition` or `Window`.

Data Types: `double`

### `Timeout` — Timeout duration
`0` (default) | nonnegative scalar

Timeout duration for a timeout-triggered signal, specified as a nonnegative scalar.

#### Dependency

To enable this property, set `Type` to `"timeout"`.

#### Scope Window Use

On the **Measurements** tab, in the **Trigger** section, click **Settings**. Under **Level Settings**, specify a nonnegative scalar in the **Timeout (s)** box.

To enable this property, set **Type** to `Timeout`.

Data Types: `double`

### `Delay` — Trigger offset
`0` (default) | real scalar

Trigger offset in seconds, specified as a finite real scalar.

#### Scope Window Use

On the **Measurements** tab, in the **Trigger** section, click **Settings**. Under **Delay/Holdoff**, specify a real scalar in the **Delay (s)** box.

Data Types: `double`

### `Holdoff` — Minimum time between triggers
`0` (default) | nonnegative scalar

Minimum time between trigger events, specified as a finite nonnegative scalar.

#### Scope Window Use

On the **Measurements** tab, in the **Trigger** section, click **Settings**. Under **Delay/Holdoff**, specify a nonnegative scalar in the **Holdoff (s)** box.

Data Types: `double`

### `Channel` — Trigger channel
`1` (default) | positive integer

Trigger channel, specified as a positive integer.

#### Scope Window Use

On the **Measurements** tab, in the **Measurements** section, select a channel.

Data Types: `double`

**Enabled — Enable trigger**
`false` (default) | `true`

Enable trigger, specified as `true` or `false`. Set this property to `true` to enable trigger.

#### Scope Window Use

On the **Measurements** tab, in the **Trigger** section, click **Enable Trigger**.

Data Types: `logical`

## Examples

### Enable Trigger Programmatically in Time Scope MATLAB Object

View a sine wave in the Time Scope window. This sine wave is streaming constantly in the display and cannot be captured without stabilization. To stabilize the sine wave, enable a trigger event programmatically on the scope display using the `Enabled` property of the `TriggerConfiguration` object. Alternatively, you can enable the trigger by clicking the **Enable Trigger** button on the **Measurements** tab of the toolstrip.

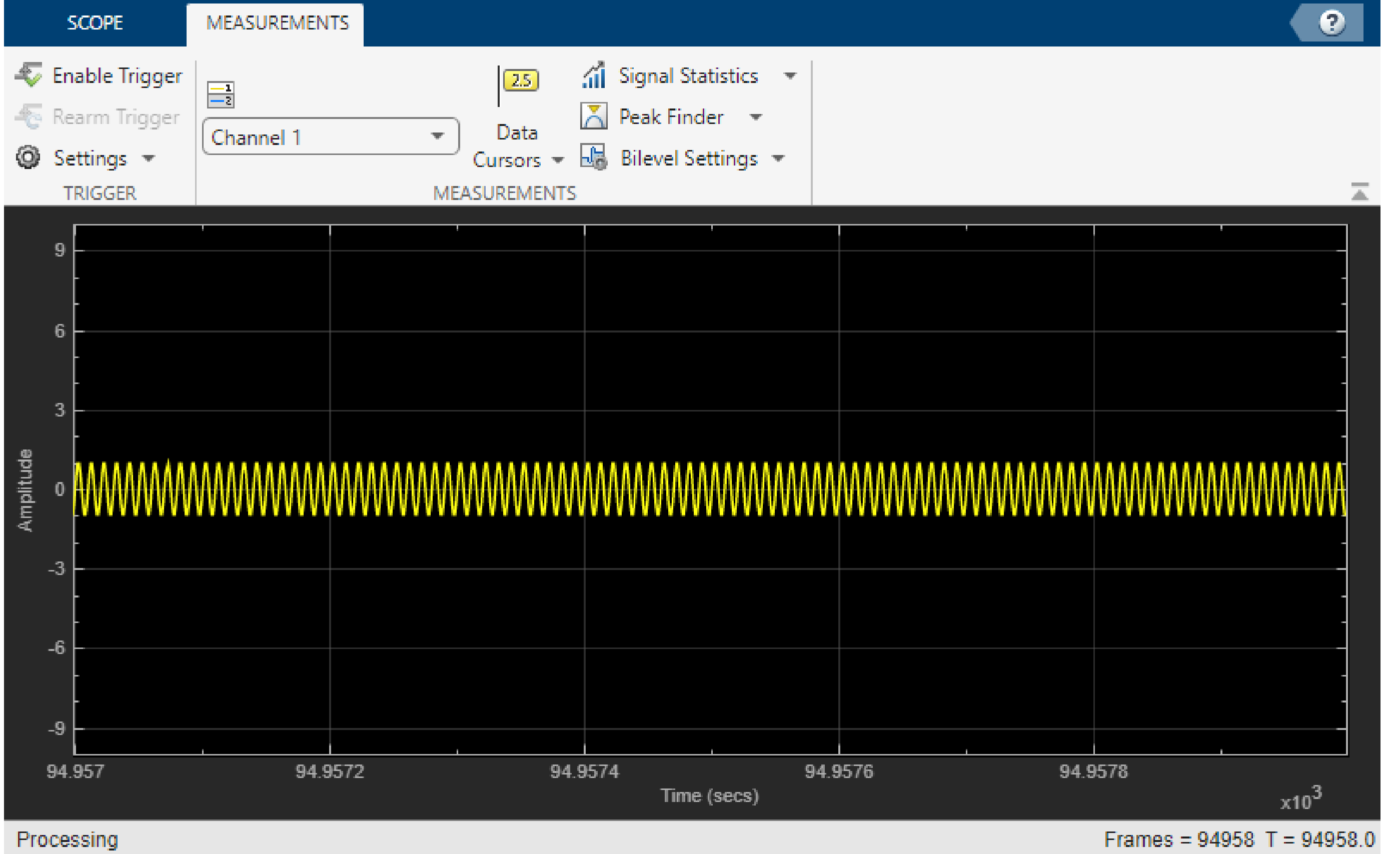
#### Create Sine Wave

Create the input sine wave using the `sin` function. Create a `timescope` MATLAB object to display the signal. Set the `TimeSpan` property to 1 second.

```
f = 100;
fs = 1000;
swv = sin(2.*pi.*f.*(0:1/fs:1-1/fs)).';
scopeNoTrigger = timescope(SampleRate=fs,...
    TimeSpanSource="property", ...
    TimeSpan=1);
```

Display the sine wave in the scope. You can see that the signal in the scope is constantly moving.

```
while(1)
    scopeNoTrigger(swv)
end
release(scopeNoTrigger)
```




**Enable Trigger**

Now enable a trigger event to stabilize the signal.

You can enable the trigger event in the scope during simulation or enable the trigger event programmatically when creating the object.

To use the programmatic approach, create another `timescope` object and enable the trigger event programmatically while creating the object.

```
scope = timescope(SampleRate=fs,...
    TimeSpanSource="property",...
    TimeSpan=1);
scope.Trigger.Enabled = true;
scope.Trigger.Type = "transition";
scope.Trigger
```

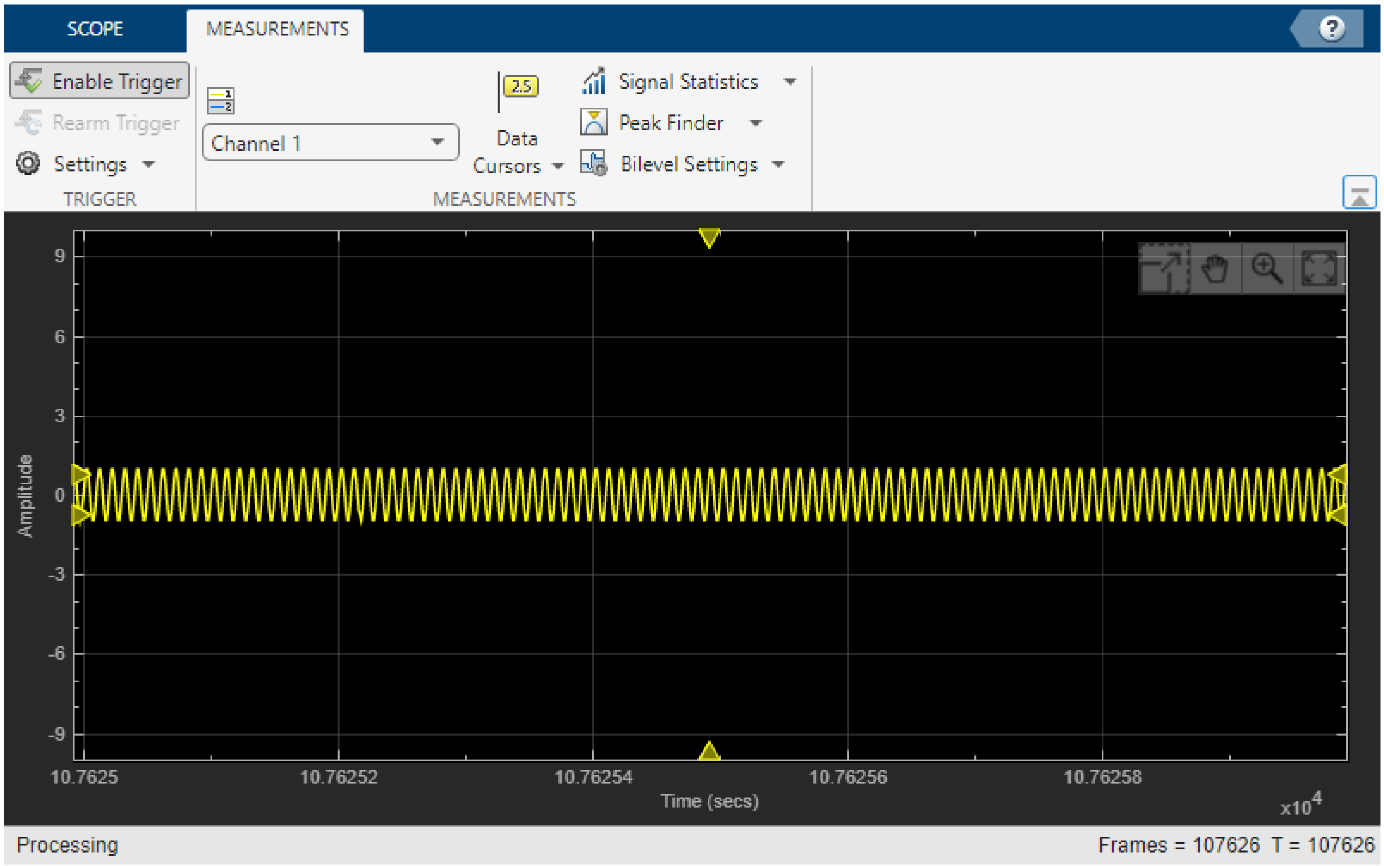
```
 TriggerConfiguration with properties:

          Mode: 'auto'
          Type: 'transition'
      Polarity: 'rise-time'
     AutoLevel: 1
      Position: 50
      LowLevel: 0.2000
     HighLevel: 2.3000
   MinDuration: 0
```

```
    MaxDuration: Inf
          Delay: 0
        Holdoff: 0
        Channel: 1
        Enabled: 1
```

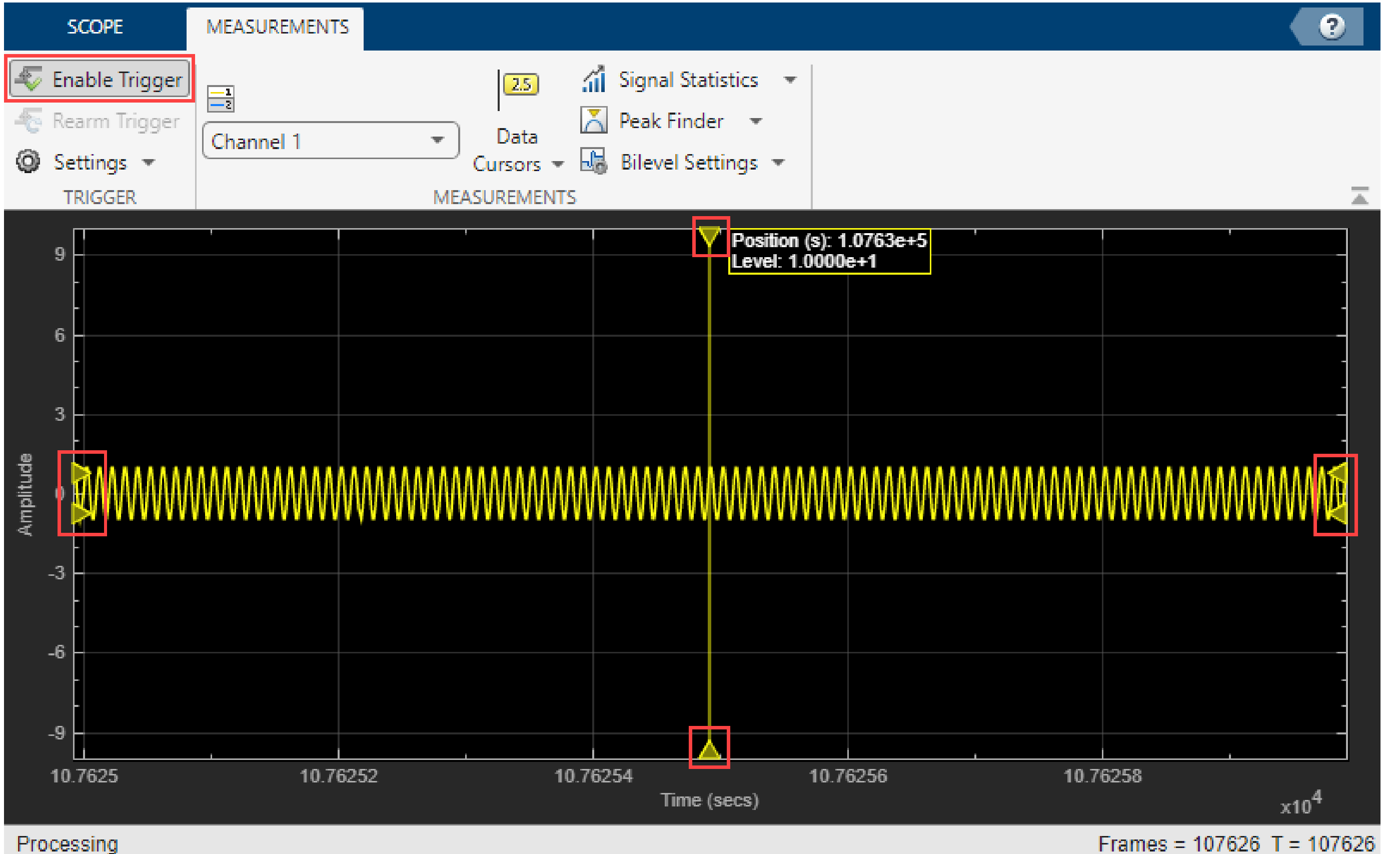
Stream in the sine wave signal again.

```
while(1)
    scope(swv)
end
release(scope)
```

The display freezes once you enable the trigger.




The triangle markers show the trigger positions and levels. For more information on the trigger, hover over the triangle.




## Version History

**Introduced in R2022a**

## See Also

`timescope`

### Topics

"Configure Time Scope MATLAB Object"

# CursorMeasurementsConfiguration

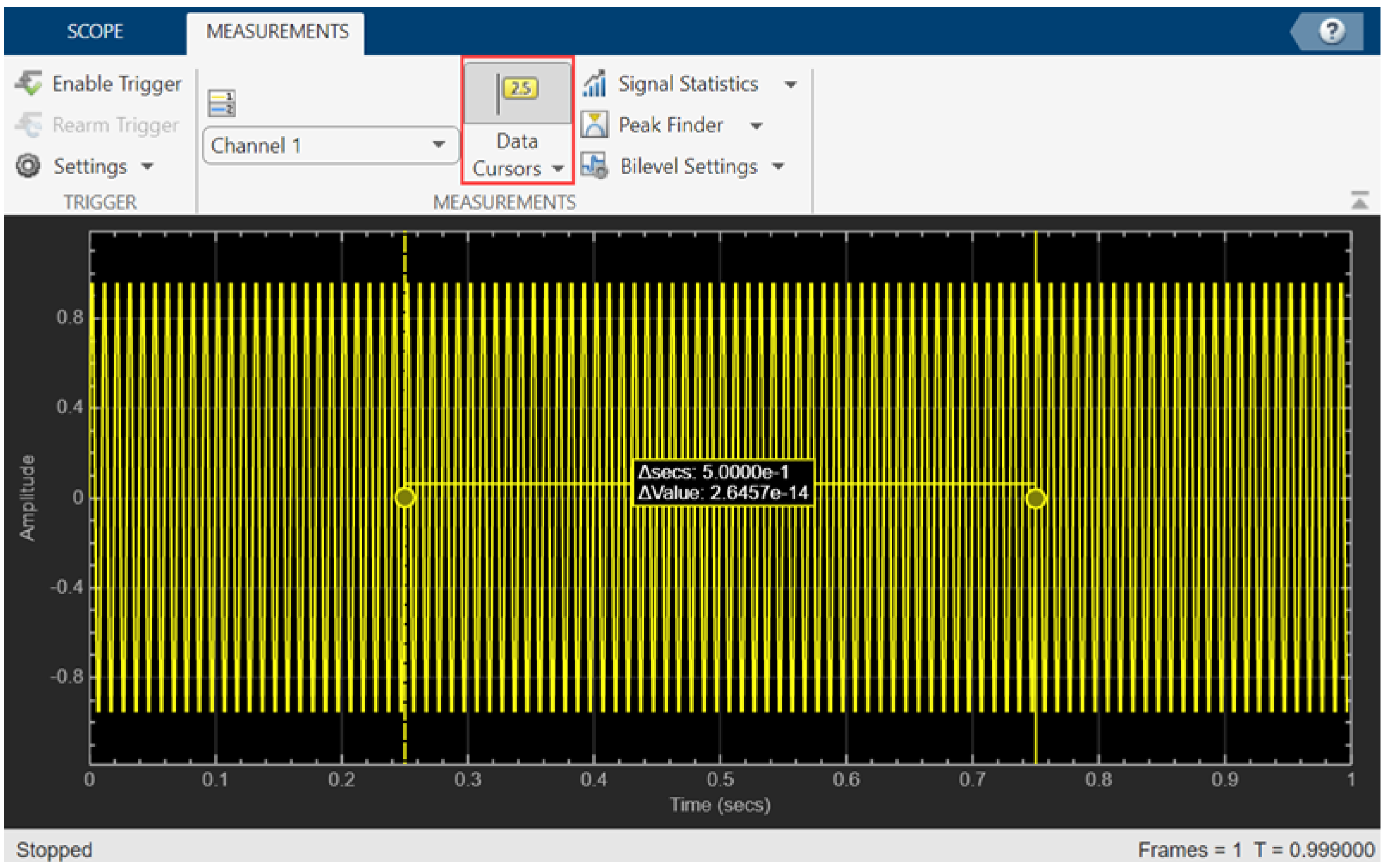
Measure signal values using vertical waveform cursors that track along the signal

## Description

Use the `CursorMeasurementsConfiguration` object to enable waveform cursors. You can control the cursor settings from the toolstrip of the scope or from the command line.

To display vertical cursors on each signal and to modify the cursor settings in the scope UI, click the **Measurements** tab and enable **Data Cursors**. Each cursor tracks a vertical line along the signal. The scope displays the difference between *x*- and *y*-values of the signal at the two cursors in the box between the cursors. The cursors appear only when the scope has at least one signal in its display. You can use the mouse to move the vertical cursors left and right.

**Time Scope Toolstrip**



# Creation

## Syntax

`cursormeas = CursorMeasurementsConfiguration()`

### Description

`cursormeas = CursorMeasurementsConfiguration()` creates a cursor measurements configuration object.

## Properties

All properties are tunable.

### `XLocation` — x-coordinates of the cursors

`[2 8]` (default) | two-element vector

*x*-coordinates of the cursors, specified as a two-element vector of real numbers.

#### Scope Window Use

On the **Measurements** tab, select **Data Cursors** and then click **Data Cursors** to specify the two elements in X location properties.

Data Types: `double`

### `SnapToData` — Position cursors on signal data points

`false` (default) | `true`

Position cursors on the signal data points, specified as `true` or `false`.

#### Scope Window Use

On the **Measurements** tab, select **Data Cursors** and then click **Data Cursors** to select **Snap to data**.

Data Types: `logical`

### `LockSpacing` — Lock spacing between cursors

`false` (default) | `true`

Lock spacing between cursors, specified as `true` or `false`. Set this property to `true` to lock the frequency difference between the cursors.

#### Scope Window Use

On the **Measurements** tab, select **Data Cursors** and then click **Data Cursors** to select **Lock cursor spacing**.

Data Types: `logical`

### `Enabled` — Enable cursor measurements

`false` (default) | `true`

Enable cursor measurements, specified as `true` or `false`. Set this property to `true` to enable cursor measurements.

**Scope Window Use**

On the **Measurements** tab, select **Data Cursors**.

Data Types: `logical`

## Examples

### Configure Cursor Measurements Programmatically in Time Scope MATLAB Object

Create a sine wave and view it in the Time Scope. Enable data cursors programmatically.

**Initialization**

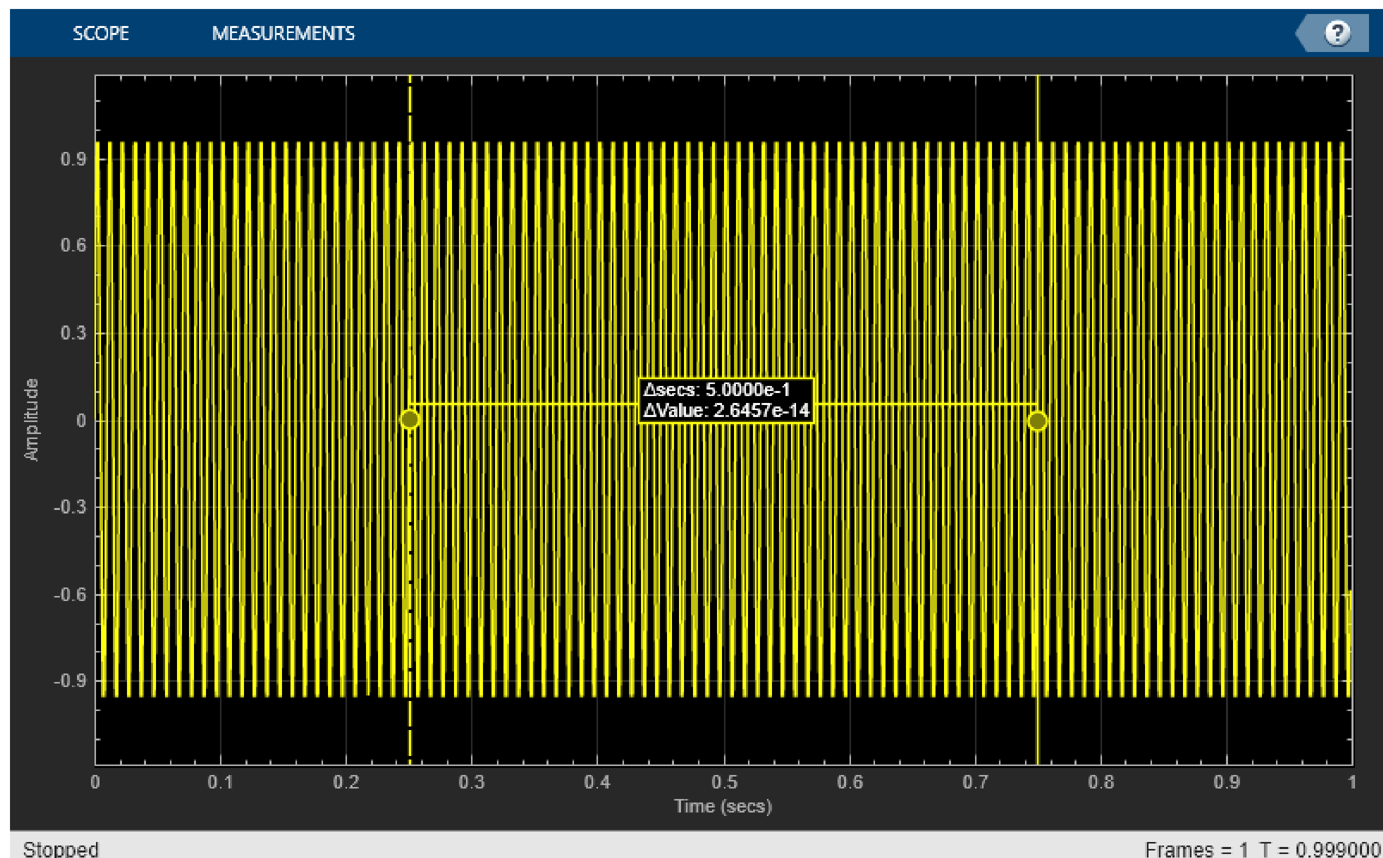
Create the input sine wave using the `sin` function. Create a `timescope` MATLAB® object to display the signal. Set the `TimeSpan` property to 1 second.

```
f = 100;
fs = 1000;
swv = sin(2.*pi.*f.*(0:1/fs:1-1/fs)).';
scope = timescope(SampleRate=fs,...
    TimeSpanSource="property",...
    TimeSpan=1);
```

**Data Cursors**

Enable data cursors in the scope programmatically by setting the `Enabled` property of the `CursorMeasurementsConfiguration` object to `true`.

```
scope.CursorMeasurements.Enabled = true;
scope(swv);
release(scope)
```




## Version History

**Introduced in R2022a**

### R2022b: Enhancements to Data Cursor Measurements

Starting in R2022b, the `CursorMeasurementsConfiguration` object has a new `LockSpacing` property. Use this property to lock the spacing between waveform cursors in the scope window.

In the **Measurements** tab of the scope UI window, these data cursor settings are new:

- **Lock cursor spacing** –– This setting corresponds to the `LockSpacing` property in the `CursorMeasurementsConfiguration` object.
- X location –– These fields are enabled and correspond to the `XLocation` property in the `CursorMeasurementsConfiguration` object.

## See Also

`timescope`

### Topics

"Configure Time Scope MATLAB Object"

# PeakFinderConfiguration

Compute and display the largest calculated peak values on the scope display

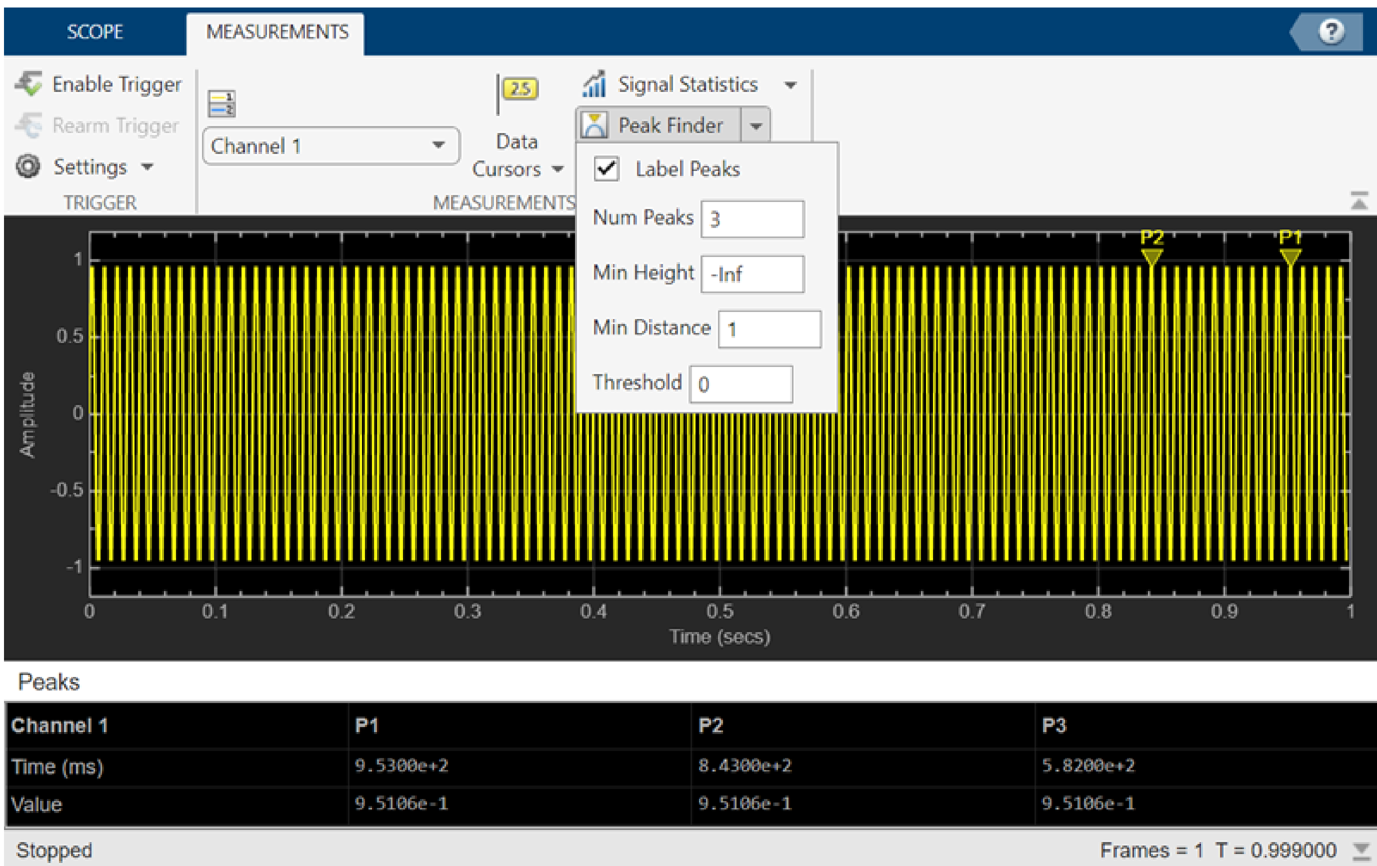
## Description

Use the `PeakFinderConfiguration` object to compute and display peaks in the scope. The scope computes and displays peaks for only the portion of the input signal that is currently on display in the scope.

You can specify the number of peaks you want the scope to display, the minimum height above which you want the scope to detect peaks, the minimum distance between peaks, and label the peaks. You can control the peak finder settings from the scope toolstrip or from the command line. The algorithm defines a peak as a local maximum with lower values present on either side of the peak. It does not consider end points as peaks. For more information on the algorithm, see the `findpeaks` function.

To modify the peak finder settings in the scope interface, click the **Measurements** tab and enable **Peak Finder**. Once you enable the **Peak Finder**, an arrow appears on the plot at each maxima and a Peaks panel appears at the bottom of the scope window.

**Time Scope Toolstrip**



# Creation

## Syntax

`pkfinder = PeakFinderConfiguration()`

### Description

`pkfinder = PeakFinderConfiguration()` creates a peak finder configuration object.

# Properties

All properties are tunable.

### `MinHeight` — Level above which scope detects peaks

`-Inf` (default) | real scalar value

Level above which the scope detects peaks, specified as a real scalar.

#### Scope Window Use

On the **Measurements** tab, select **Peak Finder**. In the peak finder settings, specify a real scalar in the **Min Height** box.

Data Types: `double`

### `NumPeaks` — Maximum number of peaks to show

`3` (default) | positive integer less than 100

Maximum number of peaks to show, specified as a positive integer less than `100`.

#### Scope Window Use

On the **Measurements** tab, select **Peak Finder**. In the peak finder settings, specify a positive integer less than 100 in the **Num Peaks** box.

Data Types: `double`

### `MinDistance` — Minimum number of samples between adjacent peaks

`1` (default) | positive integer

Minimum number of samples between adjacent peaks, specified as a positive integer.

#### Scope Window Use

On the **Measurements** tab, select **Peak Finder**. In the peak finder settings, specify a positive integer in the **Min Distance** box.

Data Types: `double`

### `Threshold` — Minimum difference in height of peak and its neighboring samples

`0` (default) | nonnegative scalar

Minimum difference in the height of the peak and its neighboring samples, specified as a nonnegative scalar.

#### Scope Window Use

On the **Measurements** tab, select **Peak Finder**. In the peak finder settings, specify a nonnegative scalar in the **Threshold** box.

Data Types: `double`

### `LabelPeaks` — Label found peaks
`false` (default) | `true`

Label found peaks, specified as `true` or `false`. The scope displays the labels (**P1**, **P2**, ...) above the arrows in the plot.

#### Scope Window Use

On the **Measurements** tab, select **Peak Finder**. In the peak finder settings, select **Label Peaks**.

Data Types: `logical`

### `LabelFormat` — Coordinates to display
`"x + y"` (default) | `"x"` | `"y"`

Coordinates to display next to the calculated peak value, specified as `"x"`, `"y"`, or `"x + y"`.

Data Types: `char` | `string`

### `Enabled` — Enable peak finder measurements
`false` (default) | `true`

Enable peak finder measurements, specified as `true` or `false`. Set this property to `true` to enable the peak finder measurements.

#### Scope Window Use

On the **Measurements** tab, select **Peak Finder**.

Data Types: `logical`

## Examples

### Enable Peak Finder Programmatically in a Time Scope Object

Create a sine wave and view it in the Time Scope. Enable the peak finder programmatically.

#### Initialization

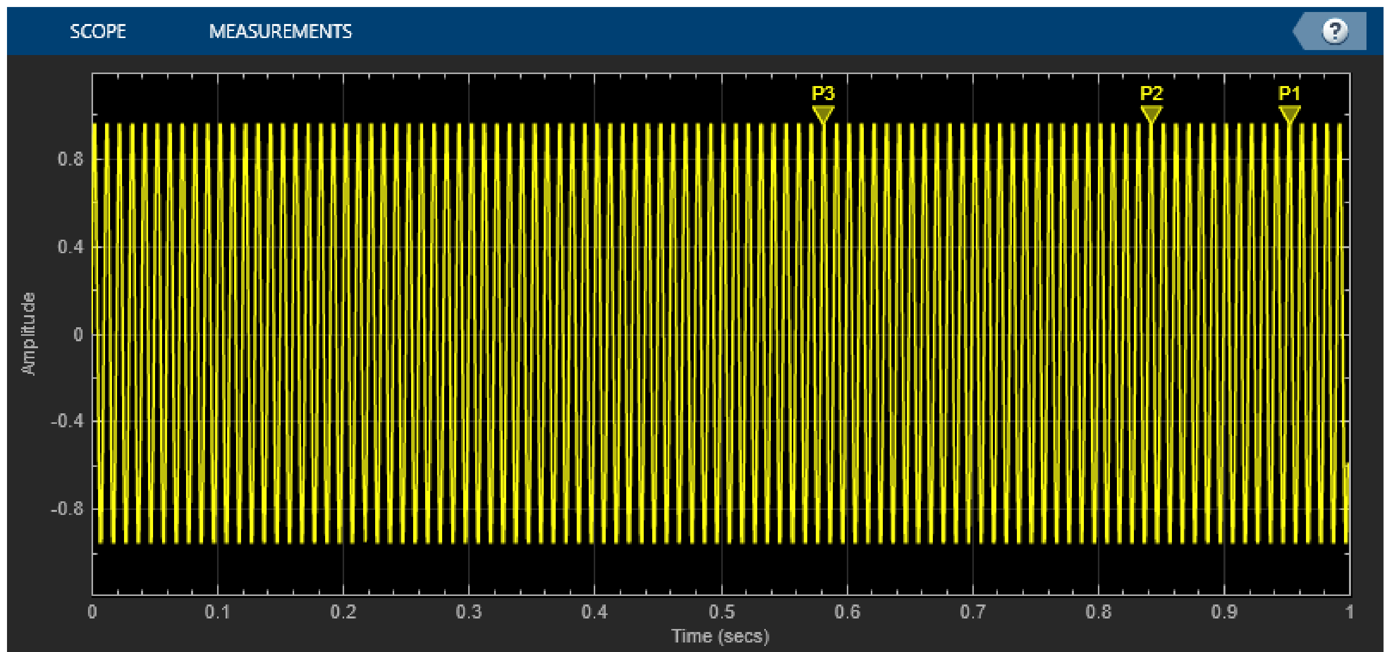
Create the input sine wave using the `sin` function. Create a `timescope` MATLAB® object to display the signal. Set the `TimeSpan` property to 1 second.

```
f = 100;
fs = 1000;
swv = sin(2.*pi.*f.*(0:1/fs:1-1/fs)).';
scope = timescope(SampleRate=fs,...
    TimeSpanSource="property", ...
    TimeSpan=1);
```

### Peaks

Enable the peak finder and label the peaks. Set the scope to show three peaks and label them.

```
scope.PeakFinder.Enabled = true;
scope.PeakFinder.LabelPeaks = true;
scope(swv)
release(scope)
```




Peaks

| Channel 1 | P1 | P2 | P3 |
|---|---|---|---|
| Time (ms) | 9.5300e+2 | 8.4300e+2 | 5.8200e+2 |
| Value | 9.5106e-1 | 9.5106e-1 | 9.5106e-1 |

Stopped Frames = 1 T = 0.999000

## Version History

**Introduced in R2022a**

## See Also

`timescope`

### Topics

"Configure Time Scope MATLAB Object"

# tunerconfig

Fusion filter tuner configuration options

## Description

The `tunerconfig` object creates a tuner configuration for a fusion filter used to tune the filter for reduced estimation error.

## Creation

### Syntax

```
config = tunerconfig(filterName)
config = tunerconfig(filter)
config = tunerconfig(filterName,Name,Value)
```

#### Description

`config = tunerconfig(filterName)` creates a `tunerconfig` object controlling the optimization algorithm of the tune function of the fusion filter by specifying a filter name.

`config = tunerconfig(filter)` creates a `tunerconfig` object controlling the optimization algorithm of the tune function of the fusion filter by specifying a filter object.

`config = tunerconfig(filterName,Name,Value)` configures the created `tunerconfig` object properties using one or more name-value pair arguments. `Name` is a property name and `Value` is the corresponding value. `Name` must appear inside quotes. You can specify several name-value pair arguments in any order as `Name1,Value1,...,NameN,ValueN`. Any unspecified properties take default values.

For example, `tunerconfig('imufilter','MaxIterations',3)` create a `tunerconfig` object for the `imufilter` object with the a maximum of three allowed iterations.

#### Inputs Arguments

**`filterName` — Fusion filter name**
`'imufilter'` | `'ahrsfilter'` | `'ahrs10filter'` | `'insfilterAsync'` | `'insfilterMARG'` | `'insfitlerErrorState'` | `'insfilterNonholonomic'`

Fusion filter name, specified as one of these options:

- `'imufilter'`
- `'ahrsfilter'`
- `'ahrs10filter'`
- `'insfilterAsync'`
- `'insfilterMARG'`

- `'insfitlerErrorState'`
- `'insfilterNonholonomic'`

**`filter` — Fusion filter**
fusion filter object

Fusion filter, specified as one of these fusion filter objects:

- `insEKF`
- `ahrs10filter`
- `insfilterAsync`
- `insfilterMARG`
- `insfilterErrorState`
- `insfilterNonholonomic`
- `ahrsfilter`
- `imufilter`

.

## Properties

**`Filter` — Class name of filter**
string

This property is read-only.

Class name of filter, specified as a string. Its value is one of these strings:

- `"imufilter"`
- `"ahrsfilter"`
- `"ahrs10filter"`
- `"insfilterAsync"`
- `"insfilterMARG"`
- `"insfitlerErrorState"`
- `"insfilterNonholonomic"`

**`TunableParameters` — Tunable parameters**
array of string (default) | cell array

Tunable parameters, specified as an array of strings or a cell array.

- If you want to tune all the elements in each parameter together (scaling up or down all the elements in a process noise matrix for example), then specify the property as an array of strings. Each string corresponds to a property name.

  For filter objects other than the `insEKF` object, this is the default option. With the default option, the property contains all the tunable parameter names as an array of strings. Each string is a tunable property name of the fusion filter.

- If you want to tune a subset of elements for at least one noise parameter, specify it as a cell array. The number of cells is the number of parameters that you want to tune.
  - You can specify any cell element as a character vector, representing the property that you want to tune. In this case, the filter tunes all the elements in the property together.
  - You can also specify any cell element as a 1-by-2 cell array, in which the first cell is a character vector, representing the property that you want tune. The second cell in the cell array is a vector of indices, representing the elements that you want to tune in the property. These indices are column-based indices.

  This is default option for the `insEKF` object.

  For example, running the following:

```
>> filter = insEKF;
config = tunerconfig(filter);
tunable = config.TunableParameters
```

  and you can obtain:

```
tunable =

  1×3 cell array

    {1×2 cell}    {'AccelerometerNoise'}    {'GyroscopeNoise'}

>> firstCell = tunable{1}

firstCell =

  1×2 cell array

    {'AdditiveProcessNoise'}    {[1 15 29 43 57 71 85 99 113 127 141 155 169]}
```

  In the filter, the additive process noise matrix is a 13-by-13 matrices, and the column-based indices represent all the diagonal elements of the matrix.

Example: `["AccelerometerNoise" "GyroscopeNoise"]`

#### `StepForward` — Factor of forward step
`1.1` (default) | scalar larger than 1

Factor of a forward step, specified as a scalar larger than 1. During the tuning process, the tuner increases or decreases the noise parameters to achieve smaller estimation errors. This property specifies the ratio of parameter increase during a parameter increase step.

#### `StepBackward` — Factor of backward step
`0.5` (default) | scalar in range (0,1)

Factor of a backward step, specified as a scalar in the range of (0,1). During the tuning process, the tuner increases or decreases the noise parameters to achieve smaller estimation errors. This property specifies the factor of parameter decrease during a parameter decrease step.

#### `MaxIterations` — Maximum number of iterations
`20` (default) | positive integer

Maximum number of iterations allowed by the tuning algorithm, specified as a positive integer.

### ObjectiveLimit — Cost at which to stop tuning process

0.1 (default) | positive scalar

Cost at which to stop the tuning process, specified as a positive scalar.

### FunctionTolerance — Minimum change in cost to continue tuning

0 (default) | nonnegative scalar

Minimum change in cost to continue tuning, specified as a nonnegative scalar. If the change in cost is smaller than the specified tolerance, the tuning process stops.

### Display — Enable showing the iteration details

"iter" (default) | "none"

Enable showing the iteration details, specified as "iter" or "none". When specified as:

- "iter" — The program shows the tuned parameter details in each iteration in the Command Window.
- "none" — The program does not show any tuning information.

### Cost — Metric for evaluating filter performance

"RMS" (default) | "Custom"

Metric for evaluating filter performance, specified as "RMS" or "Custom". When specified as:

- "RMS" — The program optimizes the root-mean-squared (RMS) error between the estimate and the truth.
- "Custom" — The program optimizes the filter performance by using a customized cost function specified by the CustomCostFcn property.

### CustomCostFcn — Customized cost function

[] (default) | function handle

Customized cost function, specified as a function handle.

#### Dependencies

To enable this property, set the Cost property to 'Custom'.

### OutputFcn — Output function called at each iteration

[] (default) | function handle

Output function called at each iteration, specified as a function handle. The function must use the following syntax:

```
stop = myOutputFcn(params,tunerValues)
```

params is a structure of the current best estimate of each parameter at the end of the current iteration. tunerValues is a structure containing information of the tuner configuration, sensor data, and truth data. It has these fields:

| Field Name | Description |
| --- | --- |
| Iteration | Iteration count of the tuner, specified as a positive integer |
| SensorData | Sensor data input to the tune function |
| GroundTruth | Ground truth input to the tune function |
| Configuration | tunerconfig object used for tuning |
| Cost | Tuning cost at the end of the current iteration |

**Tip** You can use the built-in function `tunerPlotPose` to visualize the truth data and the estimates for most of your tuning applications. See the “Visualize Tuning Results Using tunerPlotPose” on page 1-324 example for details.

## Examples

### Create Tunerconfig Object and Show Tunable Parameters

Create a tunerconfig object for the `insfilterAsync` object.

```
config = tunerconfig('insfilterAsync')
```

```
config =
  tunerconfig with properties:

               Filter: "insfilterAsync"
    TunableParameters: ["AccelerometerNoise"    "GyroscopeNoise"    "MagnetometerNoise"    "GPSPo
          StepForward: 1.1000
         StepBackward: 0.5000
        MaxIterations: 20
       ObjectiveLimit: 0.1000
    FunctionTolerance: 0
              Display: iter
                 Cost: RMS
            OutputFcn: []
```

Display the default tunable parameters.

```
config.TunableParameters
```

```
ans = 1x14 string
    "AccelerometerNoise"    "GyroscopeNoise"    "MagnetometerNoise"    "GPSPositionNoise"    "GPS
```

### Tune `insfilterAsync` to Optimize Pose Estimate

Load the recorded sensor data and ground truth data.

```
load('insfilterAsyncTuneData.mat');
```

Create timetables for the sensor data and the truth data.

```
sensorData = timetable(Accelerometer, Gyroscope, ...
    Magnetometer, GPSPosition, GPSVelocity, 'SampleRate', 100);
groundTruth = timetable(Orientation, Position, ...
    'SampleRate', 100);
```

Create an `insfilterAsync` filter object that has a few noise properties.

```
filter = insfilterAsync('State', initialState, ...
    'StateCovariance', initialStateCovariance, ...
    'AccelerometerBiasNoise', 1e-7, ...
    'GyroscopeBiasNoise', 1e-7, ...
    'MagnetometerBiasNoise', 1e-7, ...
    'GeomagneticVectorNoise', 1e-7);
```

Create a tuner configuration object for the filter. Set the maximum iterations to two. Also, set the tunable parameters as the unspecified properties.

```
config = tunerconfig('insfilterAsync','MaxIterations',8);
config.TunableParameters = setdiff(config.TunableParameters, ...
    {'GeomagneticVectorNoise', 'AccelerometerBiasNoise', ...
    'GyroscopeBiasNoise', 'MagnetometerBiasNoise'});
config.TunableParameters
```

```
ans = 1×10 string
    "AccelerationNoise"    "AccelerometerNoise"    "AngularVelocityNoise"    "GPSPositionNoise"
```

Use the tuner noise function to obtain a set of initial sensor noises used in the filter.

```
measNoise = tunernoise('insfilterAsync')
```

```
measNoise = struct with fields:
    AccelerometerNoise: 1
        GyroscopeNoise: 1
     MagnetometerNoise: 1
      GPSPositionNoise: 1
      GPSVelocityNoise: 1
```

Tune the filter and obtain the tuned parameters.

```
tunedParams = tune(filter,measNoise,sensorData,groundTruth,config);
```

```
    Iteration    Parameter               Metric
    _________    _________               ______
    1            AccelerationNoise       2.1345
    1            AccelerometerNoise      2.1264
    1            AngularVelocityNoise    1.9659
    1            GPSPositionNoise        1.9341
    1            GPSVelocityNoise        1.8420
    1            GyroscopeNoise          1.7589
    1            MagnetometerNoise       1.7362
    1            PositionNoise           1.7362
    1            QuaternionNoise         1.7218
    1            VelocityNoise           1.7218
    2            AccelerationNoise       1.7190
    2            AccelerometerNoise      1.7170
```

```
    2            AngularVelocityNoise    1.6045
    2            GPSPositionNoise        1.5948
    2            GPSVelocityNoise        1.5323
    2            GyroscopeNoise          1.4803
    2            MagnetometerNoise       1.4703
    2            PositionNoise           1.4703
    2            QuaternionNoise         1.4632
    2            VelocityNoise           1.4632
    3            AccelerationNoise       1.4596
    3            AccelerometerNoise      1.4548
    3            AngularVelocityNoise    1.3923
    3            GPSPositionNoise        1.3810
    3            GPSVelocityNoise        1.3322
    3            GyroscopeNoise          1.2998
    3            MagnetometerNoise       1.2976
    3            PositionNoise           1.2976
    3            QuaternionNoise         1.2943
    3            VelocityNoise           1.2943
    4            AccelerationNoise       1.2906
    4            AccelerometerNoise      1.2836
    4            AngularVelocityNoise    1.2491
    4            GPSPositionNoise        1.2258
    4            GPSVelocityNoise        1.1880
    4            GyroscopeNoise          1.1701
    4            MagnetometerNoise       1.1698
    4            PositionNoise           1.1698
    4            QuaternionNoise         1.1688
    4            VelocityNoise           1.1688
    5            AccelerationNoise       1.1650
    5            AccelerometerNoise      1.1569
    5            AngularVelocityNoise    1.1454
    5            GPSPositionNoise        1.1100
    5            GPSVelocityNoise        1.0778
    5            GyroscopeNoise          1.0709
    5            MagnetometerNoise       1.0675
    5            PositionNoise           1.0675
    5            QuaternionNoise         1.0669
    5            VelocityNoise           1.0669
    6            AccelerationNoise       1.0634
    6            AccelerometerNoise      1.0549
    6            AngularVelocityNoise    1.0549
    6            GPSPositionNoise        1.0180
    6            GPSVelocityNoise        0.9866
    6            GyroscopeNoise          0.9810
    6            MagnetometerNoise       0.9775
    6            PositionNoise           0.9775
    6            QuaternionNoise         0.9768
    6            VelocityNoise           0.9768
    7            AccelerationNoise       0.9735
    7            AccelerometerNoise      0.9652
    7            AngularVelocityNoise    0.9652
    7            GPSPositionNoise        0.9283
    7            GPSVelocityNoise        0.8997
    7            GyroscopeNoise          0.8947
    7            MagnetometerNoise       0.8920
    7            PositionNoise           0.8920
    7            QuaternionNoise         0.8912
    7            VelocityNoise           0.8912
```

```
    8          AccelerationNoise        0.8885
    8          AccelerometerNoise       0.8811
    8          AngularVelocityNoise     0.8807
    8          GPSPositionNoise         0.8479
    8          GPSVelocityNoise         0.8238
    8          GyroscopeNoise           0.8165
    8          MagnetometerNoise        0.8165
    8          PositionNoise            0.8165
    8          QuaternionNoise          0.8159
    8          VelocityNoise            0.8159
```

Fuse the sensor data using the tuned filter.

```
dt = seconds(diff(groundTruth.Time));
N = size(sensorData,1);
qEst = quaternion.zeros(N,1);
posEst = zeros(N,3);
% Iterate the filter for prediction and correction using sensor data.
for ii=1:N
    if ii ~= 1
        predict(filter, dt(ii-1));
    end
    if all(~isnan(Accelerometer(ii,:)))
        fuseaccel(filter,Accelerometer(ii,:), ...
            tunedParams.AccelerometerNoise);
    end
    if all(~isnan(Gyroscope(ii,:)))
        fusegyro(filter, Gyroscope(ii,:), ...
            tunedParams.GyroscopeNoise);
    end
    if all(~isnan(Magnetometer(ii,1)))
        fusemag(filter, Magnetometer(ii,:), ...
            tunedParams.MagnetometerNoise);
    end
    if all(~isnan(GPSPosition(ii,1)))
        fusegps(filter, GPSPosition(ii,:), ...
            tunedParams.GPSPositionNoise, GPSVelocity(ii,:), ...
            tunedParams.GPSVelocityNoise);
    end
    [posEst(ii,:), qEst(ii,:)] = pose(filter);
end
```

Compute the RMS errors.

```
orientationError = rad2deg(dist(qEst, Orientation));
rmsorientationError = sqrt(mean(orientationError.^2))
```

```
rmsorientationError = 2.7801
```

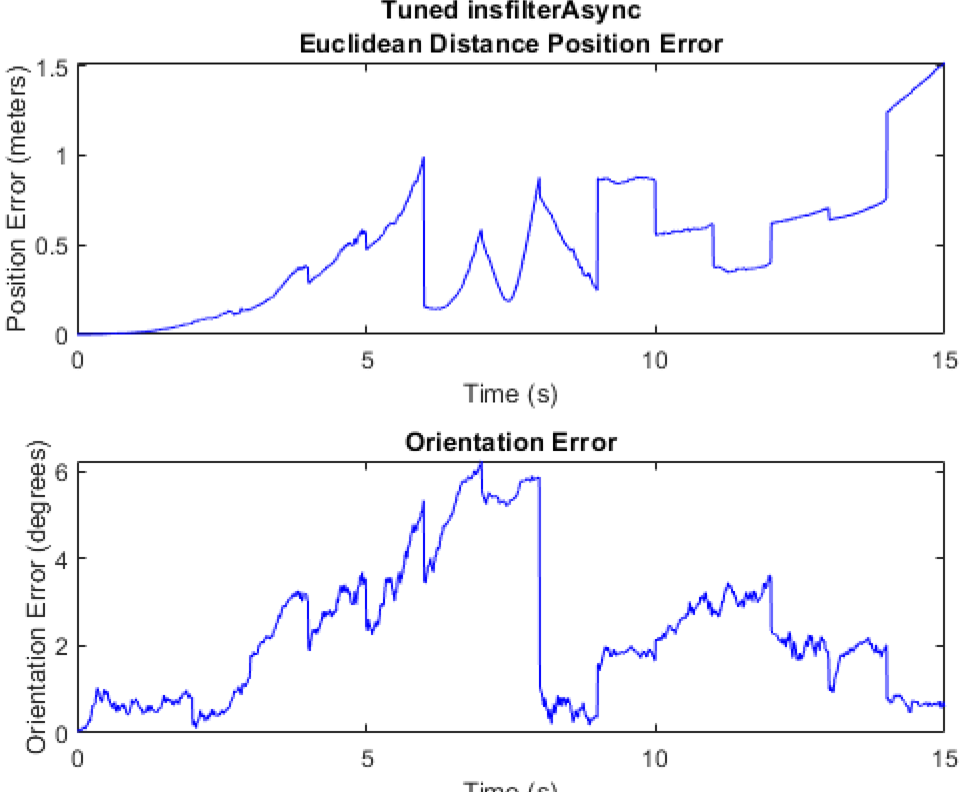
```
positionError = sqrt(sum((posEst - Position).^2, 2));
rmspositionError = sqrt(mean( positionError.^2))
```

```
rmspositionError = 0.5966
```

Visualize the results.

```
figure();
t = (0:N-1)./ groundTruth.Properties.SampleRate;
subplot(2,1,1)
```

```
plot(t, positionError, 'b');
title("Tuned insfilterAsync" + newline + "Euclidean Distance Position Error")
xlabel('Time (s)');
ylabel('Position Error (meters)')
subplot(2,1,2)
plot(t, orientationError, 'b');
title("Orientation Error")
xlabel('Time (s)');
ylabel('Orientation Error (degrees)');
```




### Tune `imufilter` to Optimize Orientation Estimate

Load recorded sensor data and ground truth data.

```
ld = load('imufilterTuneData.mat');
qTrue = ld.groundTruth.Orientation; % true orientation
```

Create an `imufilter` object and fuse the filter with the sensor data.

```
fuse = imufilter;
qEstUntuned = fuse(ld.sensorData.Accelerometer, ...
    ld.sensorData.Gyroscope);
```

Create a `tunerconfig` object and tune the imufilter to improve the orientation estimate.

```
cfg = tunerconfig('imufilter');
tune(fuse, ld.sensorData, ld.groundTruth, cfg);

    Iteration    Parameter                        Metric
    _________    _________                        ______
    1            AccelerometerNoise               0.1149
    1            GyroscopeNoise                   0.1146
    1            GyroscopeDriftNoise              0.1146
    1            LinearAccelerationNoise          0.1122
    1            LinearAccelerationDecayFactor    0.1103
    2            AccelerometerNoise               0.1102
    2            GyroscopeNoise                   0.1098
    2            GyroscopeDriftNoise              0.1098
    2            LinearAccelerationNoise          0.1070
    2            LinearAccelerationDecayFactor    0.1053
    3            AccelerometerNoise               0.1053
    3            GyroscopeNoise                   0.1048
    3            GyroscopeDriftNoise              0.1048
    3            LinearAccelerationNoise          0.1016
    3            LinearAccelerationDecayFactor    0.1002
    4            AccelerometerNoise               0.1001
    4            GyroscopeNoise                   0.0996
    4            GyroscopeDriftNoise              0.0996
    4            LinearAccelerationNoise          0.0962
    4            LinearAccelerationDecayFactor    0.0950
    5            AccelerometerNoise               0.0950
    5            GyroscopeNoise                   0.0943
    5            GyroscopeDriftNoise              0.0943
    5            LinearAccelerationNoise          0.0910
    5            LinearAccelerationDecayFactor    0.0901
    6            AccelerometerNoise               0.0900
    6            GyroscopeNoise                   0.0893
    6            GyroscopeDriftNoise              0.0893
    6            LinearAccelerationNoise          0.0862
    6            LinearAccelerationDecayFactor    0.0855
    7            AccelerometerNoise               0.0855
    7            GyroscopeNoise                   0.0848
    7            GyroscopeDriftNoise              0.0848
    7            LinearAccelerationNoise          0.0822
    7            LinearAccelerationDecayFactor    0.0818
    8            AccelerometerNoise               0.0817
    8            GyroscopeNoise                   0.0811
    8            GyroscopeDriftNoise              0.0811
    8            LinearAccelerationNoise          0.0791
    8            LinearAccelerationDecayFactor    0.0789
    9            AccelerometerNoise               0.0788
    9            GyroscopeNoise                   0.0782
    9            GyroscopeDriftNoise              0.0782
    9            LinearAccelerationNoise          0.0769
    9            LinearAccelerationDecayFactor    0.0768
    10           AccelerometerNoise               0.0768
    10           GyroscopeNoise                   0.0762
    10           GyroscopeDriftNoise              0.0762
    10           LinearAccelerationNoise          0.0754
    10           LinearAccelerationDecayFactor    0.0753
    11           AccelerometerNoise               0.0753
    11           GyroscopeNoise                   0.0747
    11           GyroscopeDriftNoise              0.0747
```

```
    11           LinearAccelerationNoise         0.0741
    11           LinearAccelerationDecayFactor   0.0740
    12           AccelerometerNoise              0.0740
    12           GyroscopeNoise                  0.0734
    12           GyroscopeDriftNoise             0.0734
    12           LinearAccelerationNoise         0.0728
    12           LinearAccelerationDecayFactor   0.0728
    13           AccelerometerNoise              0.0728
    13           GyroscopeNoise                  0.0721
    13           GyroscopeDriftNoise             0.0721
    13           LinearAccelerationNoise         0.0715
    13           LinearAccelerationDecayFactor   0.0715
    14           AccelerometerNoise              0.0715
    14           GyroscopeNoise                  0.0706
    14           GyroscopeDriftNoise             0.0706
    14           LinearAccelerationNoise         0.0700
    14           LinearAccelerationDecayFactor   0.0700
    15           AccelerometerNoise              0.0700
    15           GyroscopeNoise                  0.0690
    15           GyroscopeDriftNoise             0.0690
    15           LinearAccelerationNoise         0.0684
    15           LinearAccelerationDecayFactor   0.0684
    16           AccelerometerNoise              0.0684
    16           GyroscopeNoise                  0.0672
    16           GyroscopeDriftNoise             0.0672
    16           LinearAccelerationNoise         0.0668
    16           LinearAccelerationDecayFactor   0.0667
    17           AccelerometerNoise              0.0667
    17           GyroscopeNoise                  0.0655
    17           GyroscopeDriftNoise             0.0655
    17           LinearAccelerationNoise         0.0654
    17           LinearAccelerationDecayFactor   0.0654
    18           AccelerometerNoise              0.0654
    18           GyroscopeNoise                  0.0641
    18           GyroscopeDriftNoise             0.0641
    18           LinearAccelerationNoise         0.0640
    18           LinearAccelerationDecayFactor   0.0639
    19           AccelerometerNoise              0.0639
    19           GyroscopeNoise                  0.0627
    19           GyroscopeDriftNoise             0.0627
    19           LinearAccelerationNoise         0.0627
    19           LinearAccelerationDecayFactor   0.0624
    20           AccelerometerNoise              0.0624
    20           GyroscopeNoise                  0.0614
    20           GyroscopeDriftNoise             0.0614
    20           LinearAccelerationNoise         0.0613
    20           LinearAccelerationDecayFactor   0.0613
```

Fuse the sensor data again using the tuned filter.

```
qEstTuned = fuse(ld.sensorData.Accelerometer, ...
    ld.sensorData.Gyroscope);
```

Compare the tuned and untuned filter RMS error performances.

```
dUntuned = rad2deg(dist(qEstUntuned, qTrue));
dTuned = rad2deg(dist(qEstTuned, qTrue));
rmsUntuned = sqrt(mean(dUntuned.^2))
```

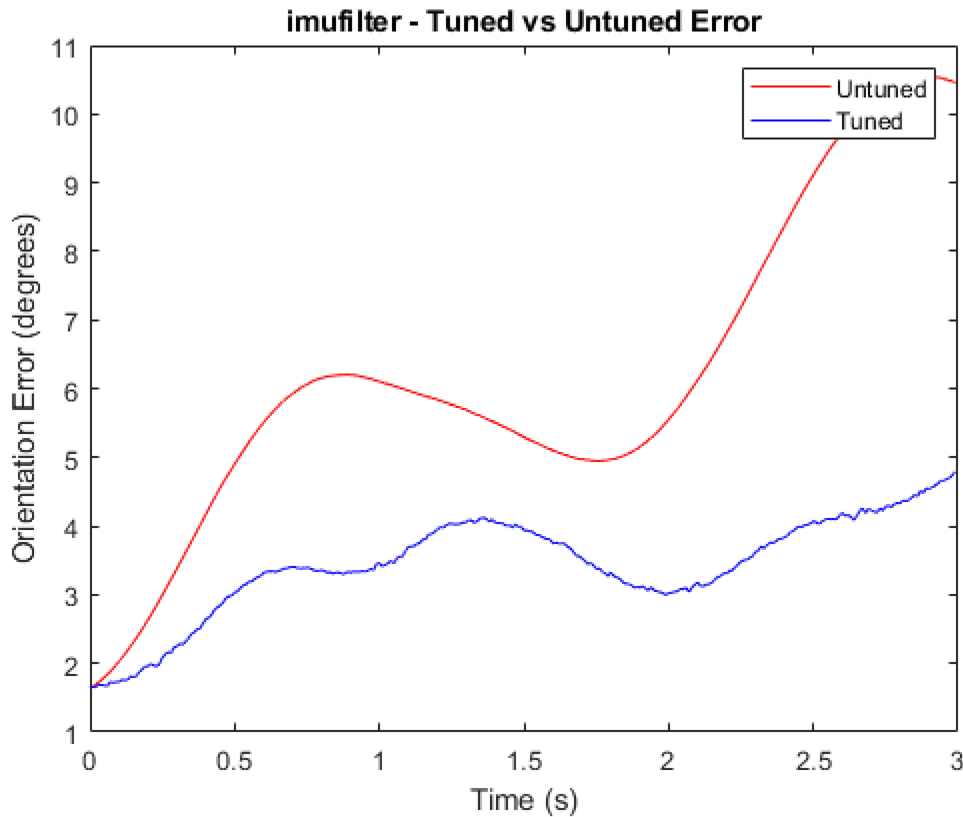
```
rmsUntuned = 6.5864
```

```
rmsTuned = sqrt(mean(dTuned.^2))
```

```
rmsTuned = 3.5098
```

Visualize the results.

```
N = numel(dUntuned);
t = (0:N-1)./ fuse.SampleRate;
plot(t, dUntuned, 'r', t, dTuned, 'b');
legend('Untuned', 'Tuned');
title('imufilter - Tuned vs Untuned Error')
xlabel('Time (s)');
ylabel('Orientation Error (degrees)');
```




### Save Tuned Parameters in MAT File Using Output Function

Load the recorded sensor data and ground truth data.

```
load('insfilterAsyncTuneData.mat');
```

Create timetables for the sensor data and the truth data.

```
sensorData = timetable(Accelerometer, Gyroscope, ...
    Magnetometer, GPSPosition, GPSVelocity, 'SampleRate', 100);
```

```
groundTruth = timetable(Orientation, Position, ...
    'SampleRate', 100);
```

Create an `insfilterAsync` filter object that has a few noise properties.

```
filter = insfilterAsync('State', initialState, ...
    'StateCovariance', initialStateCovariance, ...
    'AccelerometerBiasNoise', 1e-7, ...
    'GyroscopeBiasNoise', 1e-7, ...
    'MagnetometerBiasNoise', 1e-7, ...
    'GeomagneticVectorNoise', 1e-7);
```

Create a tuner configuration object for the filter. Define the `OutputFcn` property as a customized function, `myOutputFcn`, which saves the latest tuned parameters in a MAT file.

```
config = tunerconfig('insfilterAsync', ...
    'MaxIterations',5, ...
    'Display','none', ...
    'OutputFcn', @myOutputFcn);
config.TunableParameters = setdiff(config.TunableParameters, ...
    {'GeomagneticVectorNoise', 'AccelerometerBiasNoise', ...
    'GyroscopeBiasNoise', 'MagnetometerBiasNoise'});
config.TunableParameters
```

```
ans = 1x10 string
    "AccelerationNoise"    "AccelerometerNoise"    "AngularVelocityNoise"    "GPSPositionNoise"
```

Use the tuner noise function to obtain a set of initial sensor noises used in the filter.

```
measNoise = tunernoise('insfilterAsync')
```

```
measNoise = struct with fields:
    AccelerometerNoise: 1
        GyroscopeNoise: 1
     MagnetometerNoise: 1
      GPSPositionNoise: 1
      GPSVelocityNoise: 1
```

Tune the filter and obtain the tuned parameters.

```
tunedParams = tune(filter,measNoise,sensorData,groundTruth,config);
```

Display the save parameters using the saved file.

```
fileObject = matfile('myfile.mat');
fileObject.params
```

```
ans = struct with fields:
         AccelerationNoise: [88.8995 88.8995 88.8995]
    AccelerometerBiasNoise: [1.0000e-07 1.0000e-07 1.0000e-07]
        AccelerometerNoise: 0.7942
      AngularVelocityNoise: [0.0089 0.0089 0.0089]
          GPSPositionNoise: 1.1664
          GPSVelocityNoise: 0.5210
    GeomagneticVectorNoise: [1.0000e-07 1.0000e-07 1.0000e-07]
        GyroscopeBiasNoise: [1.0000e-07 1.0000e-07 1.0000e-07]
            GyroscopeNoise: 0.5210
```

```
     MagnetometerBiasNoise: [1.0000e-07 1.0000e-07 1.0000e-07]
         MagnetometerNoise: 1.0128
             PositionNoise: [5.2100e-07 5.2100e-07 5.2100e-07]
           QuaternionNoise: [1.3239e-06 1.3239e-06 1.3239e-06 1.3239e-06]
         ReferenceLocation: [0 0 0]
                     State: [28x1 double]
           StateCovariance: [28x28 double]
             VelocityNoise: [6.3678e-07 6.3678e-07 6.3678e-07]
```

**The output function**

```
function stop = myOutputFcn(params, ~)
save('myfile.mat','params'); % overwrite the file with latest
stop = false;
end
```

# Version History

**Introduced in R2020b**

## See Also

insfilterAsync | insfilterNonholonomic | insfilterMARG | insfilterErrorState | ahrsfilter | ahrs10filter | imufilter

# validatorOccupancyMap

State validator based on 2-D grid map

## Description

The `validatorOccupancyMap` object validates states and discretized motions based on the value in a 2-D occupancy map. An occupied map location is interpreted as an invalid state.

## Creation

### Syntax

#### Description

`validator = validatorOccupancyMap` creates a 2-D occupancy map validator associated with an SE2 state space with default settings.

`validator = validatorOccupancyMap(stateSpace)` creates a validator in the given state space definition derived from `nav.StateSpace`.

`validator = validatorOccupancyMap(stateSpace,Name,Value)` specifies the `Map` or `XYIndices` properties using `Name,Value` pair arguments.

### Properties

**`StateSpace` — State space for validating states**
`stateSpaceSE2` (default) | subclass of `nav.StateSpace`

State space for validating states, specified as a subclass of `nav.StateSpace`. Provided state space objects include:

- `stateSpaceSE2`
- `stateSpaceDubins`
- `stateSpaceReedsShepp`

**`Map` — Map used for validating states**
`binaryOccupancyMap(10,10)` (default) | `binaryOccupancyMap` object | `occupancyMap` object

Map used for validating states, specified as a `binaryOccupancyMap` or `occupancyMap` object.

**`ValidationDistance` — Interval for checking state validity**
`Inf` (default) | positive numeric scalar

Interval for sampling between states and checking state validity, specified as a positive numeric scalar.

**`XYIndices` — State variable mapping for *xy*-coordinates**
`[1 2]` (default) | `[xIdx yIdx]`

State variable mapping for *xy*-coordinates in state vector, specified as a two-element vector, `[xIdx yIdx]`. For example, if a state vector is given as `[r p y x y z]`, the *xy*-coordinates are `[4 5]`.

## Object Functions

| | |
|---|---|
| copy | Create deep copy of state validator object |
| isStateValid | Check if state is valid |
| isMotionValid | Check if path between states is valid |

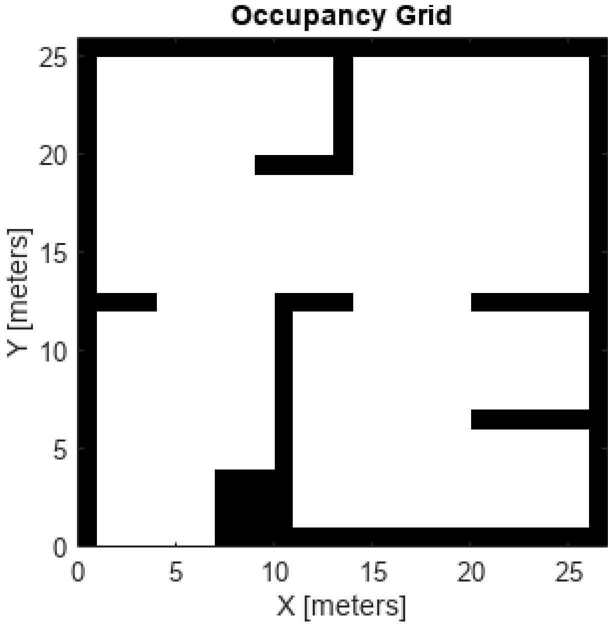
## Examples

#### Validate Path Through Occupancy Map Environment

This example shows how to validate paths through an environment.

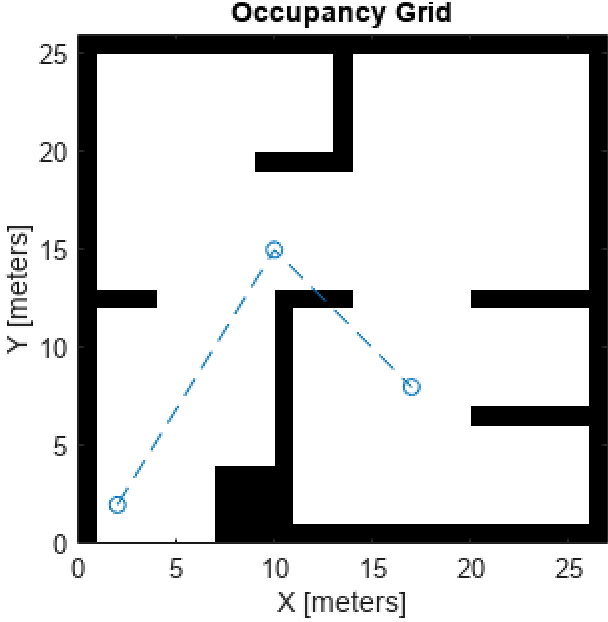
Load example maps. Use the simple map to create a binary occupancy map.

```
load exampleMaps.mat
map = occupancyMap(simpleMap);
show(map)
```




Specify a coarse path through the map.

```
path = [2 2 pi/2; 10 15 0; 17 8 -pi/2];
hold on
plot(path(:,1),path(:,2),"--o")
```




Create a state validator using the `stateSpaceSE2` definition. Specify the map and the distance for interpolating and validating path segments.

```
validator = validatorOccupancyMap(stateSpaceSE2);
validator.Map = map;
validator.ValidationDistance = 0.1;
```

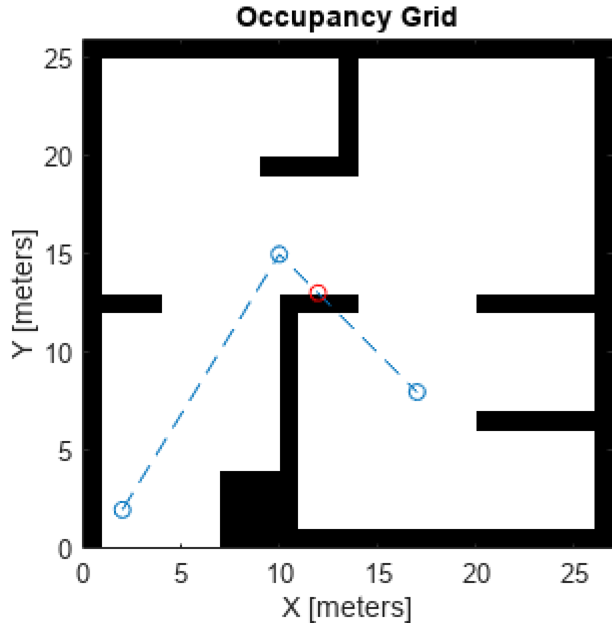
Check the points of the path are valid states. All three points are in free space, so are considered valid.

```
isValid = isStateValid(validator,path)
```

```
isValid = 3x1 logical array

   1
   1
   1
```

Check the motion between each sequential path states. The `isMotionValid` function interpolates along the path between states. If a path segment is invalid, plot the last valid point along the path.

```
startStates = [path(1,:);path(2,:)];
endStates = [path(2,:);path(3,:)];
    for i = 1:2
        [isPathValid, lastValid] = isMotionValid(validator,startStates(i,:),endStates(i,:));
        if ~isPathValid
            plot(lastValid(1),lastValid(2),'or')
        end
    end
hold off
```




## Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

Specify the `Map` and `XYIndices` properties when you create the object. For example:

```
validator = validatorOccupancyMap('Map',occMap,'XYIndices',[4 5])
```

As of MATLAB R2022a, default map behavior during code generation has changed, which may result in backwards compatibility issues. Maps such as `validatorOccupancyMap` now support fixed-size code generation (`DynamicMemoryAllocation="off"`).

1. Maps that are either default-constructed or constructed with compile-time constant size information (or matrices that are of compile-time constant size) produce fixed-size maps.
2. To restore the previous behavior, use the `coder.ignoreConst` function when specifying size inputs, or `coder.varsize` matrix variable name specified as a string scalar or character vector, prior to constructing the map.

## See Also

`stateSpaceSE2` | `nav.StateSpace` | `nav.StateValidator`

# validatorOccupancyMap3D

State validator based on 3-D grid map

## Description

The `validatorOccupancyMap3D` object validates states and discretized motions based on occupancy values in a 3-D occupancy map. The object interprets obstacle-free map locations as valid states. The object interprets occupied and unknown map locations as invalid states.

## Creation

### Syntax

```
validator = validatorOccupancyMap3D
validator = validatorOccupancyMap3D(stateSpace)
validator = validatorOccupancyMap3D(stateSpace,Name,Value)
```

#### Description

`validator = validatorOccupancyMap3D` creates a 3-D occupancy map validator associated with an SE(3) state space with default settings.

`validator = validatorOccupancyMap3D(stateSpace)` creates a validator in the specified state space. The `stateSpace` input sets the value of the StateSpace property.

`validator = validatorOccupancyMap3D(stateSpace,Name,Value)` sets properties using one or more name-value pairs. Unspecified properties have default values. Enclose each property name in quotes.

For example, `validatorOccupancyMap3D('ValidationDistance',0.1)` creates a 3-D occupancy map validator with a sampling interval of 0.1.

### Properties

**StateSpace — State space for validating states**
`stateSpaceSE3` object (default) | subclass of `nav.StateSpace`

This property is read-only.

State space for validating states, specified as a subclass of `nav.StateSpace`. These are the predefined state space objects:

- `stateSpaceSE3`
- `stateSpaceSE2`
- `stateSpaceDubins`
- `stateSpaceReedsShepp`

Example: `validatorOccupancyMap3D(stateSpaceSE3)`

**`Map` — Map used for validating states**
`occupancyMap3D` (default) | `occupancyMap3D` object

Map used for validating states, specified as an `occupancyMap3D` object.

Example: `validator.Map = occupancyMap3D(10)`

**`ValidationDistance` — Interval for checking state validity**
`Inf` (default) | positive numeric scalar

Interval for sampling between states and checking state validity, specified as a positive numeric scalar.

Example: `validator.ValidationDistance = 0.1`

Data Types: `double`

**`XYZIndices` — State variable mapping for *xyz*-coordinates**
`[1 2 3]` (default) | three-element vector

State variable mapping for *xyz*-coordinates in the state vector, specified as a three-element vector of form `[xIdx yIdx zIdx]`.

Data Types: `double`

## Object Functions

| | |
|---|---|
| copy | Create deep copy of state validator object |
| isMotionValid | Check if path between states is valid |
| isStateValid | Check if state is valid |

## Examples

### Validate Path Through 3-D Occupancy Map Environment

Create a 3-D occupancy map and associated state validator. Plan, validate, and visualize a path through the occupancy map.

#### Load and Assign Map to State Validator

Load a 3-D occupancy map of a city block into the workspace. Specify a threshold for which cells to consider as obstacle-free.

```
mapData = load('dMapCityBlock.mat');
omap = mapData.omap;
omap.FreeThreshold = 0.5;
```

Inflate the occupancy map to add a buffer zone for safe operation around the obstacles.

```
inflate(omap,1)
```

Create an SE(3) state space object with bounds for state variables.

```
ss = stateSpaceSE3([-20 220;
    -20 220;
```

```
    -10 100;
    inf inf;
    inf inf;
    inf inf;
    inf inf]);
```

Create a 3-D occupancy map state validator using the created state space.

```
sv = validatorOccupancyMap3D(ss);
```

Assign the occupancy map to the state validator object. Specify the sampling distance interval.

```
sv.Map = omap;
sv.ValidationDistance = 0.1;
```

#### Plan and Visualize Path

Create a path planner with increased maximum connection distance. Reduce the maximum number of iterations.

```
planner = plannerRRT(ss,sv);
planner.MaxConnectionDistance = 50;
planner.MaxIterations = 1000;
```

Create a user-defined evaluation function for determining whether the path reaches the goal. Specify the probability of choosing the goal state during sampling.

```
planner.GoalReachedFcn = @(~,x,y)(norm(x(1:3)-y(1:3))<5);
planner.GoalBias = 0.1;
```

Set the start and goal states.

```
start = [40 180 25 0.7 0.2 0 0.1];
goal = [150 33 35 0.3 0 0.1 0.6];
```

Plan a path using the specified start, goal, and planner.

```
[pthObj,solnInfo] = plan(planner,start,goal);
```

Check that the points of the path are valid states.

```
isValid = isStateValid(sv,pthObj.States)
```

```
isValid = 7x1 logical array

   1
   1
   1
   1
   1
   1
   1
```

Check that the motion between each sequential path state is valid.

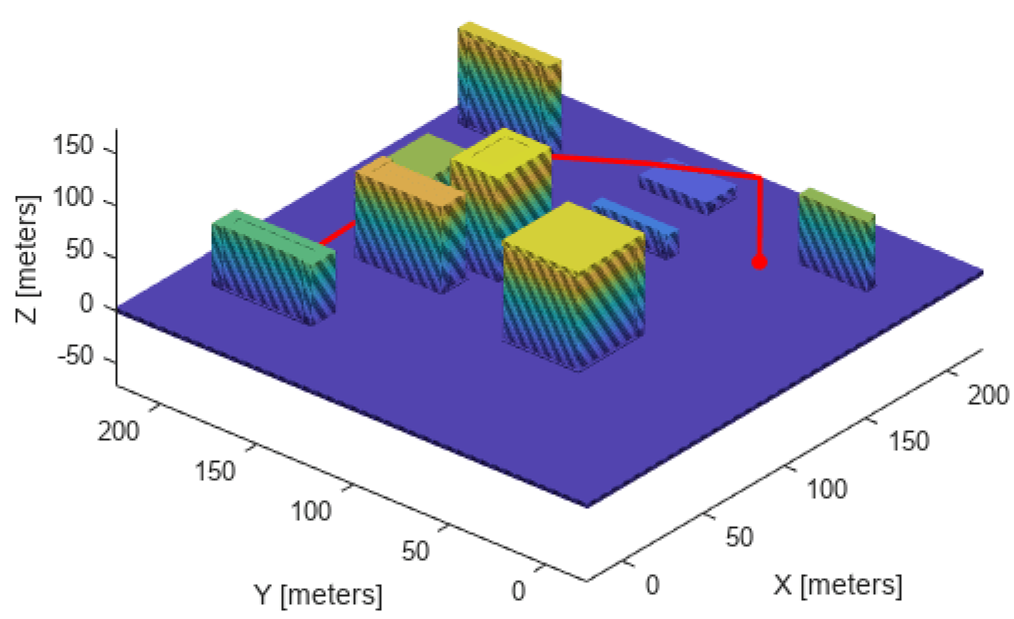
```
isPathValid = zeros(size(pthObj.States,1)-1,1,'logical');
for i = 1:size(pthObj.States,1)-1
    [isPathValid(i),~] = isMotionValid(sv,pthObj.States(i,:),...
```

```
        pthObj.States(i+1,:));
end
isPathValid
```

```
isPathValid = 6x1 logical array

   1
   1
   1
   1
   1
   1
```

Visualize the results.

```
show(omap)
hold on
scatter3(start(1,1),start(1,2),start(1,3),'g','filled') % draw start state
scatter3(goal(1,1),goal(1,2),goal(1,3),'r','filled')    % draw goal state
plot3(pthObj.States(:,1),pthObj.States(:,2),pthObj.States(:,3),...
    'r-','LineWidth',2) % draw path
```




# Version History

**Introduced in R2020b**

## Extended Capabilities

### C/C++ Code Generation
Generate C and C++ code using MATLAB® Coder™.

## See Also
`occupancyMap3D` | `stateSpaceSE3` | `validatorOccupancyMap`

# validatorVehicleCostmap

State validator based on 2-D costmap

## Description

The `validatorOccupancyMap` object validates states and discretized motions based on the value in a 2-D costmap. An occupied map location is interpreted as an invalid state.

## Creation

### Syntax

#### Description

`validator = validatorVehicleCostmap` creates a vehicle cost map validator associated with an SE2 state space with default settings.

`validator = validatorVehicleCostmap(stateSpace)` creates a validator in the given state space definition derived from `nav.StateSpace`.

`validator = validatorVehicleCostmap(stateSpace,xyIndices)`sets the `XYIndices` property to specify which variables in the state vector define the *xy*-coordinates.

`validator = validatorVehicleCostmap(stateSpace,Name,Value)` specifies the `Map` or `XYIndices` properties using `Name,Value` pair arguments.

### Properties

**`StateSpace` — State space for validating states**
`stateSpaceSE2` (default) | subclass of `nav.StateSpace`

State space for validating states, specified as a subclass of `nav.StateSpace`. Provided state space objects include:

- `stateSpaceSE2`
- `stateSpaceDubins`
- `stateSpaceReedsShepp`

**`Map` — Map used for validating states**
`vehicleCostmap(10,10)` (default) | `vehicleCostmap` object

Map used for validating states, specified as a `vehicleCostmap` object.

**`ValidationDistance` — Interval for checking state validity**
`Inf` (default) | positive numeric scalar

Interval for sampling between states and checking state validity, specified as a positive numeric scalar.

**`XYIndices` — State variable mapping for *xy*-coordinates**
`[1 2]` (default) | `[xIdx yIdx]`

State variable mapping for *xy*-coordinates in state vector, specified as a two-element vector, `[xIdx yIdx]`. For example, if a state vector is given as `[r p y x y z]`, the *xy*-coordinates are `[4 5]`.

**`ThetaIndex` — State variable mapping for *theta* coordinate**
`NaN` (default) | positive integer

State variable mapping for *theta* coordinate in state vector, specified as a positive integer. For example, if a state vector is given as `[x y theta]`, the *theta* coordinate is `3`.

## Object Functions

| | |
|---|---|
| copy | Create deep copy of state validator object |
| isStateValid | Check if state is valid |
| isMotionValid | Check if path between states is valid |

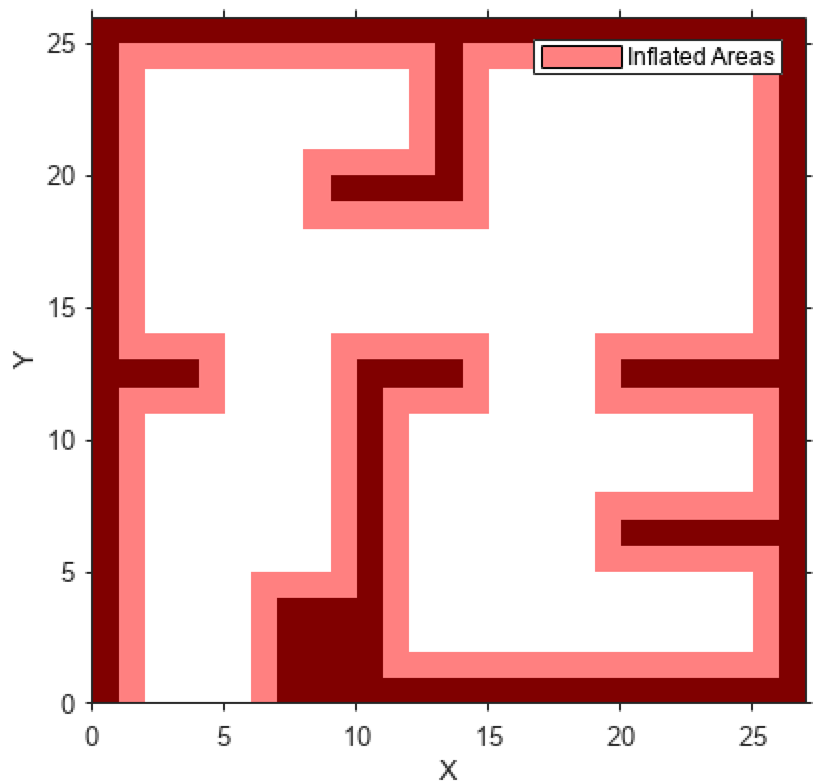
## Examples

### Validate Path Through Vehicle Costmap Environment

This example shows how to validate paths through an evironment.

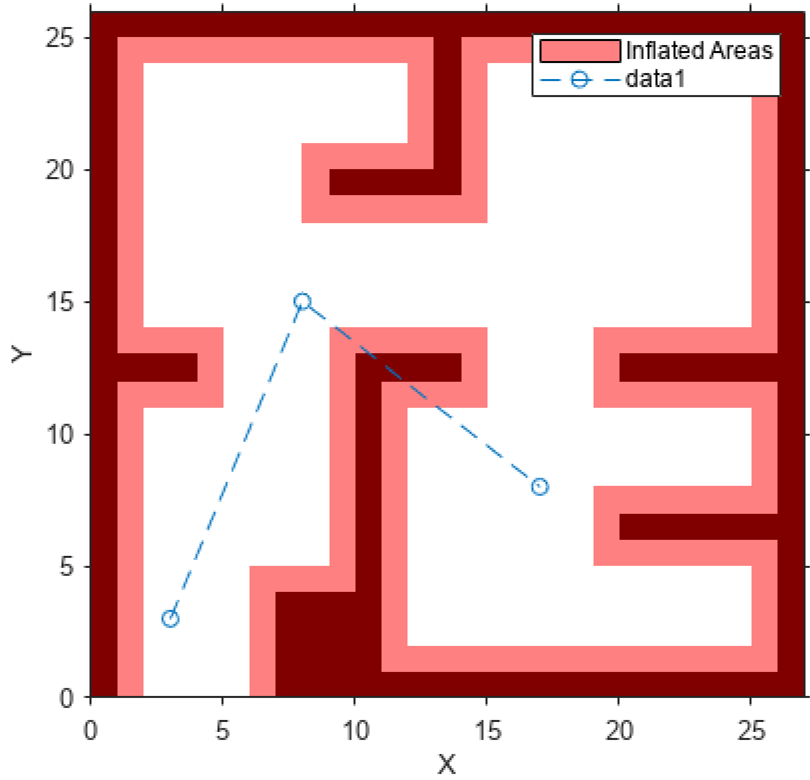
Load example maps. Use the simple map to create a vehicle cost map. Specify an inflation raidus of 1 meter.

```
load exampleMaps.mat
map = vehicleCostmap(double(simpleMap));
map.CollisionChecker = inflationCollisionChecker("InflationRadius",1);
plot(map)
```




Specify a coarse path through the map.

```
path = [3 3 pi/2; 8 15 0; 17 8 -pi/2];
hold on
plot(path(:,1),path(:,2),"--o")
```




Create a state validator using the `stateSpaceSE2` definition. Specify the map and the distance for interpolating and validating path segments.

```
validator = validatorVehicleCostmap(stateSpaceSE2);
validator.Map = map;
validator.ValidationDistance = 0.1;
```

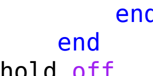
Check the points of the path are valid states. All three points are in free space, so are considered valid.

```
isValid = isStateValid(validator,path)
```

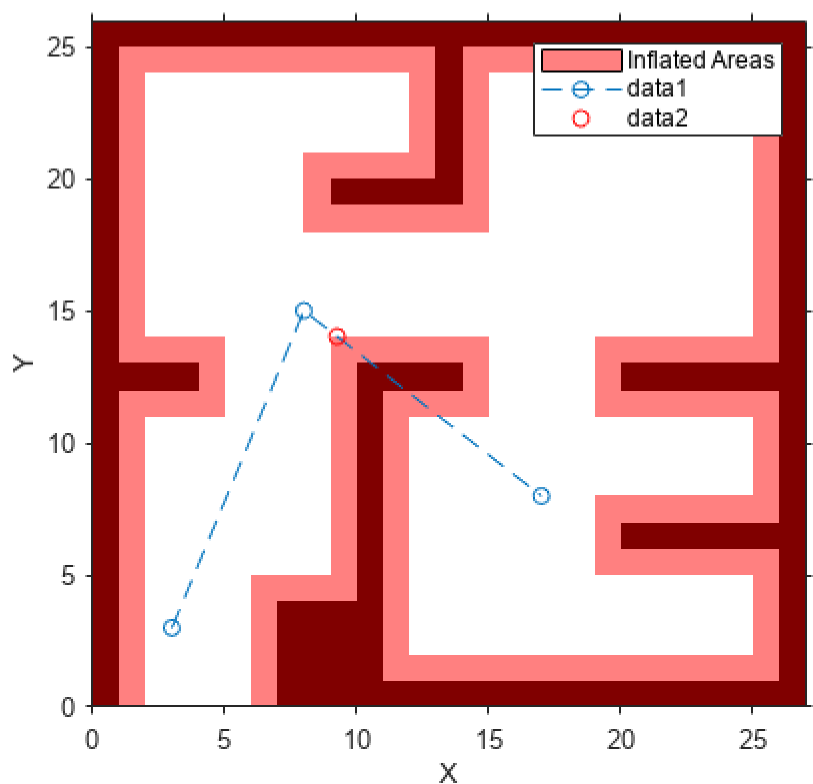
```
isValid = 3x1 logical array

   1
   1
   1
```

Check the motion between each sequential path states. The `isMotionValid` function interpolates along the path between states. If a path segment is invalid, plot the last valid point along the path.

```
startStates = [path(1,:);path(2,:)];
endStates = [path(2,:);path(3,:)];
    for i = 1:2
        [isPathValid, lastValid] = isMotionValid(validator,startStates(i,:),endStates(i,:));
        if ~isPathValid
            plot(lastValid(1),lastValid(2),'or')
```



```
        end
    end
hold off
```




# Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

For code generation, the map used inside the object must remain constant.

## See Also

`validatorOccupancyMap` | `stateSpaceSE2` | `nav.StateSpace` | `nav.StateValidator`

# copy

Create deep copy of state validator object

## Syntax

```
validator2 = copy(validator1)
```

## Description

`validator2 = copy(validator1)` creates a deep copy of the specified state validator object.

## Examples

### Create Deep Copy of 3-D Occupancy Map State Validator Object

Create a validator object and set a custom validation distance.

```
validator = validatorOccupancyMap3D;
validator.ValidationDistance = 4.5
```

```
validator = 
  validatorOccupancyMap3D with properties:

                   Map: [1x1 occupancyMap3D]
            StateSpace: [1x1 stateSpaceSE3]
            XYZIndices: [1 2 3]
    ValidationDistance: 4.5000
```

Create a deep copy of the state validator object.

```
validator2 = copy(validator)
```

```
validator2 = 
  validatorOccupancyMap3D with properties:

                   Map: [1x1 occupancyMap3D]
            StateSpace: [1x1 stateSpaceSE3]
            XYZIndices: [1 2 3]
    ValidationDistance: 4.5000
```

Verify that the `ValidationDistance` property values of the two state validator objects are equal.

```
isequal(validator.ValidationDistance,validator2.ValidationDistance)
```

```
ans = logical
   1
```

### Input Arguments

**`validator1` — State validator object**
`validatorOccupancyMap` object | `validatorOccupancyMap3D` object | `validatorVehicleCostmap` object

State validator object, specified as a `validatorOccupancyMap`, `validatorOccupancyMap3D`, or `validatorVehicleCostmap` object.

### Output Arguments

**`validator2` — State validator object**
`validatorOccupancyMap` object | `validatorOccupancyMap3D` object | `validatorVehicleCostmap` object

State validator object, returned as a `validatorOccupancyMap`, `validatorOccupancyMap3D`, or `validatorVehicleCostmap` object.

## Version History

**Introduced in R2020b**

### See Also

`validatorOccupancyMap` | `validatorOccupancyMap3D` | `validatorVehicleCostmap`

# isMotionValid

Check if path between states is valid

## Syntax

```
[isValid,lastValid] = isMotionValid(validator,state1,state2)
```

## Description

`[isValid,lastValid] = isMotionValid(validator,state1,state2)` checks if the path between two states is valid by interpolating between states. The function also returns the last valid state along the path.

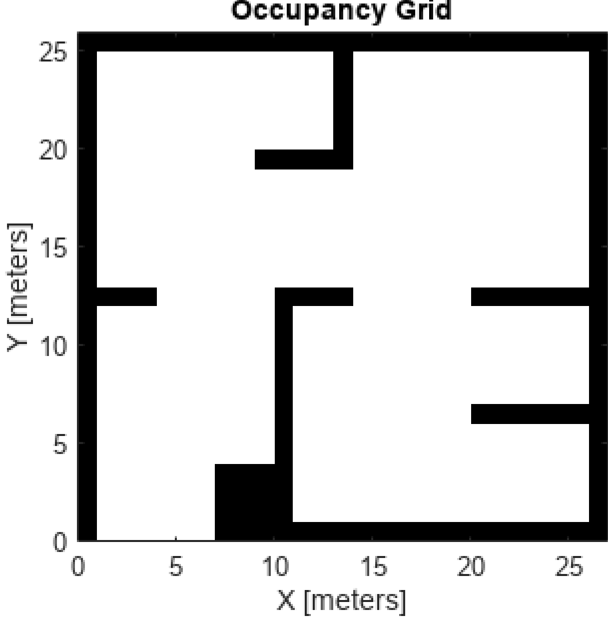
## Examples

### Validate Path Through Occupancy Map Environment

This example shows how to validate paths through an environment.

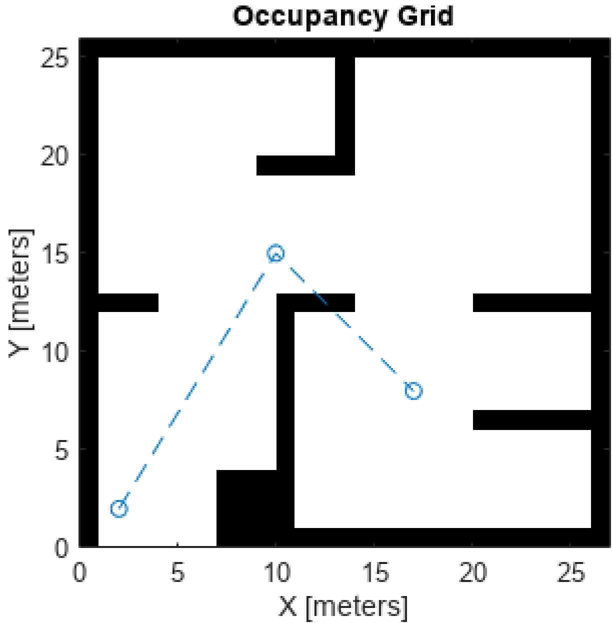
Load example maps. Use the simple map to create a binary occupancy map.

```
load exampleMaps.mat
map = occupancyMap(simpleMap);
show(map)
```




Specify a coarse path through the map.

```
path = [2 2 pi/2; 10 15 0; 17 8 -pi/2];
hold on
plot(path(:,1),path(:,2),"--o")
```




Create a state validator using the `stateSpaceSE2` definition. Specify the map and the distance for interpolating and validating path segments.

```
validator = validatorOccupancyMap(stateSpaceSE2);
validator.Map = map;
validator.ValidationDistance = 0.1;
```

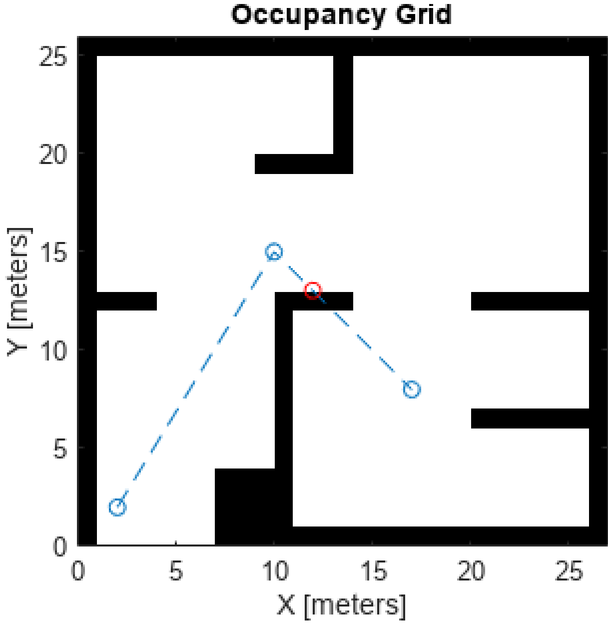
Check the points of the path are valid states. All three points are in free space, so are considered valid.

```
isValid = isStateValid(validator,path)
```

```
isValid = 3x1 logical array

   1
   1
   1
```

Check the motion between each sequential path states. The `isMotionValid` function interpolates along the path between states. If a path segment is invalid, plot the last valid point along the path.

```
startStates = [path(1,:);path(2,:)];
endStates = [path(2,:);path(3,:)];
    for i = 1:2
        [isPathValid, lastValid] = isMotionValid(validator,startStates(i,:),endStates(i,:));
        if ~isPathValid
            plot(lastValid(1),lastValid(2),'or')
        end
    end
hold off
```

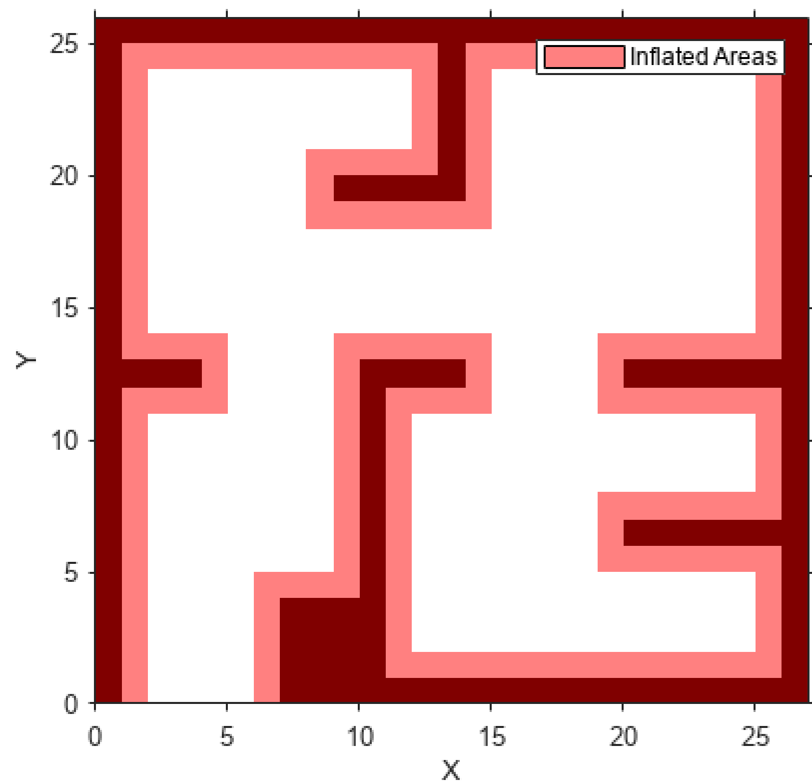



**Validate Path Through Vehicle Costmap Environment**

This example shows how to validate paths through an evironment.

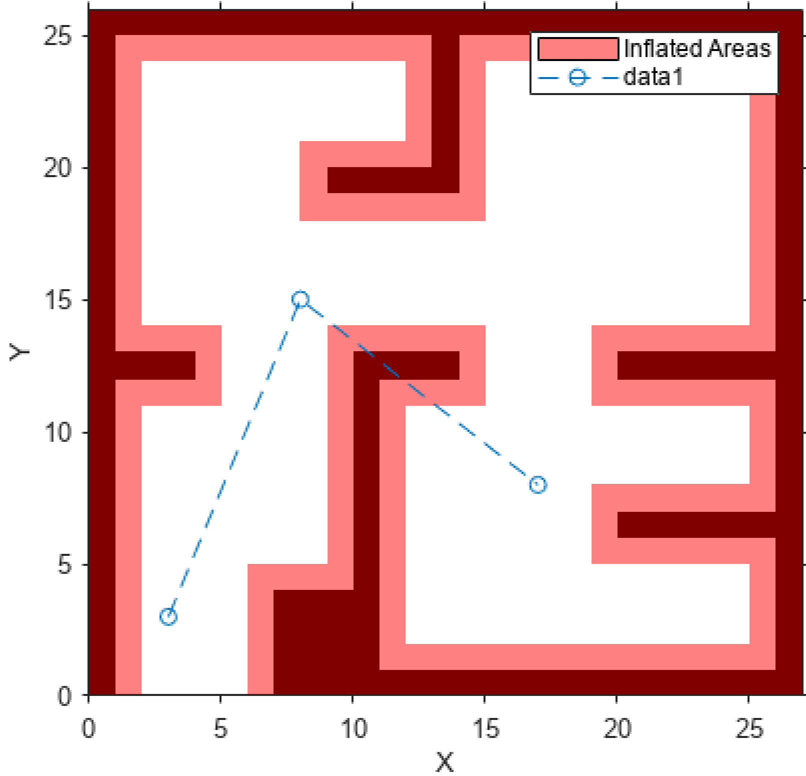
Load example maps. Use the simple map to create a vehicle cost map. Specify an inflation raidus of 1 meter.

```
load exampleMaps.mat
map = vehicleCostmap(double(simpleMap));
map.CollisionChecker = inflationCollisionChecker("InflationRadius",1);
plot(map)
```




Specify a coarse path through the map.

```
path = [3 3 pi/2; 8 15 0; 17 8 -pi/2];
hold on
plot(path(:,1),path(:,2),"--o")
```




Create a state validator using the `stateSpaceSE2` definition. Specify the map and the distance for interpolating and validating path segments.

```
validator = validatorVehicleCostmap(stateSpaceSE2);
validator.Map = map;
validator.ValidationDistance = 0.1;
```

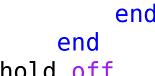
Check the points of the path are valid states. All three points are in free space, so are considered valid.

```
isValid = isStateValid(validator,path)
```

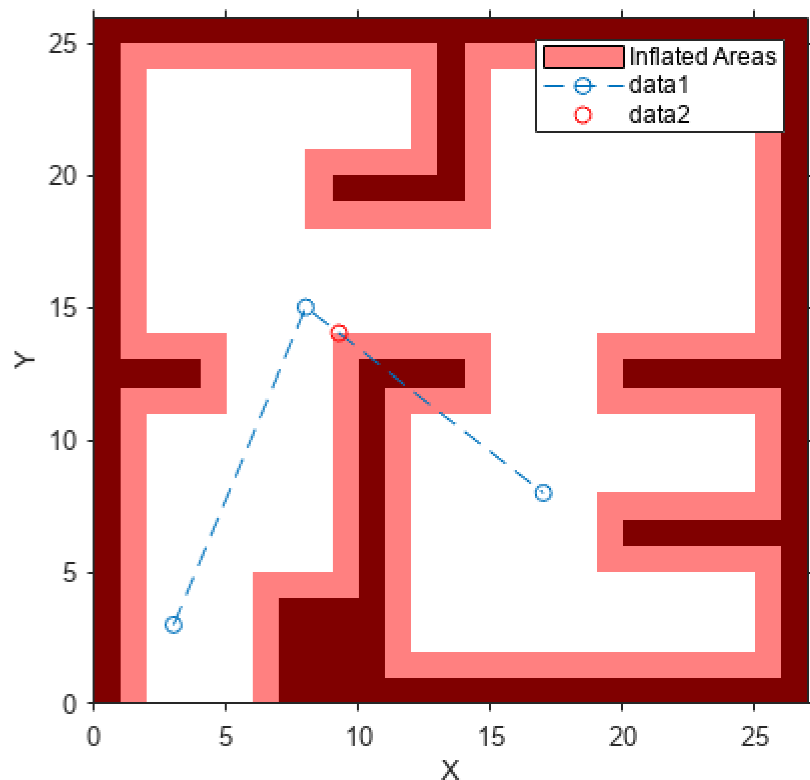
```
isValid = 3x1 logical array

   1
   1
   1
```

Check the motion between each sequential path states. The `isMotionValid` function interpolates along the path between states. If a path segment is invalid, plot the last valid point along the path.

```
startStates = [path(1,:);path(2,:)];
endStates = [path(2,:);path(3,:)];
    for i = 1:2
        [isPathValid, lastValid] = isMotionValid(validator,startStates(i,:),endStates(i,:));
        if ~isPathValid
            plot(lastValid(1),lastValid(2),'or')
```



```
        end
    end
hold off
```




**Validate Path Through 3-D Occupancy Map Environment**

Create a 3-D occupancy map and associated state validator. Plan, validate, and visualize a path through the occupancy map.

**Load and Assign Map to State Validator**

Load a 3-D occupancy map of a city block into the workspace. Specify a threshold for which cells to consider as obstacle-free.

```
mapData = load('dMapCityBlock.mat');
omap = mapData.omap;
omap.FreeThreshold = 0.5;
```

Inflate the occupancy map to add a buffer zone for safe operation around the obstacles.

```
inflate(omap,1)
```

Create an SE(3) state space object with bounds for state variables.

```
ss = stateSpaceSE3([-20 220;
    -20 220;
```

```
    -10 100;
    inf inf;
    inf inf;
    inf inf;
    inf inf]);
```

Create a 3-D occupancy map state validator using the created state space.

```
sv = validatorOccupancyMap3D(ss);
```

Assign the occupancy map to the state validator object. Specify the sampling distance interval.

```
sv.Map = omap;
sv.ValidationDistance = 0.1;
```

**Plan and Visualize Path**

Create a path planner with increased maximum connection distance. Reduce the maximum number of iterations.

```
planner = plannerRRT(ss,sv);
planner.MaxConnectionDistance = 50;
planner.MaxIterations = 1000;
```

Create a user-defined evaluation function for determining whether the path reaches the goal. Specify the probability of choosing the goal state during sampling.

```
planner.GoalReachedFcn = @(~,x,y)(norm(x(1:3)-y(1:3))<5);
planner.GoalBias = 0.1;
```

Set the start and goal states.

```
start = [40 180 25 0.7 0.2 0 0.1];
goal = [150 33 35 0.3 0 0.1 0.6];
```

Plan a path using the specified start, goal, and planner.

```
[pthObj,solnInfo] = plan(planner,start,goal);
```

Check that the points of the path are valid states.

```
isValid = isStateValid(sv,pthObj.States)
```

```
isValid = 7x1 logical array

   1
   1
   1
   1
   1
   1
   1
```

Check that the motion between each sequential path state is valid.

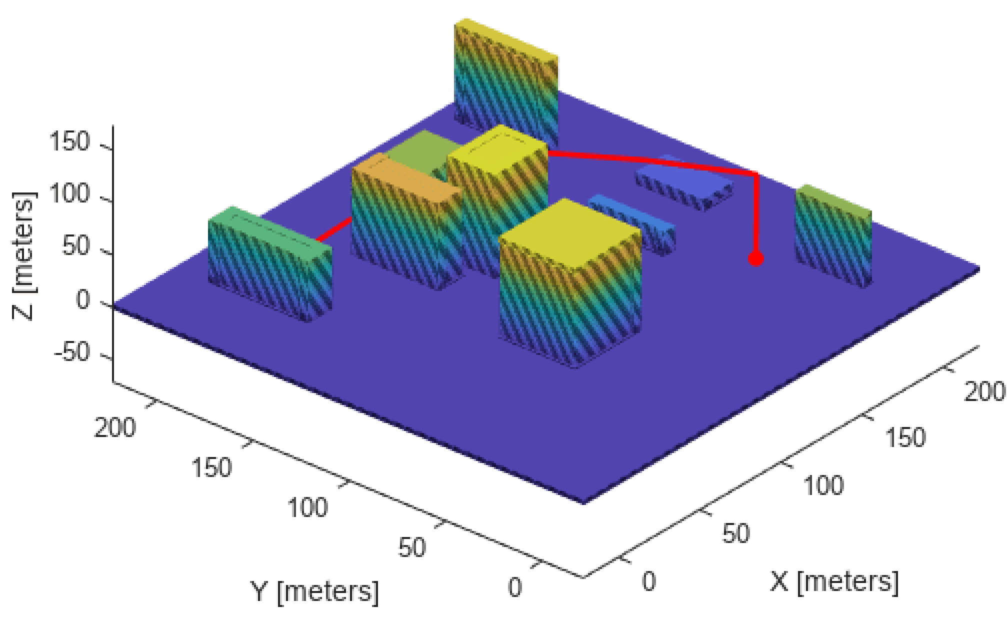
```
isPathValid = zeros(size(pthObj.States,1)-1,1,'logical');
for i = 1:size(pthObj.States,1)-1
    [isPathValid(i),~] = isMotionValid(sv,pthObj.States(i,:),...
```

```
        pthObj.States(i+1,:));
end
isPathValid
```

```
isPathValid = 6x1 logical array

   1
   1
   1
   1
   1
   1
```

Visualize the results.

```
show(omap)
hold on
scatter3(start(1,1),start(1,2),start(1,3),'g','filled') % draw start state
scatter3(goal(1,1),goal(1,2),goal(1,3),'r','filled')    % draw goal state
plot3(pthObj.States(:,1),pthObj.States(:,2),pthObj.States(:,3),...
    'r-','LineWidth',2) % draw path
```




## Input Arguments

**validator — State validator object**
object of subclass of nav.StateValidator

State validator object, specified as an object of subclass of `nav.StateValidator`. These are the predefined state validator objects:

- `validatorOccupancyMap`
- `validatorVehicleCostmap`
- `validatorOccupancyMap3D`

**`state1` — Initial state positions**
*n*-element row vector | *m*-by-*n* matrix

Initial state positions, specified as an *n*-element row vector or *m*-by-*n* matrix. *n* is the dimension of the state space specified in `validator`. *m* is the number of states to validate.

Data Types: `single` | `double`

**`state2` — Final state positions**
*n*-element row vector | *m*-by-*n* matrix

Final state positions, specified as an *n*-element row vector or *m*-by-*n* matrix. *n* is the dimension of the state space specified in `validator`. *m* is the number of states to validate.

Data Types: `single` | `double`

## Output Arguments

**`isValid` — Valid states**
*m*-element logical column vector

Valid states, returned as an *m*-element logical column vector.

Data Types: `logical`

**`lastValid` — Final valid state along each path**
*n*-element row vector | *m*-by-*n* matrix

Final valid state along each path, returned as an *n*-element row vector or *m*-by-*n* matrix. *n* is the dimension of the state space specified in the state space property in `validator`. *m* is the number of paths validated. Each row contains the final valid state along the associated path.

Data Types: `single` | `double`

# Version History

**Introduced in R2019b**

## See Also

`isStateValid` | `stateSpaceSE2` | `nav.StateSpace` | `nav.StateValidator`

# isStateValid

Check if state is valid

## Syntax

```
isValid = isStateValid(validator,states)
```

## Description

`isValid = isStateValid(validator,states)` checks if a set of given states are valid.

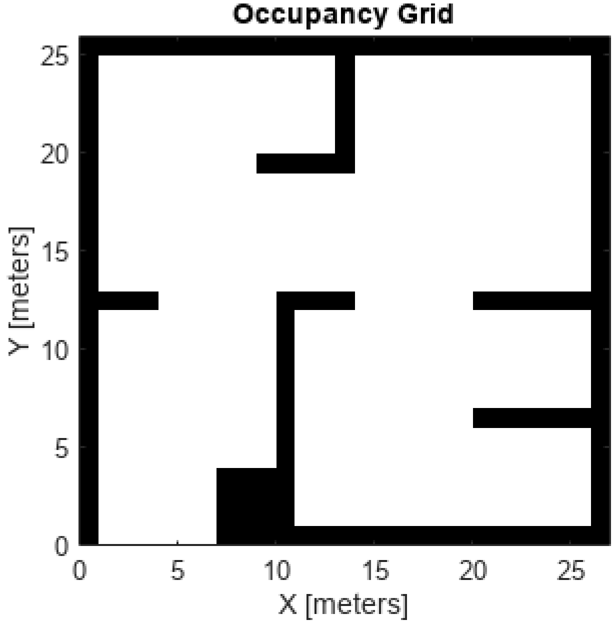
## Examples

### Validate Path Through Occupancy Map Environment

This example shows how to validate paths through an environment.

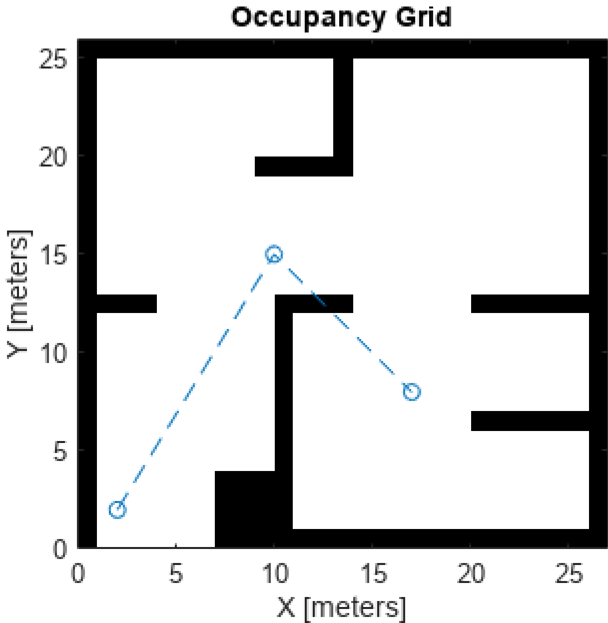
Load example maps. Use the simple map to create a binary occupancy map.

```
load exampleMaps.mat
map = occupancyMap(simpleMap);
show(map)
```




Specify a coarse path through the map.

```
path = [2 2 pi/2; 10 15 0; 17 8 -pi/2];
hold on
plot(path(:,1),path(:,2),"--o")
```




Create a state validator using the `stateSpaceSE2` definition. Specify the map and the distance for interpolating and validating path segments.

```
validator = validatorOccupancyMap(stateSpaceSE2);
validator.Map = map;
validator.ValidationDistance = 0.1;
```

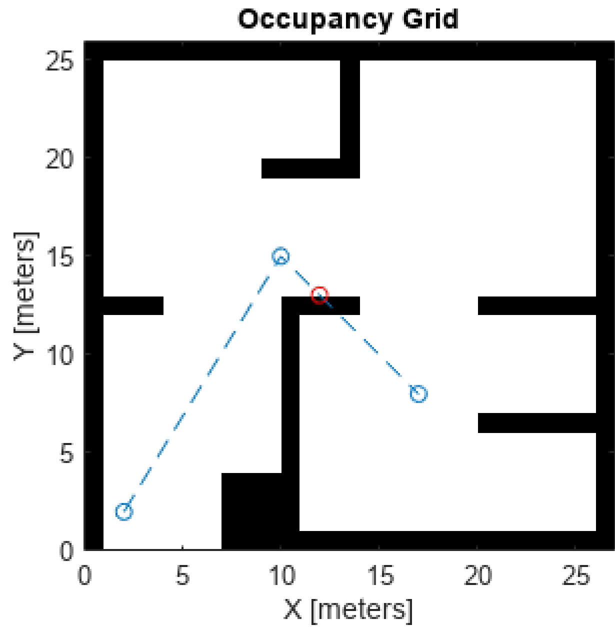
Check the points of the path are valid states. All three points are in free space, so are considered valid.

```
isValid = isStateValid(validator,path)
```

```
isValid = 3x1 logical array

   1
   1
   1
```

Check the motion between each sequential path states. The `isMotionValid` function interpolates along the path between states. If a path segment is invalid, plot the last valid point along the path.

```
startStates = [path(1,:);path(2,:)];
endStates = [path(2,:);path(3,:)];
    for i = 1:2
        [isPathValid, lastValid] = isMotionValid(validator,startStates(i,:),endStates(i,:));
        if ~isPathValid
            plot(lastValid(1),lastValid(2),'or')
        end
    end
hold off
```

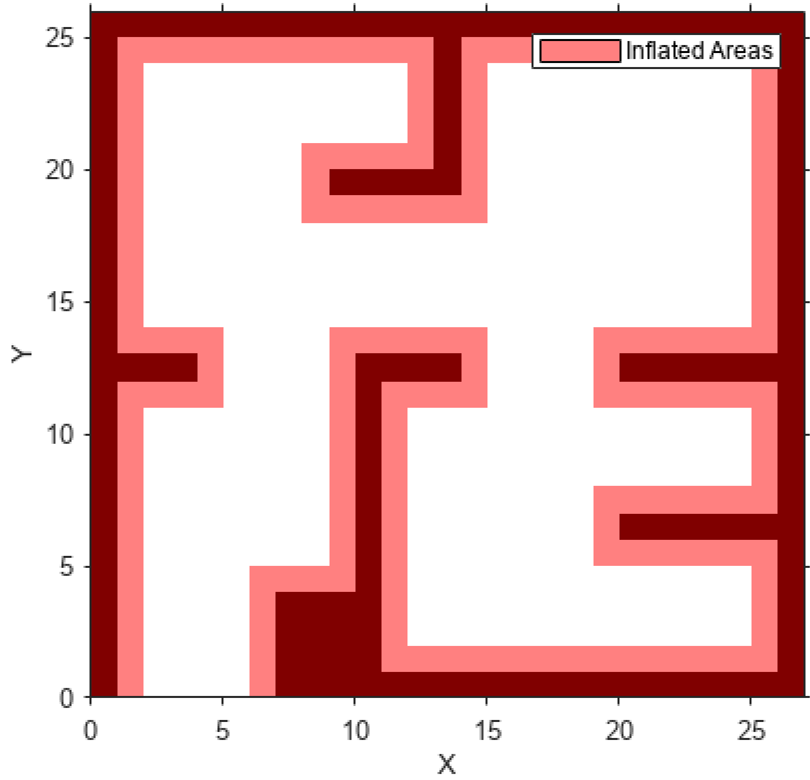



#### Validate Path Through Vehicle Costmap Environment

This example shows how to validate paths through an evironment.

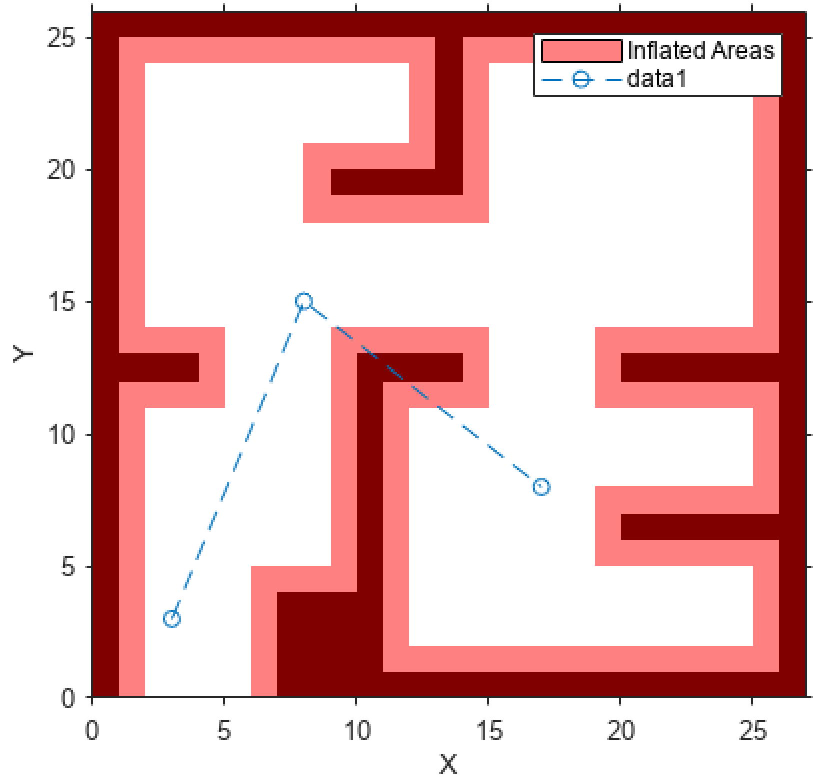
Load example maps. Use the simple map to create a vehicle cost map. Specify an inflation raidus of 1 meter.

```
load exampleMaps.mat
map = vehicleCostmap(double(simpleMap));
map.CollisionChecker = inflationCollisionChecker("InflationRadius",1);
plot(map)
```




Specify a coarse path through the map.

```
path = [3 3 pi/2; 8 15 0; 17 8 -pi/2];
hold on
plot(path(:,1),path(:,2),"--o")
```




Create a state validator using the `stateSpaceSE2` definition. Specify the map and the distance for interpolating and validating path segments.

```
validator = validatorVehicleCostmap(stateSpaceSE2);
validator.Map = map;
validator.ValidationDistance = 0.1;
```

Check the points of the path are valid states. All three points are in free space, so are considered valid.

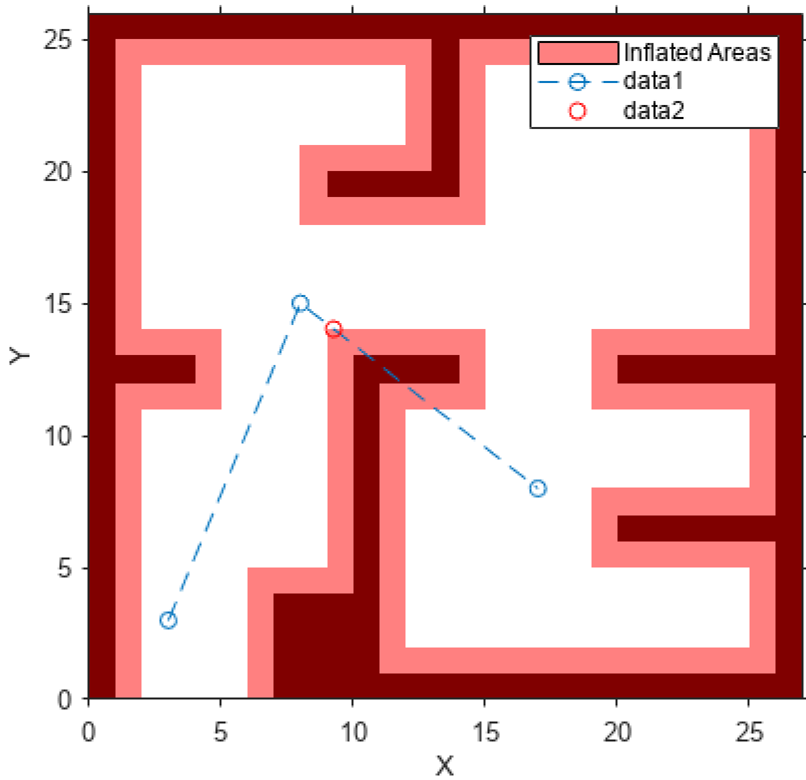
```
isValid = isStateValid(validator,path)
```

```
isValid = 3x1 logical array

   1
   1
   1
```

Check the motion between each sequential path states. The `isMotionValid` function interpolates along the path between states. If a path segment is invalid, plot the last valid point along the path.

```
startStates = [path(1,:);path(2,:)];
endStates = [path(2,:);path(3,:)];
    for i = 1:2
        [isPathValid, lastValid] = isMotionValid(validator,startStates(i,:),endStates(i,:));
        if ~isPathValid
            plot(lastValid(1),lastValid(2),'or')
```

```
        end
    end
hold off
```




**Validate Path Through 3-D Occupancy Map Environment**

Create a 3-D occupancy map and associated state validator. Plan, validate, and visualize a path through the occupancy map.

**Load and Assign Map to State Validator**

Load a 3-D occupancy map of a city block into the workspace. Specify a threshold for which cells to consider as obstacle-free.

```
mapData = load('dMapCityBlock.mat');
omap = mapData.omap;
omap.FreeThreshold = 0.5;
```

Inflate the occupancy map to add a buffer zone for safe operation around the obstacles.

```
inflate(omap,1)
```

Create an SE(3) state space object with bounds for state variables.

```
ss = stateSpaceSE3([-20 220;
    -20 220;
```

```
    -10 100;
    inf inf;
    inf inf;
    inf inf;
    inf inf]);
```

Create a 3-D occupancy map state validator using the created state space.

```
sv = validatorOccupancyMap3D(ss);
```

Assign the occupancy map to the state validator object. Specify the sampling distance interval.

```
sv.Map = omap;
sv.ValidationDistance = 0.1;
```

#### Plan and Visualize Path

Create a path planner with increased maximum connection distance. Reduce the maximum number of iterations.

```
planner = plannerRRT(ss,sv);
planner.MaxConnectionDistance = 50;
planner.MaxIterations = 1000;
```

Create a user-defined evaluation function for determining whether the path reaches the goal. Specify the probability of choosing the goal state during sampling.

```
planner.GoalReachedFcn = @(~,x,y)(norm(x(1:3)-y(1:3))<5);
planner.GoalBias = 0.1;
```

Set the start and goal states.

```
start = [40 180 25 0.7 0.2 0 0.1];
goal = [150 33 35 0.3 0 0.1 0.6];
```

Plan a path using the specified start, goal, and planner.

```
[pthObj,solnInfo] = plan(planner,start,goal);
```

Check that the points of the path are valid states.

```
isValid = isStateValid(sv,pthObj.States)
```

```
isValid = 7x1 logical array

   1
   1
   1
   1
   1
   1
   1
```

Check that the motion between each sequential path state is valid.

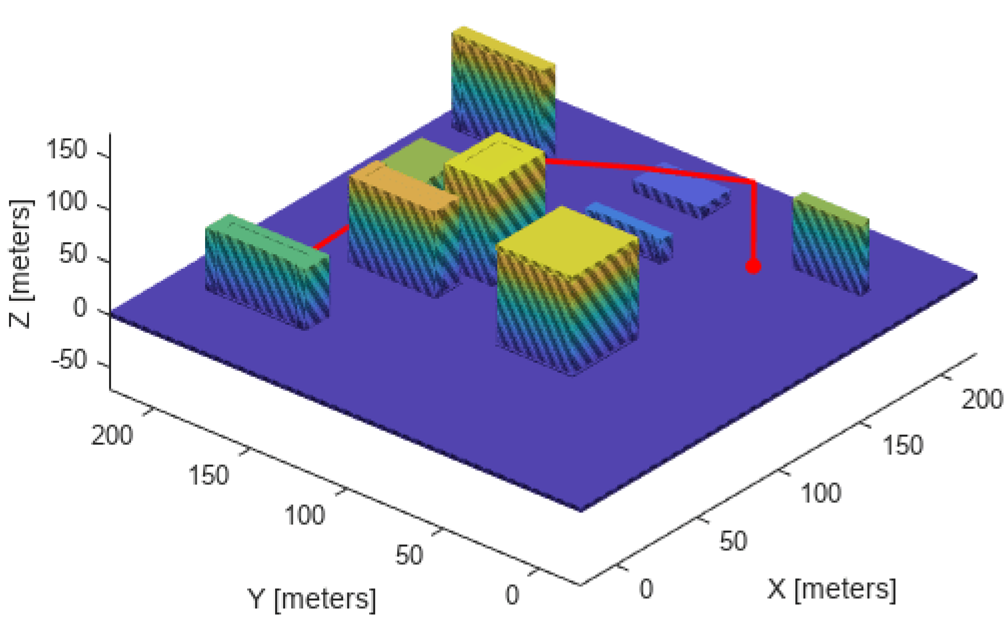
```
isPathValid = zeros(size(pthObj.States,1)-1,1,'logical');
for i = 1:size(pthObj.States,1)-1
    [isPathValid(i),~] = isMotionValid(sv,pthObj.States(i,:),...
```

```
        pthObj.States(i+1,:));
end
isPathValid
```

```
isPathValid = 6x1 logical array

   1
   1
   1
   1
   1
   1
```

Visualize the results.

```
show(omap)
hold on
scatter3(start(1,1),start(1,2),start(1,3),'g','filled') % draw start state
scatter3(goal(1,1),goal(1,2),goal(1,3),'r','filled')    % draw goal state
plot3(pthObj.States(:,1),pthObj.States(:,2),pthObj.States(:,3),...
    'r-','LineWidth',2) % draw path
```




## Input Arguments

**`validator` — State validator object**

object of subclass of `nav.StateValidator`

State validator object, specified as an object of subclass of `nav.StateValidator`. These are the predefined state validator objects:

- `validatorOccupancyMap`
- `validatorVehicleCostmap`
- `validatorOccupancyMap3D`

**`states` — State positions**
*n*-element row vector | *m*-by-*n* matrix

State positions, specified as an *n*-element row vector or *m*-by-*n* matrix. *n* is the dimension of the state space specified in `validator`. *m* is the number of states to validate.

Data Types: `single` | `double`

## Output Arguments

**`isValid` — Valid states**
*m*-element logical column vector

Valid states, returned as an *m*-element logical column vector.

Data Types: `logical`

# Version History

**Introduced in R2019b**

## See Also

`isMotionValid` | `stateSpaceSE2` | `nav.StateSpace` | `nav.StateValidator`

# waypointTrajectory

Waypoint trajectory generator

## Description

The `waypointTrajectory` System object generates trajectories based on specified waypoints. When you create the System object, you can choose to specify the time of arrival, velocity, or ground speed at each waypoint. You can optionally specify other properties such as orientation at each waypoint. See “Algorithms” on page 2-1797 for more details.

To generate a trajectory from waypoints:

1. Create the `waypointTrajectory` object and set its properties.
2. Call the object as if it were a function.

To learn more about how System objects work, see What Are System Objects?.

# Creation

## Syntax

```
trajectory = waypointTrajectory
trajectory = waypointTrajectory(Waypoints,TimeOfArrival)
trajectory = waypointTrajectory(Waypoints,GroundSpeed=groundSpeed)
trajectory = waypointTrajectory(Waypoints,Velocities=velocities)
trajectory = waypointTrajectory( ___ ,Name=Value)
```

### Description

`trajectory = waypointTrajectory` returns a System object, `trajectory`, that generates a trajectory based on default stationary waypoints.

`trajectory = waypointTrajectory(Waypoints,TimeOfArrival)` specifies the time of arrival at which the generated trajectory passes through each waypoint. See the `TimeOfArrival` property for more details.

---

**Tip** When you specify the `TimeOfArrival` argument, you must not specify these properties:

- `JerkLimit`
- `InitialTime`
- `WaitTime`

---

`trajectory = waypointTrajectory(Waypoints,GroundSpeed=groundSpeed)` specifies the ground speed at which the generated trajectory passes through at each waypoint. See the `GroundSpeed` property for more details.

`trajectory = waypointTrajectory(Waypoints,Velocities=velocities)` specifies the velocity at which the generated trajectory passes through at each waypoint. See the `Velocities` property for more details.

`trajectory = waypointTrajectory(___,Name=Value)` sets each property by using name-value arguments. Unspecified properties have default or inferred values. You can use this syntax with any of the previous syntaxes.

Example: `trajectory = waypointTrajectory([10,10,0;20,20,0;20,20,10],[0,0.5,10])` creates a waypoint trajectory System object, `trajectory`, that starts at waypoint `[10,10,0]`, and then passes through `[20,20,0]` after 0.5 seconds and `[20,20,10]` after 10 seconds.

## Properties

Unless otherwise indicated, properties are *nontunable*, which means you cannot change their values after calling the object. Objects lock when you call them, and the `release` function unlocks them.

If a property is *tunable*, you can change its value at any time.

For more information on changing property values, see System Design in MATLAB Using System Objects.

**`SampleRate` — Sample rate of trajectory (Hz)**
`100` (default) | positive scalar

Sample rate of trajectory in Hz, specified as a positive scalar.

**Tunable:** Yes

Data Types: `double`

**`SamplesPerFrame` — Number of samples per output frame**
`1` (default) | positive scalar integer

Number of samples per output frame, specified as a positive scalar integer.

Data Types: `double`

**`Waypoints` — Positions in the navigation coordinate system (m)**
*N*-by-3 matrix

Positions in the navigation coordinate system in meters, specified as an *N*-by-3 matrix. The columns of the matrix correspond to the first, second, and third axes, respectively. The rows of the matrix, *N*, correspond to individual waypoints.

---

**Tip** To let the trajectory wait at a specific waypoint, use one of the two options:

- If you specified the `TimeOfArrival` input argument, repeat the waypoint coordinate in two consecutive rows.
- If you did not specify the `TimeOfArrival` input argument, specify the wait time using the `WaitTime` property.

---

Data Types: `double`

### `TimeOfArrival` — Time at each waypoint (s)

*N*-element column vector of nonnegative increasing numbers

Time corresponding to arrival at each waypoint in seconds, specified as an *N*-element column vector. The first element of `TimeOfArrival` must be `0`. The number of samples, *N*, must be the same as the number of samples (rows) defined by `Waypoints`.

#### Dependencies

To set this property, you must not specify these properties:

- `JerkLimit`
- `InitialTime`
- `WaitTime`

Data Types: `double`

### `Velocities` — Velocity in navigation coordinate system at each waypoint (m/s)

*N*-by-3 matrix

Velocity in the navigation coordinate system at each waypoint in meters per second, specified as an *N*-by-3 matrix. The columns of the matrix correspond to the first, second, and third axes, respectively. The number of samples, *N*, must be the same as the number of samples (rows) defined by `Waypoints`.

If the velocity is specified as a non-zero value, the object automatically calculates the course of the trajectory based on the velocity. If the velocity is specified as zero, the object infers the course of the trajectory from adjacent waypoints.

Data Types: `double`

### `Course` — Horizontal direction of travel (degree)

*N*-element real vector

Horizontal direction of travel, specified as an *N*-element real vector in degrees. The number of samples, *N*, must be the same as the number of samples (rows) defined by `Waypoints`. If neither `Velocities` nor `Course` is specified, course is inferred from the waypoints.

#### Dependencies

To set this property, the Velocities property must not be specified.

Data Types: `double`

### `GroundSpeed` — Groundspeed at each waypoint (m/s)

*N*-element real vector

Groundspeed at each waypoint, specified as an *N*-element real vector in m/s. If the property is not specified, it is inferred from the waypoints. The number of samples, *N*, must be the same as the number of samples (rows) defined by `Waypoints`.

- To render forward motion, specify positive ground speed values.
- To render backward motion, specify negative ground speed values.
- To render reverse motion, separate positive and negative groundspeed values by a zero groundspeed value.

#### Dependencies

To set this property, the Velocities property must not be specified.

Data Types: `double`

### `ClimbRate` — Climb rate at each waypoint (m/s)
*N*-element real vector

Climb Rate at each waypoint in meters per second, specified as an *N*-element real vector. The number of samples, *N*, must be the same as the number of samples (rows) defined by `Waypoints`. If neither `Velocities` nor `Course` is specified, climb rate is inferred from the waypoints.

#### Dependencies

To set this property, the Velocities property must not be specified.

Data Types: `double`

### `JerkLimit` — Longitudinal jerk limit ($m/s^3$)
`Inf` (default) | positive scalar

Longitudinal jerk limit, specified as a positive scalar in $m/s^3$. Jerk is the time derivative of the acceleration. When you specify this property, the object produces a horizontal trapezoidal acceleration profile based on the jerk limit. If the `waypointTrajectory` object cannot achieve the specified `JerkLimit`, the object issues an error. You can set this property only during object creation.

#### Dependencies

To set this property, the TimeOfArrival property must not be specified.

Data Types: `double`

### `InitialTime` — Time before trajectory starts (s)
`0` (default) | nonnegative scalar

Time before the trajectory starts, specified as a nonnegative scalar in seconds. The object reports quantities, such as position and velocity, as `NaN` before the trajectory starts. You can set this property only during object creation.

#### Dependencies

To set this property, the TimeOfArrival property must not be specified. Instead, you must specify either the `GroundSpeed` or `Velocities` property when creating the object.

Data Types: `double`

### `WaitTime` — Wait time at each waypoint (s)
*N*-element vector of `0` (default) | *N*-element vector of nonnegative scalars

Wait time at each waypoint, specified as an *N*-element vector of nonnegative scalars. *N* must be the same as the number of samples (rows) defined by `Waypoints`. You can set this property only during object creation.

#### Dependencies

To set this property, the TimeOfArrival property must not be specified.

If you specified the TimeOfArrival property, then you cannot specify wait time through this property. Instead, specify wait time by repeating the waypoint coordinate in two consecutive rows in the Waypoints property.

Data Types: `double`

**`Orientation` — Orientation at each waypoint**
*N*-element quaternion column vector | 3-by-3-by-*N* array of real numbers

Orientation at each waypoint, specified as an *N*-element `quaternion` column vector or 3-by-3-by-*N* array of real numbers. Each `quaternion` must have a norm of `1`. Each 3-by-3 rotation matrix must be an orthonormal matrix. The number of quaternions or rotation matrices, *N*, must be the same as the number of samples (rows) defined by `Waypoints`.

If `Orientation` is specified by quaternions, the underlying class must be `double`.

Data Types: `double`

**`AutoPitch` — Align pitch angle with direction of motion**
`false` (default) | `true`

Align pitch angle with the direction of motion, specified as `true` or `false`. When specified as `true`, the pitch angle automatically aligns with the direction of motion. If specified as `false`, the pitch angle is set to zero (level orientation).

**Dependencies**

To set this property, the Orientation property must not be specified.

**`AutoBank` — Align roll angle to counteract centripetal force**
`false` (default) | `true`

Align roll angle to counteract the centripetal force, specified as `true` or `false`. When specified as `true`, the roll angle automatically counteracts the centripetal force. If specified as `false`, the roll angle is set to zero (flat orientation).

**Dependencies**

To set this property, the Orientation property must not be specified.

**`ReferenceFrame` — Reference frame of trajectory**
`'NED'` (default) | `'ENU'`

Reference frame of the trajectory, specified as `'NED'` (North-East-Down) or `'ENU'` (East-North-Up).

## Usage

## Syntax

```
[position,orientation,velocity,acceleration,angularVelocity] = trajectory()
```

### Description

`[position,orientation,velocity,acceleration,angularVelocity] = trajectory()` outputs a frame of trajectory data based on specified creation arguments and properties.

### Output Arguments

**`position` — Position in local navigation coordinate system (m)**
*M*-by-3 matrix

Position in the local navigation coordinate system in meters, returned as an *M*-by-3 matrix.

*M* is specified by the SamplesPerFrame property.

Data Types: `double`

**`orientation` — Orientation in local navigation coordinate system**
*M*-element quaternion column vector | 3-by-3-by-*M* real array

Orientation in the local navigation coordinate system, returned as an *M*-by-1 `quaternion` column vector or a 3-by-3-by-*M* real array.

Each quaternion or 3-by-3 rotation matrix is a frame rotation from the local navigation coordinate system to the current body coordinate system.

*M* is specified by the SamplesPerFrame property.

Data Types: `double`

**`velocity` — Velocity in local navigation coordinate system (m/s)**
*M*-by-3 matrix

Velocity in the local navigation coordinate system in meters per second, returned as an *M*-by-3 matrix.

*M* is specified by the SamplesPerFrame property.

Data Types: `double`

**`acceleration` — Acceleration in local navigation coordinate system (m/s$^2$)**
*M*-by-3 matrix

Acceleration in the local navigation coordinate system in meters per second squared, returned as an *M*-by-3 matrix.

*M* is specified by the SamplesPerFrame property.

Data Types: `double`

**`angularVelocity` — Angular velocity in local navigation coordinate system (rad/s)**
*M*-by-3 matrix

Angular velocity in the local navigation coordinate system in radians per second, returned as an *M*-by-3 matrix.

*M* is specified by the SamplesPerFrame property.

Data Types: `double`

## Object Functions

To use an object function, specify the System object as the first input argument. For example, to release system resources of a System object named `obj`, use this syntax:

```
release(obj)
```

### Specific to waypointTrajectory

| | |
|---|---|
| waypointInfo | Get waypoint information table |
| lookupPose | Obtain pose information for certain time |
| perturbations | Perturbation defined on object |
| perturb | Apply perturbations to object |

### Common to All System Objects

| | |
|---|---|
| clone | Create duplicate System object |
| step | Run System object algorithm |
| release | Release resources and allow changes to System object property values and input characteristics |
| reset | Reset internal states of System object |
| isDone | End-of-data status |

## Examples

#### Create Default waypointTrajectory

```
trajectory = waypointTrajectory
```

```
trajectory = 
  waypointTrajectory with properties:

         SampleRate: 100
    SamplesPerFrame: 1
          Waypoints: [2x3 double]
      TimeOfArrival: [2x1 double]
         Velocities: [2x3 double]
             Course: [2x1 double]
        GroundSpeed: [2x1 double]
          ClimbRate: [2x1 double]
        Orientation: [2x1 quaternion]
          AutoPitch: 0
           AutoBank: 0
     ReferenceFrame: 'NED'
```

Inspect the default waypoints and times of arrival by calling `waypointInfo`. By default, the waypoints indicate a stationary position for one second.

```
waypointInfo(trajectory)
```

```
ans=2×2 table
    TimeOfArrival     Waypoints 
    _____________    ___________
```

```
     0           0     0     0
     1           0     0     0
```

### Create Square Trajectory

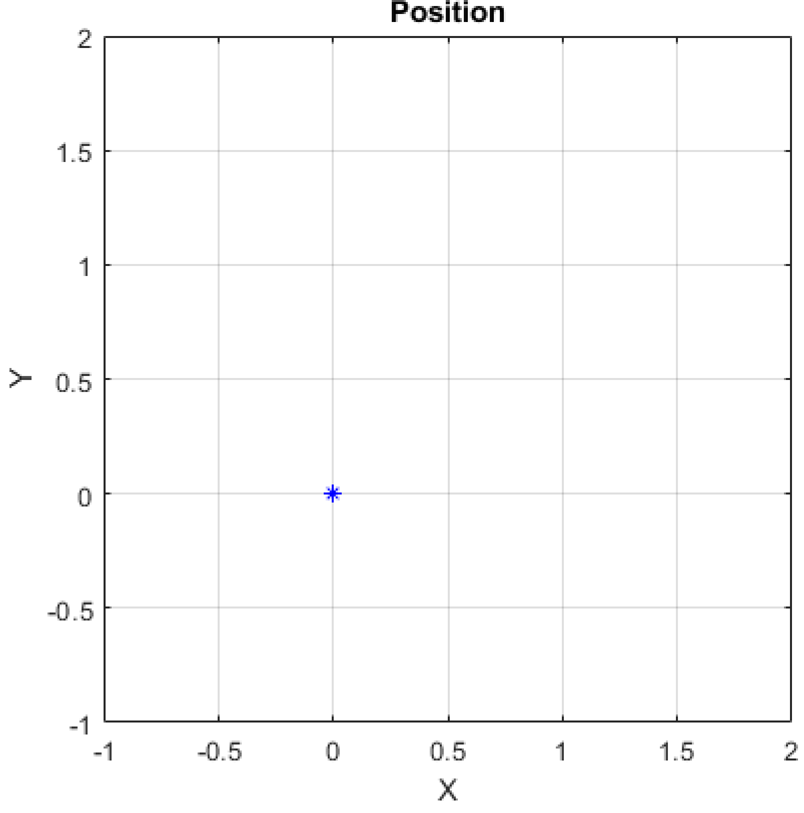
Create a square trajectory and examine the relationship between waypoint constraints, sample rate, and the generated trajectory.

Create a square trajectory by defining the vertices of the square. Define the orientation at each waypoint as pointing in the direction of motion. Specify a 1 Hz sample rate and use the default `SamplesPerFrame` of 1.

```
waypoints = [0,0,0; ... % Initial position
             0,1,0; ...
             1,1,0; ...
             1,0,0; ...
             0,0,0];    % Final position

toa = 0:4; % time of arrival

orientation = quaternion([0,0,0; ...
                          45,0,0; ...
                          135,0,0; ...
                          225,0,0; ...
                          0,0,0], ...
                          "eulerd","ZYX","frame");

trajectory = waypointTrajectory(waypoints, ...
    TimeOfArrival=toa, ...
    Orientation=orientation, ...
    SampleRate=1);
```

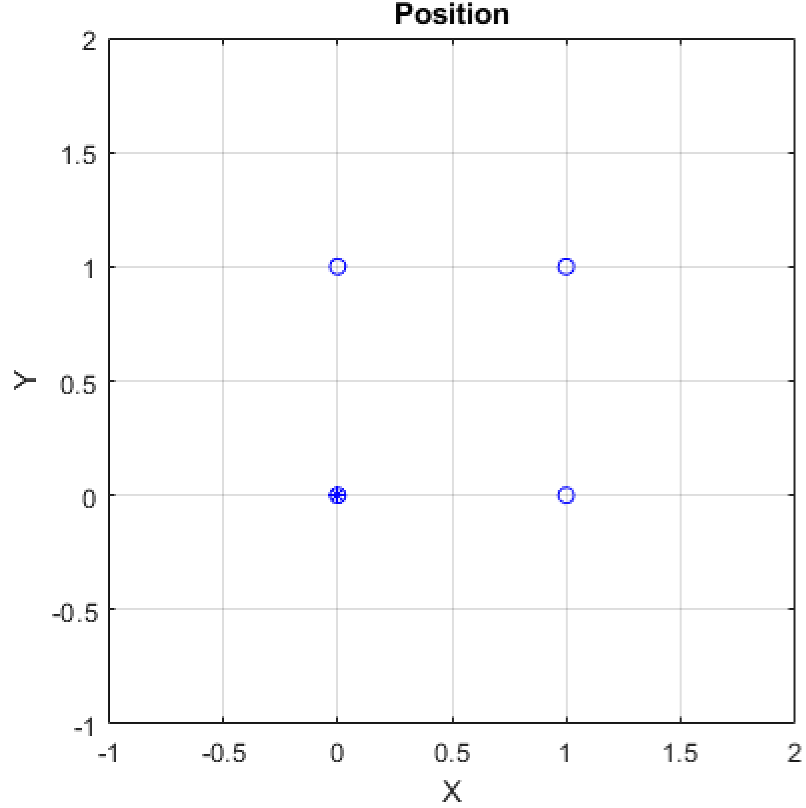
Create a figure and plot the initial position of the platform.

```
figure(1)
plot(waypoints(1,1),waypoints(1,2),"b*")
title("Position")
axis([-1,2,-1,2])
axis square
xlabel("X")
ylabel("Y")
grid on
hold on
```



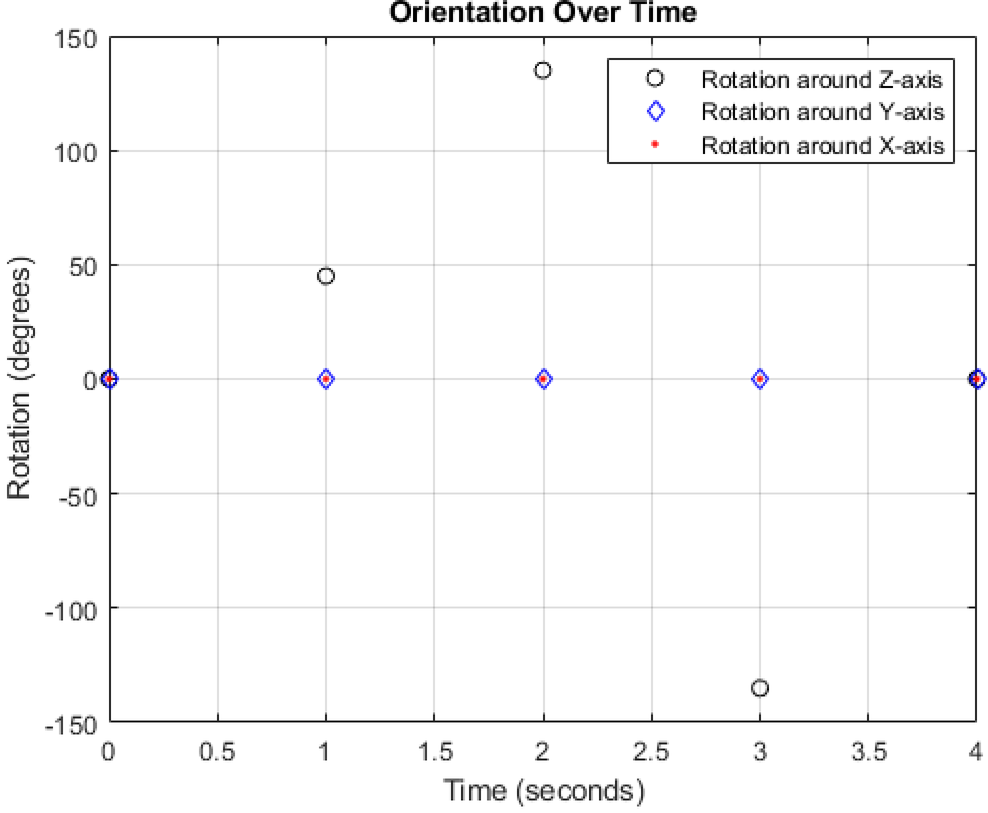

In a loop, step through the trajectory to output the current position and current orientation. Plot the current position and log the orientation. Use `pause` to mimic real-time processing.

```
orientationLog = zeros(toa(end)*trajectory.SampleRate,1,"quaternion");
count = 1;
while ~isDone(trajectory)
   [currentPosition,orientationLog(count)] = trajectory();

   plot(currentPosition(1),currentPosition(2),"bo")

   pause(trajectory.SamplesPerFrame/trajectory.SampleRate)
   count = count + 1;
end
hold off
```




Convert the orientation quaternions to Euler angles for easy interpretation, and then plot orientation over time.

```
figure(2)
eulerAngles = eulerd([orientation(1);orientationLog],"ZYX","frame");
plot(toa,eulerAngles(:,1),"ko", ...
     toa,eulerAngles(:,2),"bd", ...
     toa,eulerAngles(:,3),"r.");
title("Orientation Over Time")
legend("Rotation around Z-axis","Rotation around Y-axis","Rotation around X-axis")
xlabel("Time (seconds)")
ylabel("Rotation (degrees)")
grid on
```



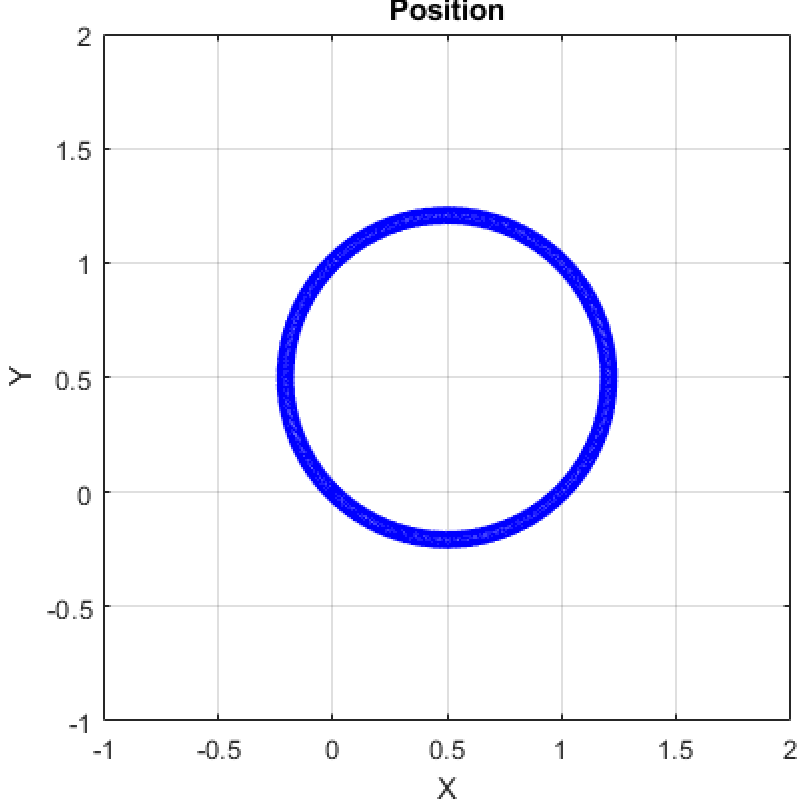

So far, the trajectory object has only output the waypoints that were specified during construction. To interpolate between waypoints, increase the sample rate to a rate faster than the time of arrivals of the waypoints. Set the `trajectory` sample rate to 100 Hz and call `reset`.

```
trajectory.SampleRate = 100;
reset(trajectory)
```

Create a figure and plot the initial position of the platform. In a loop, step through the trajectory to output the current position and current orientation. Plot the current position and log the orientation. Use `pause` to mimic real-time processing.

```
figure(1)
plot(waypoints(1,1),waypoints(1,2),"b*")
title("Position")
axis([-1,2,-1,2])
axis square
xlabel("X")
ylabel("Y")
grid on
hold on

orientationLog = zeros(toa(end)*trajectory.SampleRate,1,"quaternion");
count = 1;
while ~isDone(trajectory)
   [currentPosition,orientationLog(count)] = trajectory();

   plot(currentPosition(1),currentPosition(2),"bo")
```

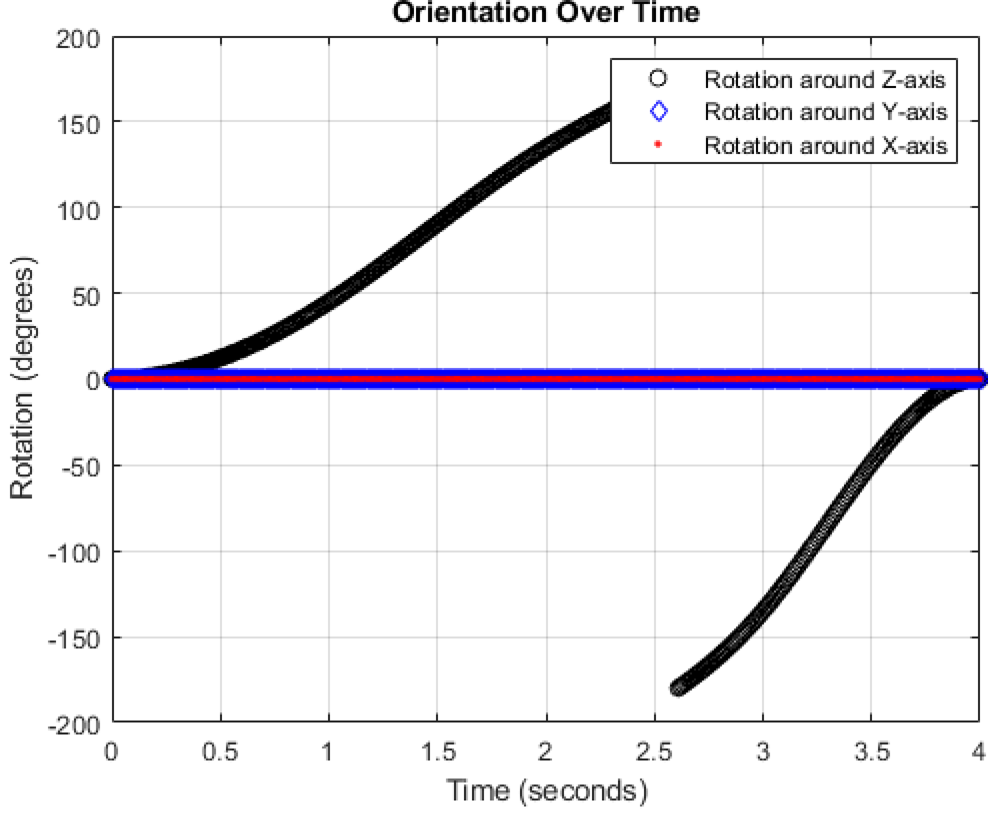
```
    pause(trajectory.SamplesPerFrame/trajectory.SampleRate)
    count = count + 1;
end
hold off
```




The trajectory output now appears circular. This is because the `waypointTrajectory` System object™ minimizes the acceleration and angular velocity when interpolating, which results in smoother, more realistic motions in most scenarios.

Convert the orientation quaternions to Euler angles for easy interpretation, and then plot orientation over time. The orientation is also interpolated.

```
figure(2)
eulerAngles = eulerd([orientation(1);orientationLog],"ZYX","frame");
t = 0:1/trajectory.SampleRate:4;
plot(t,eulerAngles(:,1),"ko", ...
     t,eulerAngles(:,2),"bd", ...
     t,eulerAngles(:,3),"r.");
title("Orientation Over Time")
legend("Rotation around Z-axis","Rotation around Y-axis","Rotation around X-axis")
xlabel("Time (seconds)")
ylabel("Rotation (degrees)")
grid on
```

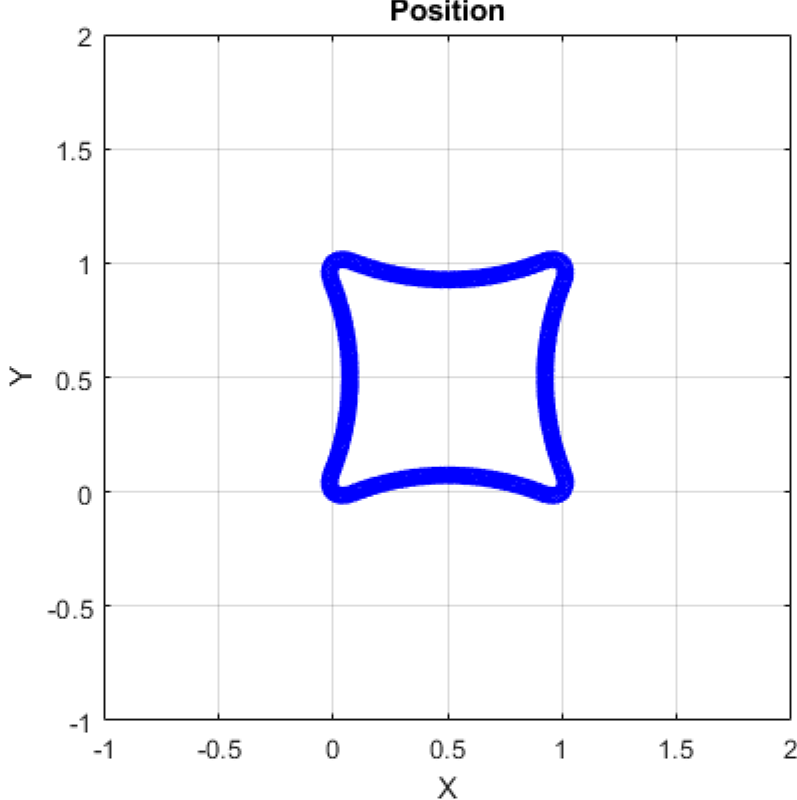



The `waypointTrajectory` algorithm interpolates the waypoints to create a smooth trajectory. To return to the square trajectory, provide more waypoints, especially around sharp changes. To track corresponding times, waypoints, and orientation, specify all the trajectory info in a single matrix.

```
                  % Time, Waypoint, Orientation
trajectoryInfo = [0,   0,0,0,    0,0,0; ... % Initial position
                  0.1, 0,0.1,0,  0,0,0; ...

                  0.9, 0,0.9,0,  0,0,0; ...
                  1,   0,1,0,    45,0,0; ...
                  1.1, 0.1,1,0,  90,0,0; ...

                  1.9, 0.9,1,0,  90,0,0; ...
                  2,   1,1,0,    135,0,0; ...
                  2.1, 1,0.9,0,  180,0,0; ...

                  2.9, 1,0.1,0,  180,0,0; ...
                  3,   1,0,0,    225,0,0; ...
                  3.1, 0.9,0,0,  270,0,0; ...

                  3.9, 0.1,0,0,  270,0,0; ...
                  4,   0,0,0,    270,0,0];    % Final position

trajectory = waypointTrajectory(trajectoryInfo(:,2:4), ...
    TimeOfArrival=trajectoryInfo(:,1), ...
    Orientation=quaternion(trajectoryInfo(:,5:end),"eulerd","ZYX","frame"), ...
    SampleRate=100);
```

Create a figure and plot the initial position of the platform. In a loop, step through the trajectory to output the current position and current orientation. Plot the current position and log the orientation. Use `pause` to mimic real-time processing.

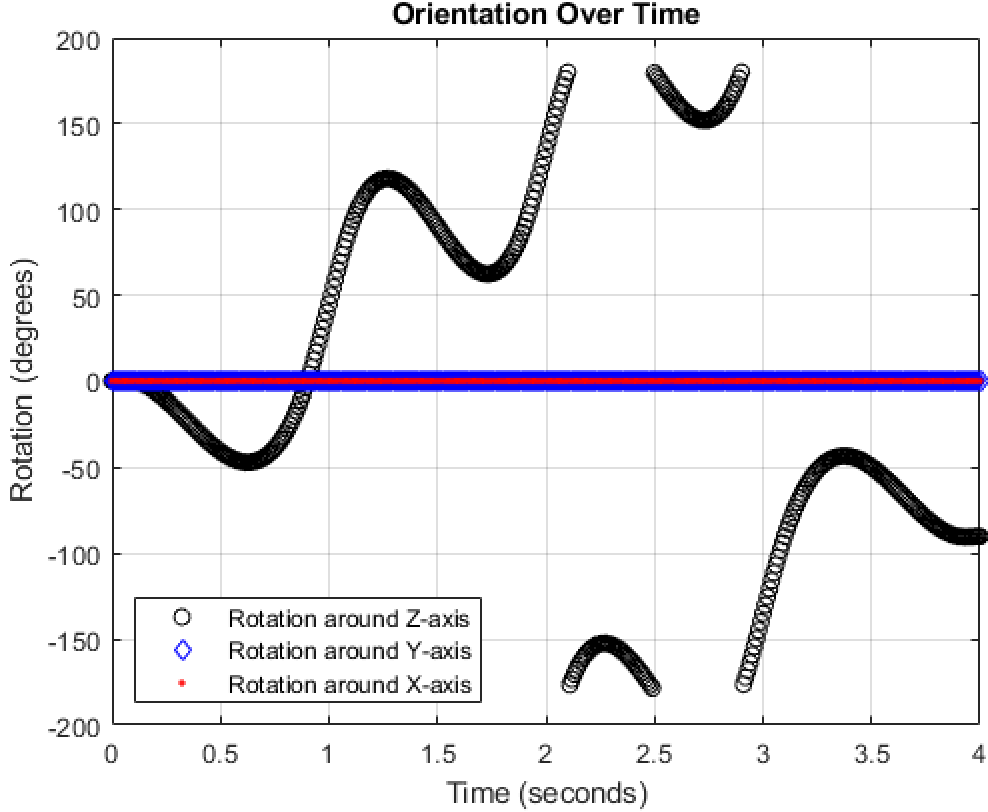
```
figure(1)
plot(waypoints(1,1),waypoints(1,2),"b*")
title("Position")
axis([-1,2,-1,2])
axis square
xlabel("X")
ylabel("Y")
grid on
hold on

orientationLog = zeros(toa(end)*trajectory.SampleRate,1,"quaternion");
count = 1;
while ~isDone(trajectory)
   [currentPosition,orientationLog(count)] = trajectory();

   plot(currentPosition(1),currentPosition(2),"bo")

   pause(trajectory.SamplesPerFrame/trajectory.SampleRate)
   count = count+1;
end
hold off
```




The trajectory output now appears more square-like, especially around the vertices with waypoints.

Convert the orientation quaternions to Euler angles for easy interpretation, and then plot orientation over time.

```
figure(2)
eulerAngles = eulerd([orientation(1);orientationLog],"ZYX","frame");
t = 0:1/trajectory.SampleRate:4;
eulerAngles = plot(t,eulerAngles(:,1),"ko", ...
                   t,eulerAngles(:,2),"bd", ...
                   t,eulerAngles(:,3),"r.");
title("Orientation Over Time")
legend("Rotation around Z-axis", ...
       "Rotation around Y-axis", ...
       "Rotation around X-axis", ...
       "Location", "SouthWest")
xlabel("Time (seconds)")
ylabel("Rotation (degrees)")
grid on
```




#### Create Arc Trajectory

This example shows how to create an arc trajectory using the `waypointTrajectory` System object™. `waypointTrajectory` creates a path through specified waypoints that minimizes acceleration and angular velocity. After creating an arc trajectory, you restrict the trajectory to be within preset bounds.

### Create an Arc Trajectory

Define a constraints matrix consisting of waypoints, times of arrival, and orientation for an arc trajectory. The generated trajectory passes through the waypoints at the specified times with the specified orientation. The `waypointTrajectory` System object requires orientation to be specified using quaternions or rotation matrices. Convert the Euler angles saved in the constraints matrix to quaternions when specifying the `Orientation` property.

```
          % Arrival, Waypoints, Orientation
constraints = [0,    20,20,0,    90,0,0;
               3,    50,20,0,    90,0,0;
               4,    58,15.5,0,  162,0,0;
               5.5,  59.5,0,0    180,0,0];

trajectory = waypointTrajectory(constraints(:,2:4), ...
    TimeOfArrival=constraints(:,1), ...
    Orientation=quaternion(constraints(:,5:7),"eulerd","ZYX","frame"));
```

Call `waypointInfo` on `trajectory` to return a table of your specified constraints. The creation properties `Waypoints`, `TimeOfArrival`, and `Orientation` are variables of the table. The table is convenient for indexing while plotting.

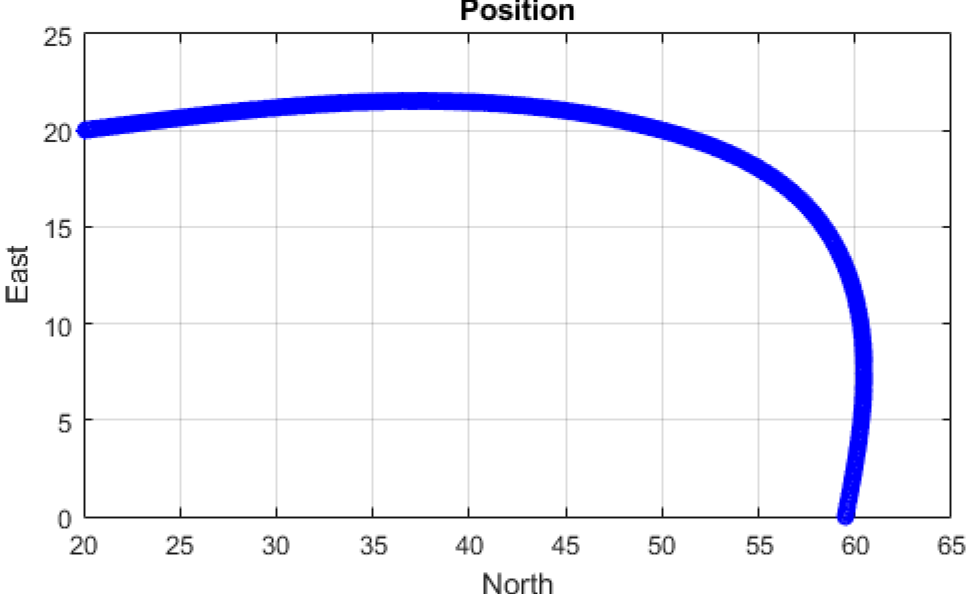
```
tInfo = waypointInfo(trajectory)
```

```
tInfo =

  4x3 table

    TimeOfArrival         Waypoints            Orientation
    _____________    ____________________    ________________

          0            20      20       0    {1x1 quaternion}
          3            50      20       0    {1x1 quaternion}
          4            58    15.5       0    {1x1 quaternion}
        5.5          59.5       0       0    {1x1 quaternion}
```

The trajectory object outputs the current position, velocity, acceleration, and angular velocity at each call. Call `trajectory` in a loop and plot the position over time. Cache the other outputs.

```
figure(1)
plot(tInfo.Waypoints(1,1),tInfo.Waypoints(1,2),"b*")
title("Position")
axis([20,65,0,25])
xlabel("North")
ylabel("East")
grid on
daspect([1 1 1])
hold on

orient = zeros(tInfo.TimeOfArrival(end)*trajectory.SampleRate,1,"quaternion");
vel = zeros(tInfo.TimeOfArrival(end)*trajectory.SampleRate,3);
acc = vel;
angVel = vel;

count = 1;
while ~isDone(trajectory)
```

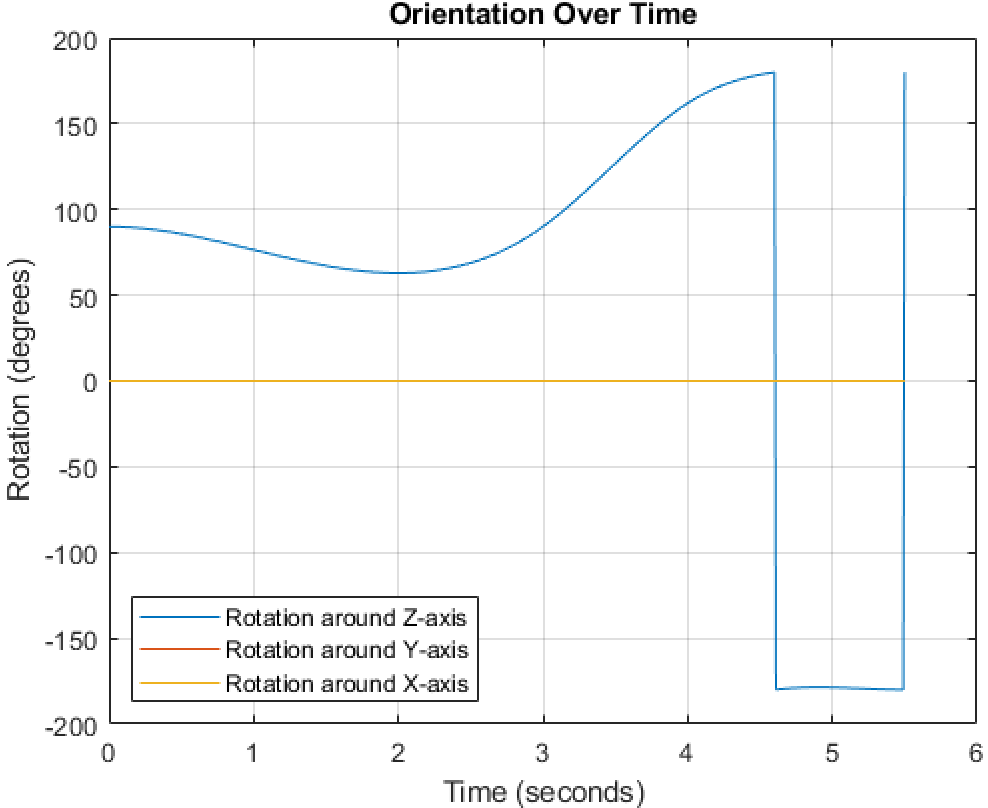
```
    [pos,orient(count),vel(count,:),acc(count,:),angVel(count,:)] = trajectory();

    plot(pos(1),pos(2),"bo")

    pause(trajectory.SamplesPerFrame/trajectory.SampleRate)
    count = count + 1;
end
```



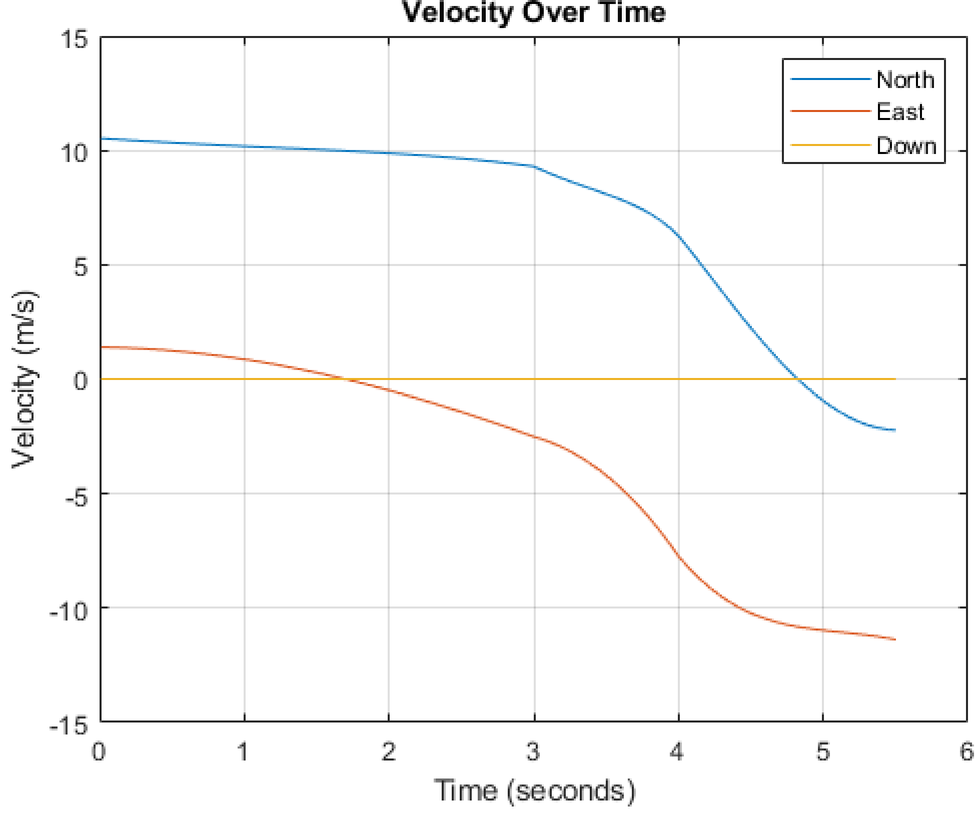

Inspect the orientation, velocity, acceleration, and angular velocity over time. The `waypointTrajectory` System object™ creates a path through the specified constraints that minimized acceleration and angular velocity.

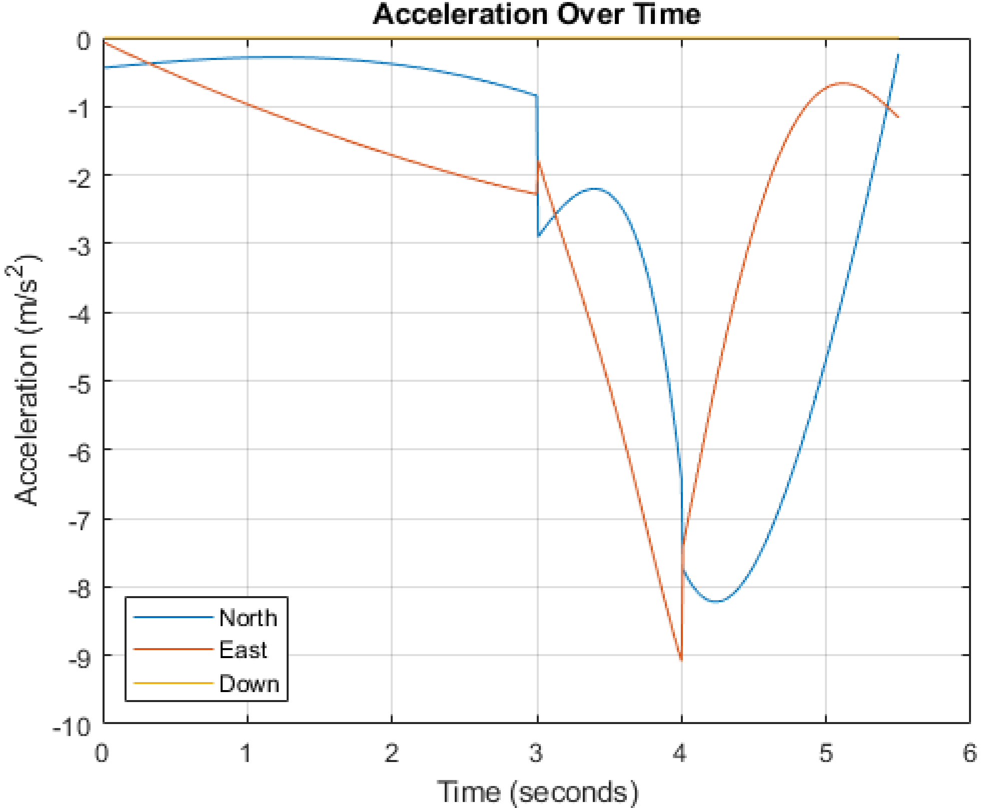
```
figure(2)
timeVector = 0:(1/trajectory.SampleRate):tInfo.TimeOfArrival(end);
eulerAngles = eulerd([tInfo.Orientation{1};orient],"ZYX","frame");
plot(timeVector,eulerAngles(:,1), ...
     timeVector,eulerAngles(:,2), ...
     timeVector,eulerAngles(:,3));
title("Orientation Over Time")
legend("Rotation around Z-axis", ...
       "Rotation around Y-axis", ...
       "Rotation around X-axis", ...
       "Location","southwest")
xlabel("Time (seconds)")
ylabel("Rotation (degrees)")
grid on
```

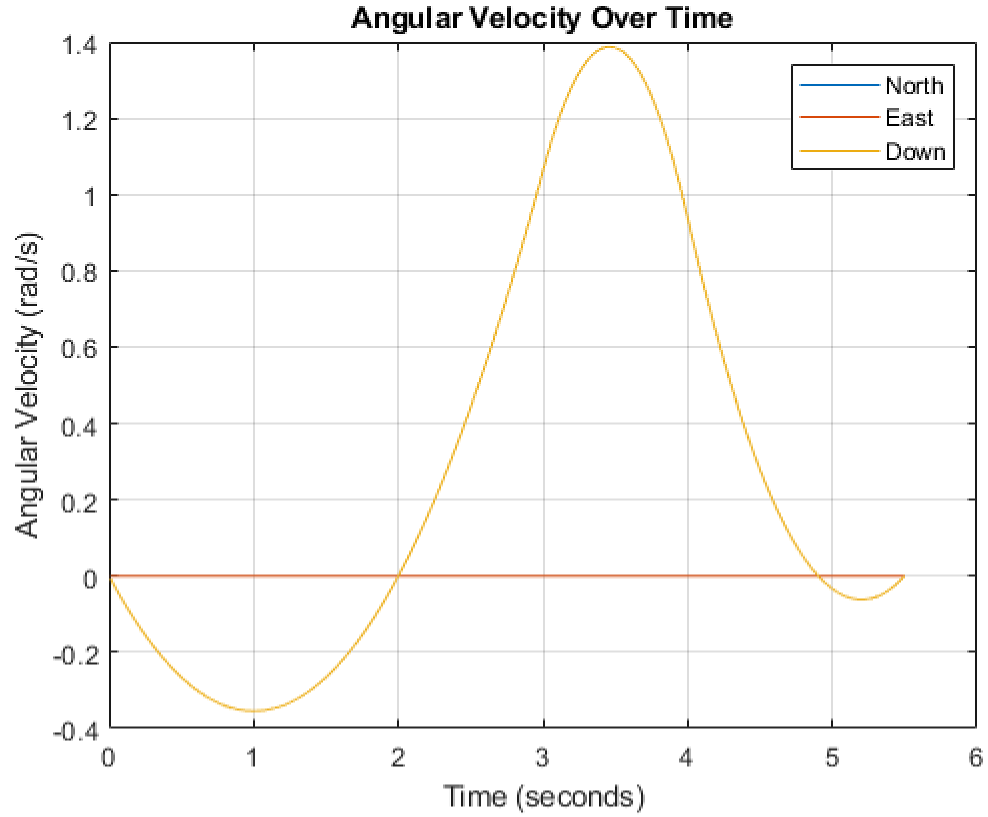
```
figure(3)
plot(timeVector(2:end),vel(:,1), ...
     timeVector(2:end),vel(:,2), ...
     timeVector(2:end),vel(:,3));
title("Velocity Over Time")
legend("North","East","Down")
xlabel("Time (seconds)")
ylabel("Velocity (m/s)")
grid on

figure(4)
plot(timeVector(2:end),acc(:,1), ...
     timeVector(2:end),acc(:,2), ...
     timeVector(2:end),acc(:,3));
title("Acceleration Over Time")
legend("North","East","Down","Location","southwest")
xlabel("Time (seconds)")
ylabel("Acceleration (m/s^2)")
grid on

figure(5)
plot(timeVector(2:end),angVel(:,1), ...
     timeVector(2:end),angVel(:,2), ...
     timeVector(2:end),angVel(:,3));
title("Angular Velocity Over Time")
legend("North","East","Down")
xlabel("Time (seconds)")
ylabel("Angular Velocity (rad/s)")
grid on
```



Orientation Over Time
Rotation (degrees)
Time (seconds)
Rotation around Z-axis
Rotation around Y-axis
Rotation around X-axis
200
150
100
50
0
-50
-100
-150
-200
0
1
2
3
4
5
6


Velocity Over Time
North
East
Down
Velocity (m/s)
Time (seconds)
15
10
5
0
-5
-10
-15
0
1
2
3
4
5
6

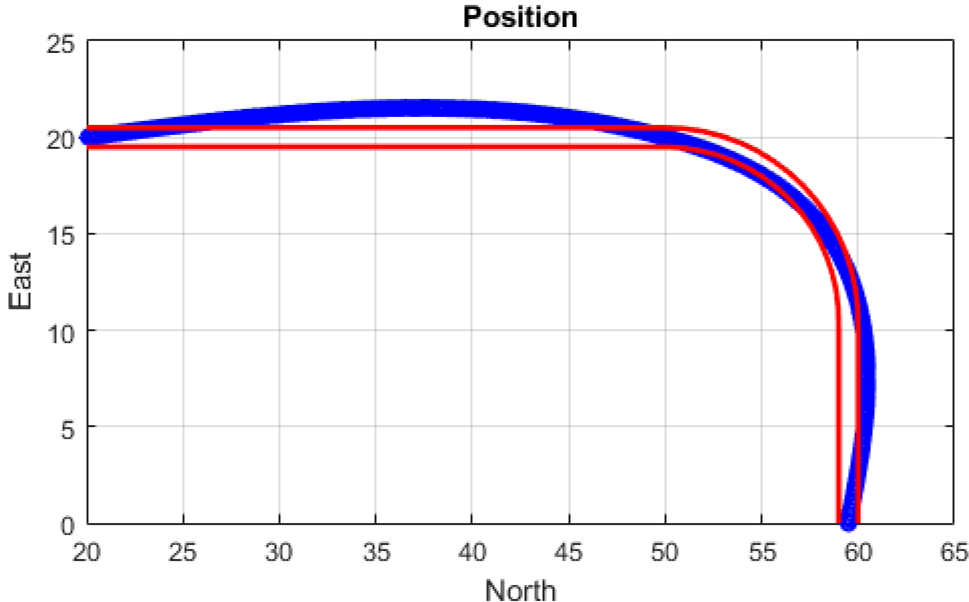

Acceleration Over Time
Acceleration (m/s$^2$)
Time (seconds)
North
East
Down
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
0
1
2
3
4
5
6




#### Restrict Arc Trajectory Within Preset Bounds

You can specify additional waypoints to create trajectories within given bounds. Create upper and lower bounds for the arc trajectory.

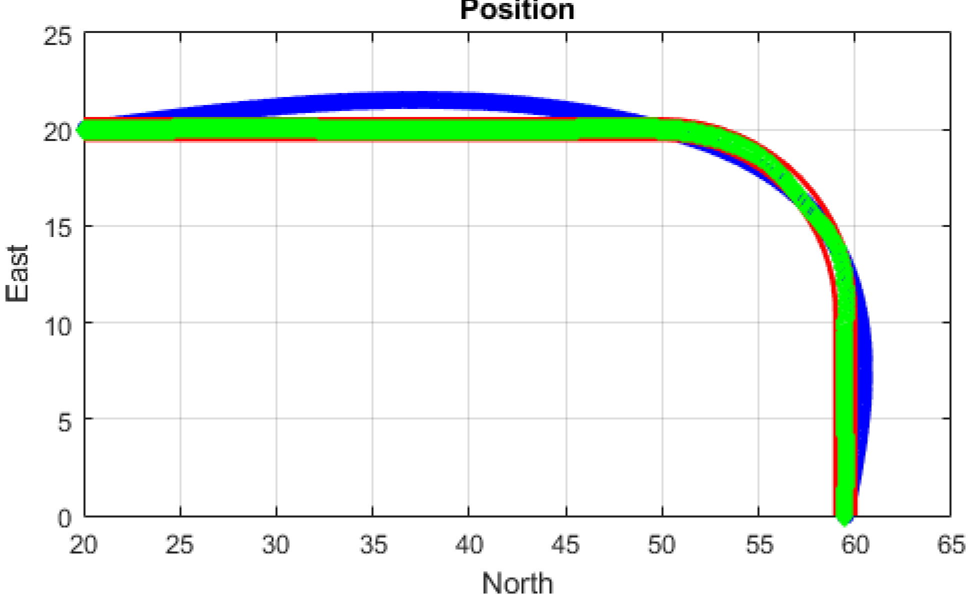
```
figure(1)
xUpperBound = [(20:50)';50+10*sin(0:0.1:pi/2)';60*ones(11,1)];
yUpperBound = [20.5.*ones(31,1);10.5+10*cos(0:0.1:pi/2)';(10:-1:0)'];

xLowerBound = [(20:49)';50+9*sin(0:0.1:pi/2)';59*ones(11,1)];
yLowerBound = [19.5.*ones(30,1);10.5+9*cos(0:0.1:pi/2)';(10:-1:0)'];

plot(xUpperBound,yUpperBound,"r","LineWidth",2);
plot(xLowerBound,yLowerBound,"r","LineWidth",2)
```




To create a trajectory within the bounds, add additional waypoints. Create a new `waypointTrajectory` System object™, and then call it in a loop to plot the generated trajectory. Cache the orientation, velocity, acceleration, and angular velocity output from the `trajectory` object.

```
              % Time,  Waypoint,     Orientation
constraints = [0,     20,20,0,       90,0,0;
               1.5,   35,20,0,       90,0,0;
               2.5    45,20,0,       90,0,0;
               3,     50,20,0,       90,0,0;
               3.3,   53,19.5,0,     108,0,0;
               3.6,   55.5,18.25,0,  126,0,0;
               3.9,   57.5,16,0,     144,0,0;
               4.2,   59,14,0,       162,0,0;
               4.5,   59.5,10,0      180,0,0;
               5,     59.5,5,0       180,0,0;
               5.5,   59.5,0,0       180,0,0];

trajectory = waypointTrajectory(constraints(:,2:4), ...
    TimeOfArrival=constraints(:,1), ...
    Orientation=quaternion(constraints(:,5:7),"eulerd","ZYX","frame"));
tInfo = waypointInfo(trajectory);

figure(1)
plot(tInfo.Waypoints(1,1),tInfo.Waypoints(1,2),"b*")

count = 1;
```

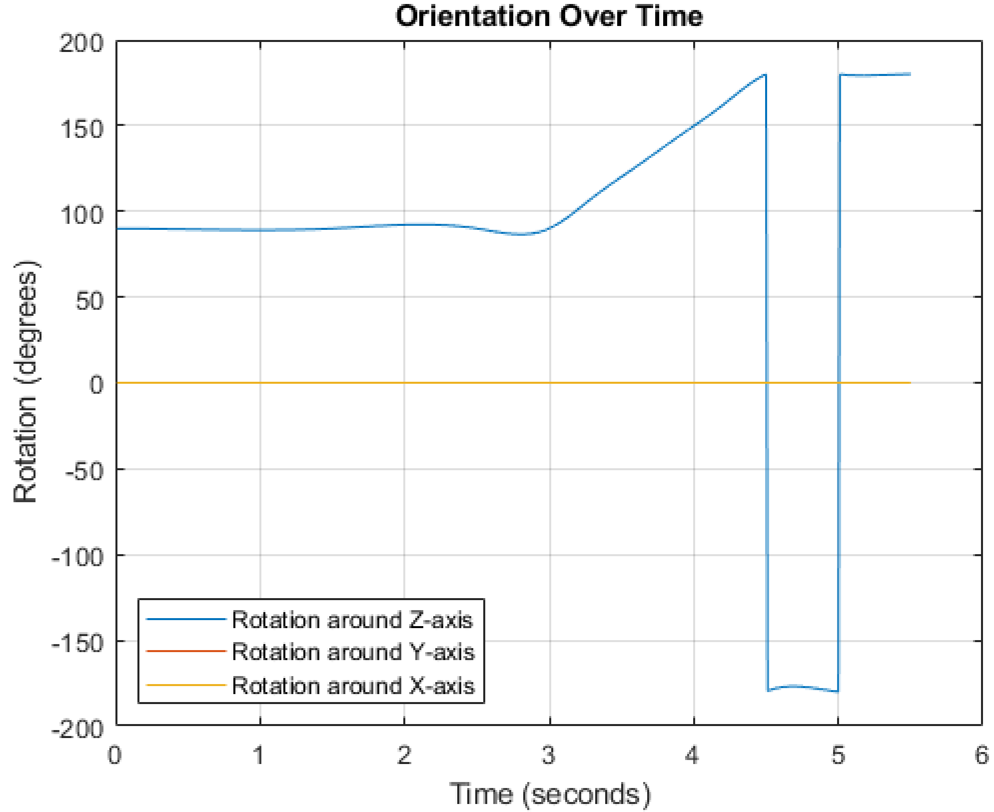
```
while ~isDone(trajectory)
   [pos,orient(count),vel(count,:),acc(count,:),angVel(count,:)] = trajectory();

   plot(pos(1),pos(2),"gd")

   pause(trajectory.SamplesPerFrame/trajectory.SampleRate)
   count = count + 1;
end
```

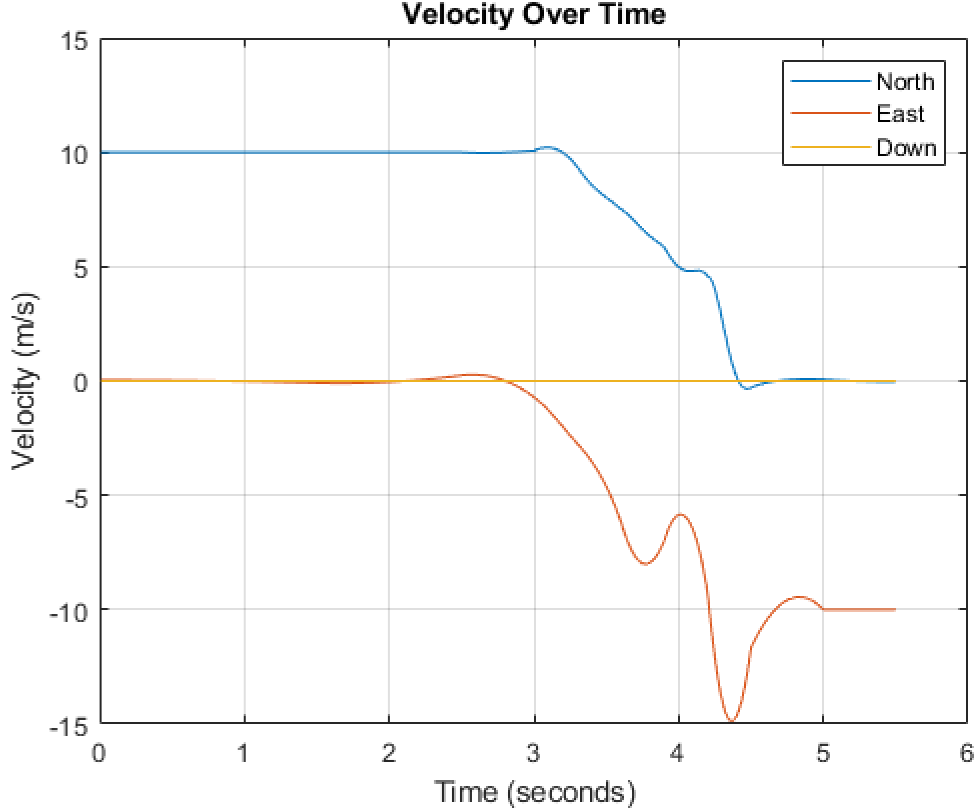


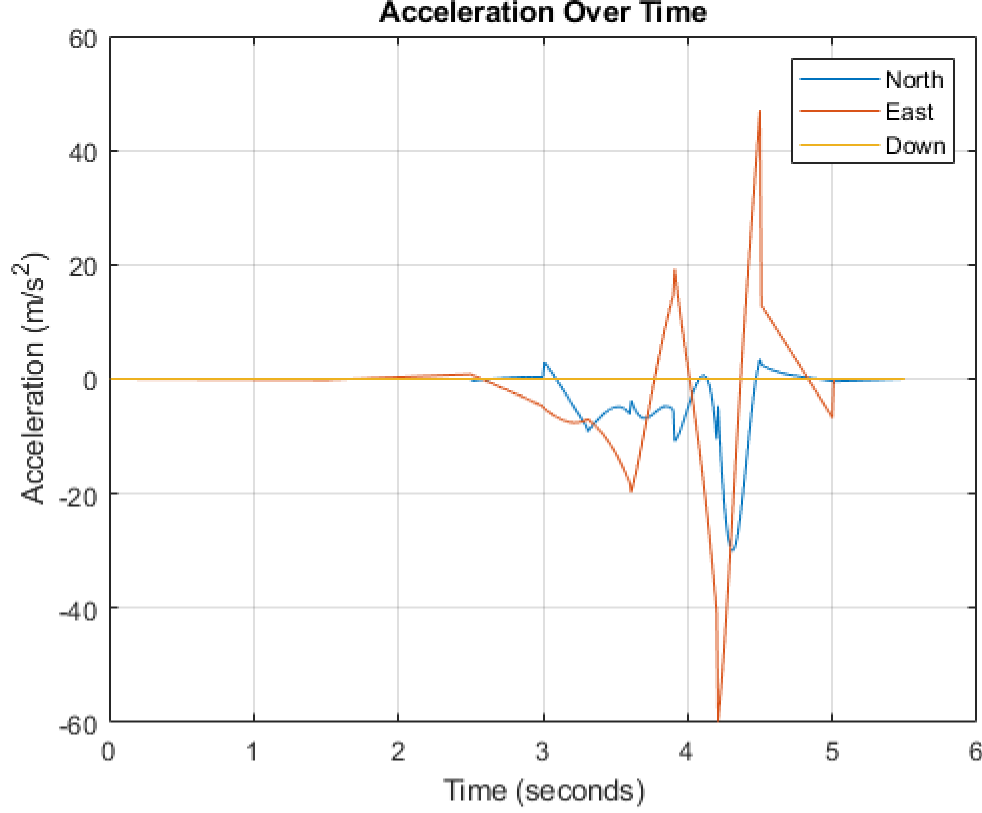

The generated trajectory now fits within the specified boundaries. Visualize the orientation, velocity, acceleration, and angular velocity of the generated trajectory.

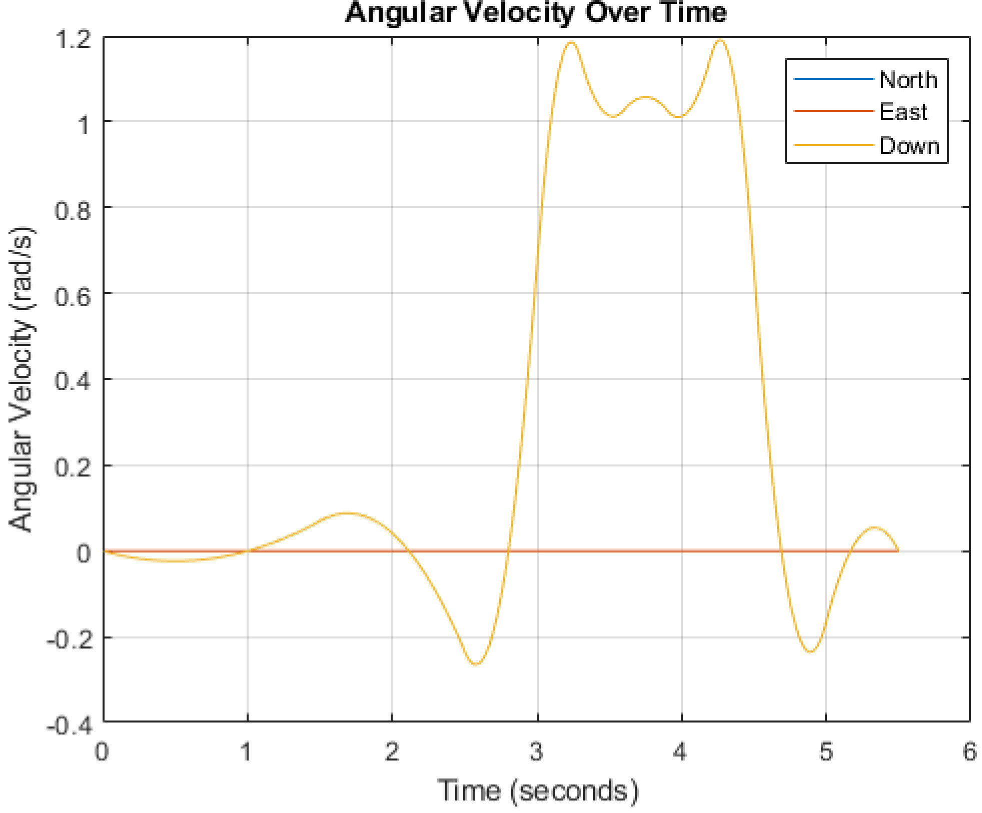
```
figure(2)
timeVector = 0:(1/trajectory.SampleRate):tInfo.TimeOfArrival(end);
eulerAngles = eulerd(orient,"ZYX","frame");
plot(timeVector(2:end),eulerAngles(:,1), ...
     timeVector(2:end),eulerAngles(:,2), ...
     timeVector(2:end),eulerAngles(:,3));
title("Orientation Over Time")
legend("Rotation around Z-axis", ...
       "Rotation around Y-axis", ...
       "Rotation around X-axis", ...
       "Location","southwest")
xlabel("Time (seconds)")
ylabel("Rotation (degrees)")
grid on

figure(3)
```

```
plot(timeVector(2:end),vel(:,1), ...
     timeVector(2:end),vel(:,2), ...
     timeVector(2:end),vel(:,3));
title("Velocity Over Time")
legend("North","East","Down")
xlabel("Time (seconds)")
ylabel("Velocity (m/s)")
grid on

figure(4)
plot(timeVector(2:end),acc(:,1), ...
     timeVector(2:end),acc(:,2), ...
     timeVector(2:end),acc(:,3));
title("Acceleration Over Time")
legend("North","East","Down")
xlabel("Time (seconds)")
ylabel("Acceleration (m/s^2)")
grid on

figure(5)
plot(timeVector(2:end),angVel(:,1), ...
     timeVector(2:end),angVel(:,2), ...
     timeVector(2:end),angVel(:,3));
title("Angular Velocity Over Time")
legend("North","East","Down")
xlabel("Time (seconds)")
ylabel("Angular Velocity (rad/s)")
grid on
```


Orientation Over Time
Rotation (degrees)
Time (seconds)
Rotation around Z-axis
Rotation around Y-axis
Rotation around X-axis
200
150
100
50
0
-50
-100
-150
-200
0
1
2
3
4
5
6


Velocity Over Time
North
East
Down
Velocity (m/s)
Time (seconds)
15
10
5
0
-5
-10
-15
0
1
2
3
4
5
6

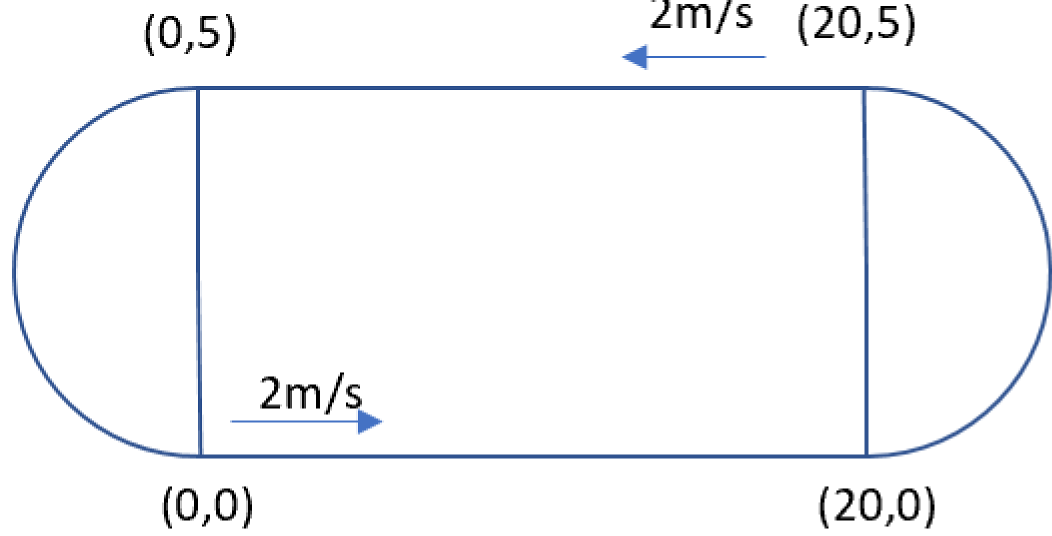

Acceleration Over Time
North
East
Down
Acceleration (m/s$^2$)
Time (seconds)
60
40
20
0
-20
-40
-60
0
1
2
3
4
5
6




Note that while the generated trajectory now fits within the spatial boundaries, the acceleration and angular velocity of the trajectory are somewhat erratic. This is due to over-specifying waypoints.

#### Generate Racetrack Trajectory Using `waypointTrajectory`

Consider a racetrack trajectory as the following.




The four corner points of the trajectory are (0,0,0), (20,0,0), (20,5,0) and (0,5,0) in meters, respectively. Therefore, specify the waypoints of a loop as:

```
wps = [0 0 0;
      20 0 0;
      20 5 0;
      0  5 0;
      0  0 0];
```

Assume the trajectory has a constant speed of 2 m/s, and thus the velocities at the five waypoints are:

```
vels = [2 0 0;
        2 0 0;
       -2 0 0;
       -2 0 0;
        2 0 0];
```

The time of arrival for the five waypoints is:

```
t = cumsum([0 20/2 5*pi/2/2 20/2 5*pi/2/2]');
```

The orientation of the trajectory at the five waypoints are:

```
eulerAngs = [0 0 0;
             0 0 0;
           180 0 0;
           180 0 0;
             0 0 0]; % Angles in degrees.
% Convert Euler angles to quaternions.
quats = quaternion(eulerAngs,"eulerd","ZYX","frame");
```

Specify the sample rate as 100 for smoothing trajectory lines.

```
fs = 100;
```

Construct the `waypointTrajectory`.

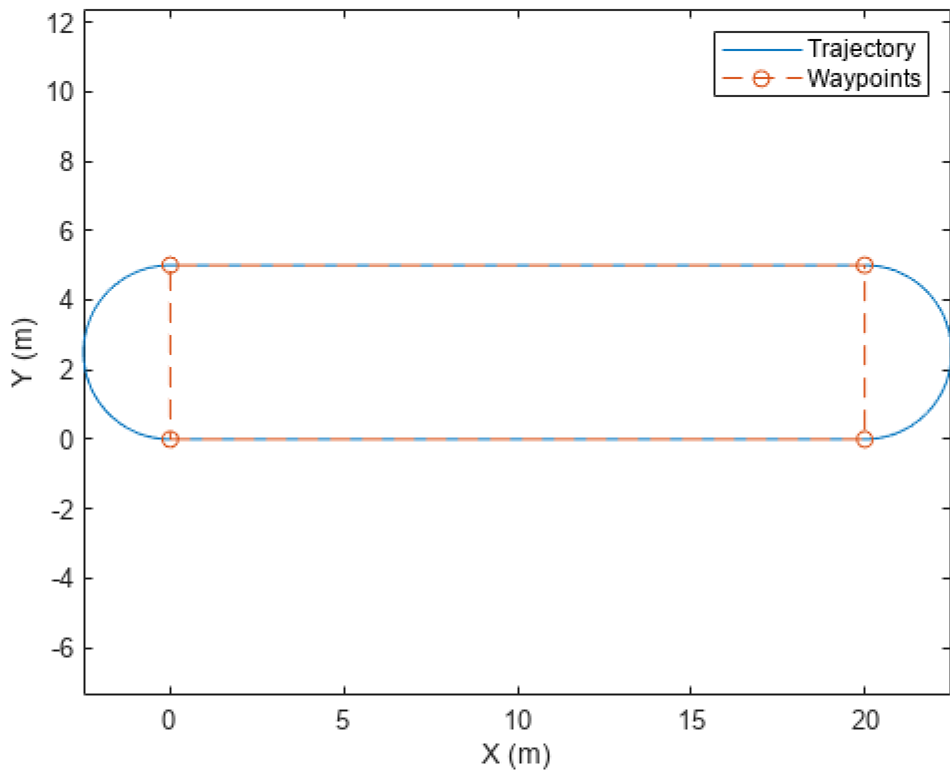
```
traj = waypointTrajectory(wps,SampleRate=fs, ...
        Velocities=vels,...
        TimeOfArrival=t,...
        Orientation=quats);
```

Sample and plot the trajectory.

```
[pos, orient, vel, acc, angvel] = traj();
i = 1;

spf = traj.SamplesPerFrame;
while ~isDone(traj)
    idx = (i+1):(i+spf);
    [pos(idx,:), orient(idx,:), ...
        vel(idx,:), acc(idx,:), angvel(idx,:)] = traj();
    i = i+spf;
end
```

Plot the trajectory and the specified waypoints.

```
plot(pos(:,1),pos(:,2), wps(:,1),wps(:,2), "--o")
xlabel("X (m)")
ylabel("Y (m)")
zlabel("Z (m)")
legend({"Trajectory", "Waypoints"})
axis equal
```



### Create Trajectory Using Waypoints and Ground Speed

Create a `waypointTrajectory` object that connects two waypoints. The velocity of the trajectory at the two waypoints is 0 m/s and 10 m/s, respectively. Restrict the jerk limit to 0.5 m/s$^3$ to enable the trapezoidal acceleration profile.

```
waypoints = [0  0  0;
             10 50 10];
speeds = [0 10];
jerkLimit = 0.5;
trajectory = waypointTrajectory(waypoints,GroundSpeed=speeds,JerkLimit=jerkLimit);
```

Obtain the initial time and final time of the trajectory by querying the `TimeOfArrival` property. Create time stamps to sample the trajectory.

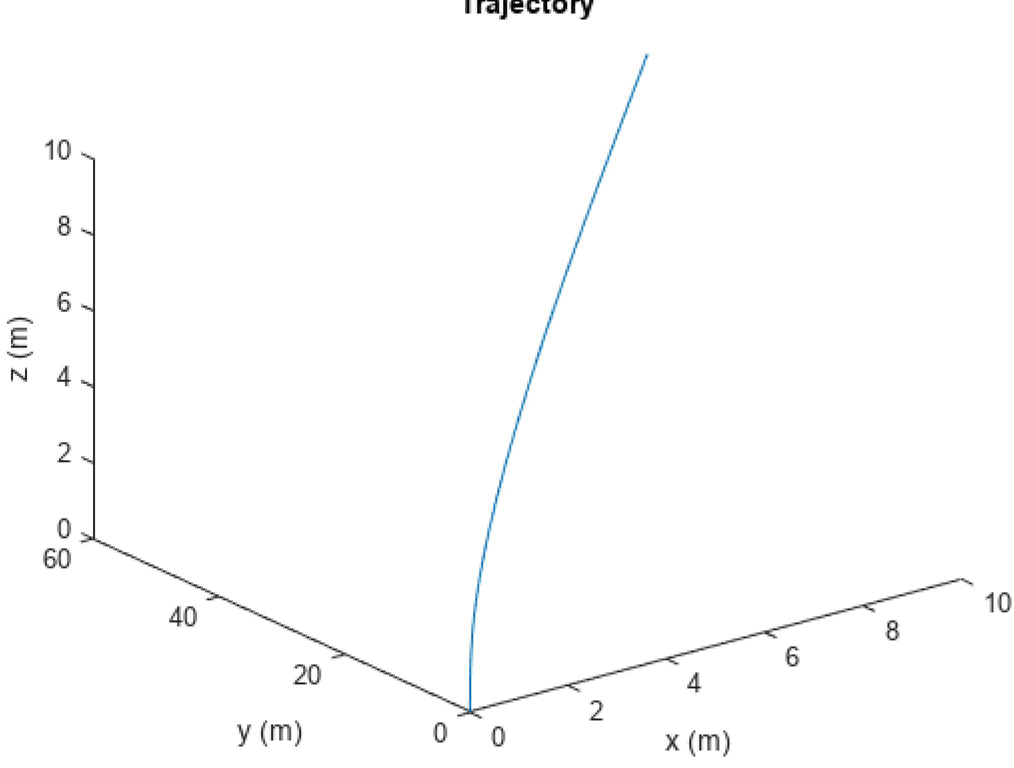
```
t0 = trajectory.TimeOfArrival(1);
tf = trajectory.TimeOfArrival(end);
sampleTimes = linspace(t0,tf,100);
```

Obtain the position, velocity, and acceleration information at these sampled time stamps using the `lookupPose` object function.

```
[position,~,velocity,acceleration,~] = lookupPose(trajectory,sampleTimes);
```

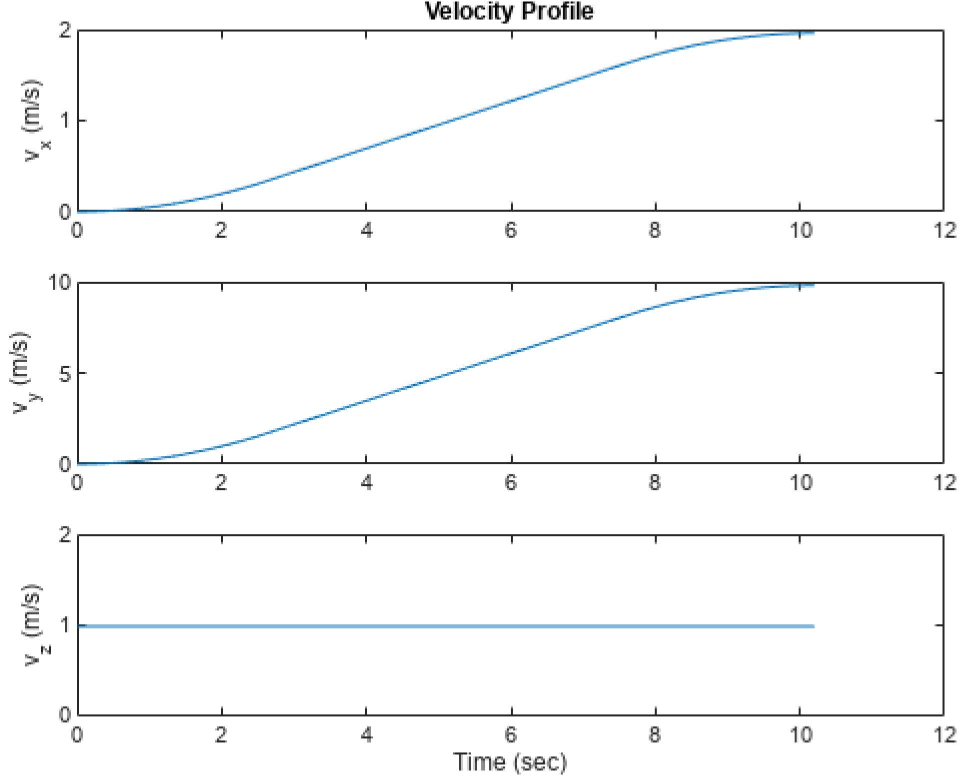
Plot the trajectory.

```
figure()
plot3(position(:,1),position(:,2),position(:,3))
xlabel("x (m)")
ylabel("y (m)")
zlabel("z (m)")
title("Trajectory")
```



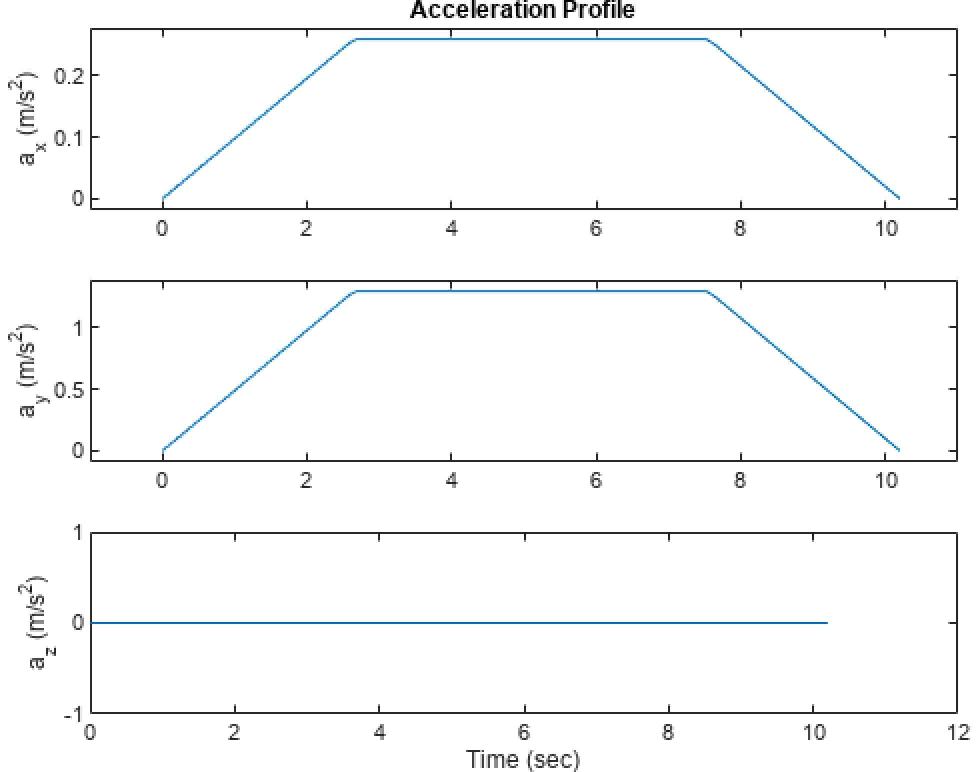

Plot the velocity profile.

```
figure()
subplot(3,1,1)
plot(sampleTimes,velocity(:,1));
ylabel("v_x (m/s)")
title("Velocity Profile")
subplot(3,1,2)
plot(sampleTimes,velocity(:,2));
ylabel("v_y (m/s)")
subplot(3,1,3)
plot(sampleTimes,velocity(:,3));
ylabel("v_z (m/s)")
xlabel("Time (sec)")
```




Plot the acceleration profile. From the results, the acceleration profile of the planar motion is trapezoidal.

```
figure()
subplot(3,1,1)
plot(sampleTimes,acceleration(:,1));
axis padded
ylabel("a_x (m/s^2)")
title("Acceleration Profile")
subplot(3,1,2)
plot(sampleTimes,acceleration(:,2));
ylabel("a_y (m/s^2)")
axis padded
subplot(3,1,3)
plot(sampleTimes,acceleration(:,3));
ylabel("a_z (m/s^2)")
xlabel("Time (sec)")
```




## Algorithms

The `waypointTrajectory` System object defines a trajectory that smoothly passes through waypoints. The trajectory connects the waypoints through an interpolation that assumes the gravity direction expressed in the trajectory reference frame is constant. Generally, you can use `waypointTrajectory` to model platform or vehicle trajectories within a hundreds of kilometers distance span.

The planar path of the trajectory (the *x*-*y* plane projection) consists of piecewise, clothoid curves. The curvature of the curve between two consecutive waypoints varies linearly with the curve length between them. The tangent direction of the path at each waypoint is chosen to minimize discontinuities in the curvature, unless the course is specified explicitly via the `Course` property or implicitly via the `Velocities` property. Once the path is established, the object uses cubic Hermite interpolation to compute the location of the vehicle throughout the path as a function of time and the planar distance traveled. If the `JerkLimit` property is specified, the objects produces a horizontal trapezoidal acceleration profile for any segment that is between two waypoints. The trapezoidal acceleration profile consists of three subsegments:

- A constant-magnitude jerk subsegment
- A constant-magnitude acceleration subsegment
- A constant-magnitude jerk subsegment

The normal component (*z*-component) of the trajectory is subsequently chosen to satisfy a shape-preserving piecewise spline (PCHIP) unless the climb rate is specified explicitly via the `ClimbRate`

property or the third column of the `Velocities` property. Choose the sign of the climb rate based on the selected `ReferenceFrame`:

- When an 'ENU' reference frame is selected, specifying a positive climb rate results in an increasing value of *z*.
- When an 'NED' reference frame is selected, specifying a positive climb rate results in a decreasing value of *z*.

You can define the orientation of the vehicle through the path in two primary ways:

- If the `Orientation` property is specified, then the object uses a piecewise-cubic, quaternion spline to compute the orientation along the path as a function of time.
- If the `Orientation` property is not specified, then the yaw of the vehicle is always aligned with the path. The roll and pitch are then governed by the `AutoBank` and `AutoPitch` property values, respectively.

| AutoBank | AutoPitch | Description |
| --- | --- | --- |
| `false` | `false` | The vehicle is always level (zero pitch and roll). This is typically used for large marine vessels. |
| `false` | `true` | The vehicle pitch is aligned with the path, and its roll is always zero. This is typically used for ground vehicles. |
| `true` | `false` | The vehicle pitch and roll are chosen so that its local *z*-axis is aligned with the net acceleration (including gravity). This is typically used for rotary-wing craft. |
| `true` | `true` | The vehicle roll is chosen so that its local transverse plane aligns with the net acceleration (including gravity). The vehicle pitch is aligned with the path. This is typically used for two-wheeled vehicles and fixed-wing aircraft. |

# Version History

**Introduced in R2019b**

### R2023a: Specify `waypointTrajectory` using ground speed or velocity input and new properties

When creating a `waypointTrajectory` object, if you specify the velocity or ground speed input, the time-of-arrival input is no longer required. When you do not specify the time-of-arrival input, you can use these new properties:

- `JerkLimit` — Longitudinal limit of trajectory jerk. Jerk is the derivative of the translational acceleration. If you specify a finite value for the jerk limit, `waypointTrajectory` produces a horizontal trapezoidal acceleration profile based on `JerkLimit`.
- `InitialTime` — Time before trajectory starts. If specified as nonzero, `waypointTrajectory` delays the start of the trajectory by the initial time.
- `WaitTime`— Wait time at each waypoint. If specified as nonzero for a waypoint, `waypointTrajectory` waits at the waypoint.

#### R2022b: Specify wait and reverse motion for waypoint trajectory

You can now specify wait and reverse motion using the `waypointTrajectory` System object.

- To let the trajectory wait at a specific waypoint, simply repeat the waypoint coordinate in two consecutive rows when specifying the `Waypoints` property.
- To render reverse motion, separate positive (forward) and negative (backward) groundspeed values by a zero value in the `GroundSpeed` property.

## Extended Capabilities

#### C/C++ Code Generation
Generate C and C++ code using MATLAB® Coder™.

The object function, `waypointInfo`, does not support code generation.

Usage notes and limitations:

See “System Objects in MATLAB Code Generation” (MATLAB Coder).

## See Also

#### Objects
`kinematicTrajectory`

# lookupPose

Obtain pose information for certain time

## Syntax

```
[position,orientation,velocity,acceleration,angularVelocity] = lookupPose(
traj,sampleTimes)
```

## Description

`[position,orientation,velocity,acceleration,angularVelocity] = lookupPose(traj,sampleTimes)` returns the pose information of the waypoint trajectory at the specified sample times. If any sample time is beyond the duration of the trajectory, the corresponding pose information is returned as `NaN`.

## Input Arguments

**`traj` — Waypoint trajectory**
`waypointTrajectory` object

Waypoint trajectory, specified as a `waypointTrajectory` object.

**`sampleTimes` — Sample times**
*M*-element vector of nonnegative scalar

Sample times in seconds, specified as an *M*-element vector of nonnegative scalars.

## Output Arguments

**`position` — Position in local navigation coordinate system (m)**
*M*-by-3 matrix

Position in the local navigation coordinate system in meters, returned as an *M*-by-3 matrix.

*M* is specified by the `sampleTimes` input.

Data Types: `double`

**`orientation` — Orientation in local navigation coordinate system**
*M*-element quaternion column vector | 3-by-3-by-*M* real array

Orientation in the local navigation coordinate system, returned as an *M*-by-1 `quaternion` column vector or a 3-by-3-by-*M* real array.

Each quaternion or 3-by-3 rotation matrix is a frame rotation from the local navigation coordinate system to the current body coordinate system.

*M* is specified by the `sampleTimes` input.

Data Types: `double`

**`velocity` — Velocity in local navigation coordinate system (m/s)**
*M*-by-3 matrix

Velocity in the local navigation coordinate system in meters per second, returned as an *M*-by-3 matrix.

*M* is specified by the `sampleTimes` input.

Data Types: `double`

**`acceleration` — Acceleration in local navigation coordinate system (m/s$^2$)**
*M*-by-3 matrix

Acceleration in the local navigation coordinate system in meters per second squared, returned as an *M*-by-3 matrix.

*M* is specified by the `sampleTimes` input.

Data Types: `double`

**`angularVelocity` — Angular velocity in local navigation coordinate system (rad/s)**
*M*-by-3 matrix

Angular velocity in the local navigation coordinate system in radians per second, returned as an *M*-by-3 matrix.

*M* is specified by the `sampleTimes` input.

Data Types: `double`

# Version History

**Introduced in R2019b**

## See Also

**Objects**
`waypointTrajectory`

**Functions**
`waypointInfo` | `perturbations` | `perturb`

# waypointInfo

Get waypoint information table

## Syntax

```
trajectoryInfo = waypointInfo(trajectory)
```

## Description

`trajectoryInfo = waypointInfo(trajectory)` returns a table of waypoints, times of arrival, velocities, and orientation for the `trajectory` System object.

## Input Arguments

**`trajectory` — Object of `waypointTrajectory`**
object

Object of the `waypointTrajectory` System object.

## Output Arguments

**`trajectoryInfo` — Trajectory information**
table

Trajectory information, returned as a table with variables corresponding to set creation properties: Waypoints, TimeOfArrival, Velocities, and Orientation.

The trajectory information table always has variables `Waypoints` and `TimeOfArrival`. If the `Velocities` property is set during construction, the trajectory information table additionally returns velocities. If the `Orientation` property is set during construction, the trajectory information table additionally returns orientation.

# Version History

**Introduced in R2019b**

## See Also

**Objects**
`waypointTrajectory`

**Functions**
`lookupPose` | `perturbations` | `perturb`

# perturb

Apply perturbations to object

## Syntax

```
offsets = perturb(obj)
```

## Description

`offsets = perturb(obj)` applies the perturbations defined on the object, `obj` and returns the offset values. You can define perturbations on the object by using the `perturbations` function.

## Examples

### Perturb Waypoint Trajectory

Define a waypoint trajectory. By default, this trajectory contains two waypoints.

```
traj = waypointTrajectory
```

```
traj = 
  waypointTrajectory with properties:

         SampleRate: 100
    SamplesPerFrame: 1
          Waypoints: [2x3 double]
      TimeOfArrival: [2x1 double]
         Velocities: [2x3 double]
             Course: [2x1 double]
        GroundSpeed: [2x1 double]
          ClimbRate: [2x1 double]
        Orientation: [2x1 quaternion]
          AutoPitch: 0
           AutoBank: 0
     ReferenceFrame: 'NED'
```

Define perturbations on the `Waypoints` property and the `TimeOfArrival` property.

```
rng(2020);
perturbs1 = perturbations(traj,'Waypoints','Normal',1,1)
```

```
perturbs1=2×3 table
       Property          Type            Value      
    _______________    ________    _________________

    "Waypoints"        "Normal"    {[  1]}    {[  1]}
    "TimeOfArrival"    "None"      {[NaN]}    {[NaN]}
```

```
perturbs2 = perturbations(traj,'TimeOfArrival','Selection',{[0;1],[0;2]})
```

```
perturbs2=2×3 table
       Property           Type                     Value
    _______________    ___________    ________________________________

    "Waypoints"        "Normal"       {[     1]}    {[            1]}
    "TimeOfArrival"    "Selection"    {1x2 cell}    {[0.5000 0.5000]}
```

Perturb the trajectory.

```
offsets = perturb(traj)
```

```
offsets=2×1 struct array with fields:
    Property
    Offset
    PerturbedValue
```

The `Waypoints` property and the `TimeOfArrival` property have changed.

```
traj.Waypoints
```

```
ans = 2×3

    1.8674    1.0203    0.7032
    2.3154   -0.3207    0.0999
```

```
traj.TimeOfArrival
```

```
ans = 2×1

     0
     2
```

### Perturb Accuracy of insSensor

Create an `insSensor` object.

```
sensor = insSensor
```

```
sensor = 
  insSensor with properties:

           MountingLocation: [0 0 0]            m     
              RollAccuracy: 0.2                 deg   
             PitchAccuracy: 0.2                 deg   
               YawAccuracy: 1                   deg   
          PositionAccuracy: [1 1 1]             m     
          VelocityAccuracy: 0.05                m/s   
      AccelerationAccuracy: 0                   m/s²  
   AngularVelocityAccuracy: 0                   deg/s 
                 TimeInput: 0                         
              RandomStream: 'Global stream'           
```

Define the perturbation on the `RollAccuracy` property as three values with an equal possibility each.

```
values = {0.1 0.2 0.3}
```

```
values=1×3 cell array
    {[0.1000]}    {[0.2000]}    {[0.3000]}
```

```
probabilities = [1/3 1/3 1/3]
```

```
probabilities = 1×3

    0.3333    0.3333    0.3333
```

```
perturbations(sensor,'RollAccuracy','Selection',values,probabilities)
```

```
ans=7×3 table
            Property                 Type                       Value
    _________________________    ___________    _____________________________________

    "RollAccuracy"               "Selection"    {1x3 cell}    {[0.3333 0.3333 0.3333]}
    "PitchAccuracy"              "None"         {[   NaN]}    {[                 NaN]}
    "YawAccuracy"                "None"         {[   NaN]}    {[                 NaN]}
    "PositionAccuracy"           "None"         {[   NaN]}    {[                 NaN]}
    "VelocityAccuracy"           "None"         {[   NaN]}    {[                 NaN]}
    "AccelerationAccuracy"       "None"         {[   NaN]}    {[                 NaN]}
    "AngularVelocityAccuracy"    "None"         {[   NaN]}    {[                 NaN]}
```

Perturb the `sensor` object using the perturb function.

```
rng(2020)
perturb(sensor);
sensor
```

```
sensor = 
  insSensor with properties:

           MountingLocation: [0 0 0]            m
               RollAccuracy: 0.5                deg
              PitchAccuracy: 0.2                deg
                YawAccuracy: 1                  deg
           PositionAccuracy: [1 1 1]            m
           VelocityAccuracy: 0.05               m/s
       AccelerationAccuracy: 0                  m/s²
    AngularVelocityAccuracy: 0                  deg/s
                  TimeInput: 0
               RandomStream: 'Global stream'
```

The `RollAccuracy` is perturbed to `0.5` deg.

#### Perturb imuSensor Parameters

Create an `imuSensor` object and show its perturbable properties.

```
imu = imuSensor;
perturbations(imu)
```

```
ans=17×3 table
                  Property                      Type             Value
    ______________________________________    ______    ____________________

    "Accelerometer.MeasurementRange"          "None"    {[NaN]}    {[NaN]}
    "Accelerometer.Resolution"                "None"    {[NaN]}    {[NaN]}
    "Accelerometer.ConstantBias"              "None"    {[NaN]}    {[NaN]}
    "Accelerometer.NoiseDensity"              "None"    {[NaN]}    {[NaN]}
    "Accelerometer.BiasInstability"           "None"    {[NaN]}    {[NaN]}
    "Accelerometer.RandomWalk"                "None"    {[NaN]}    {[NaN]}
    "Accelerometer.TemperatureBias"           "None"    {[NaN]}    {[NaN]}
    "Accelerometer.TemperatureScaleFactor"    "None"    {[NaN]}    {[NaN]}
    "Gyroscope.MeasurementRange"              "None"    {[NaN]}    {[NaN]}
    "Gyroscope.Resolution"                    "None"    {[NaN]}    {[NaN]}
    "Gyroscope.ConstantBias"                  "None"    {[NaN]}    {[NaN]}
    "Gyroscope.NoiseDensity"                  "None"    {[NaN]}    {[NaN]}
    "Gyroscope.BiasInstability"               "None"    {[NaN]}    {[NaN]}
    "Gyroscope.RandomWalk"                    "None"    {[NaN]}    {[NaN]}
    "Gyroscope.TemperatureBias"               "None"    {[NaN]}    {[NaN]}
    "Gyroscope.TemperatureScaleFactor"        "None"    {[NaN]}    {[NaN]}
      ⋮
```

Specify the perturbation for the `NoiseDensity` property of the accelerometer as a uniform distribution.

```
perturbations(imu,'Accelerometer.NoiseDensity', ...
    'Uniform',1e-5,1e-3);
```

Specify the perturbation for the `RandomWalk` property of the gyroscope as a truncated normal distribution.

```
 perts = perturbations(imu,'Gyroscope.RandomWalk', ...
    'TruncatedNormal',2,1e-5,0,Inf);
```

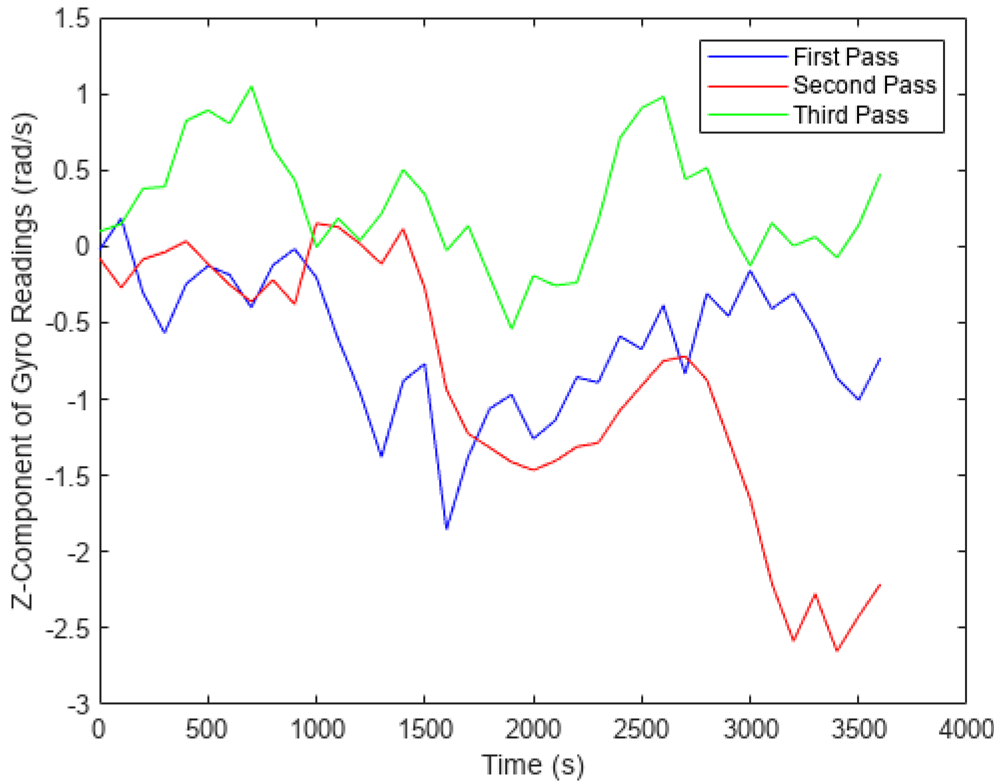
Load prerecorded IMU data.

```
load imuSensorData.mat
numSamples = size(orientations);
```

Simulate the `imuSensor` three times with different perturbation realizations.

```
rng(2021); % For repeatable results
numRuns = 3;
colors = ['b' 'r' 'g'];
for idx = 1:numRuns

    % Clone IMU to maintain original values
    imuCopy = clone(imu);

    % Perturb noise values
```

```
    offsets = perturb(imuCopy);

    % Obtain the measurements
    [accelReadings,gyroReadings] = imuCopy(accelerations,angularVelocities,orientations);

    % Plot the results
    plot(times,gyroReadings(:,3),colors(idx));
    hold on;
end
xlabel('Time (s)')
ylabel('Z-Component of Gyro Readings (rad/s)')
legend("First Pass","Second Pass","Third Pass");
hold off
```




## Input Arguments

**obj — Object for perturbation**
objects

Object for perturbation, specified as an object. The objects that you can perturb include:

- `waypointTrajectory`
- `kinematicTrajectory`
- `insSensor`

- `imuSensor`

## Output Arguments

**`offsets` — Property offsets**
array of structure

Property offsets, returned as an array of structures. Each structure contains these fields:

| Field Name | Description |
| --- | --- |
| `Property` | Name of perturbed property |
| `Offset` | Offset values applied in the perturbation |
| `PerturbedValue` | Property values after the perturbation |

# Version History

**Introduced in R2020b**

## See Also

`perturbations`

# perturbations

Perturbation defined on object

## Syntax

```
perturbs = perturbations(obj)
perturbs = perturbations(obj,property)
perturbs = perturbations(obj,property,'None')
perturbs = perturbations(obj,property,'Selection',values,probabilities)
perturbs = perturbations(obj,property,'Normal',mean,deviation)
perturbs = perturbations(obj,property,'TruncatedNormal',mean,deviation,
lowerLimit,upperLimit)
perturbs = perturbations(obj,property,'Uniform',minVal,maxVal)
perturbs = perturbations(obj,property,'Custom',perturbFcn)
```

## Description

`perturbs = perturbations(obj)` returns the list of property perturbations, `perturbs`, defined on the object, `obj`. The returned `perturbs` lists all the perturbable properties. If any property is not perturbed, then its corresponding `Type` is returned as `"Null"` and its corresponding `Value` is returned as `{Null,Null}`.

`perturbs = perturbations(obj,property)` returns the current perturbation applied to the specified `property`.

`perturbs = perturbations(obj,property,'None')` defines a `property` that must not be perturbed.

`perturbs = perturbations(obj,property,'Selection',values,probabilities)` defines the `property` perturbation offset drawn from a set of `values` that have corresponding `probabilities`.

`perturbs = perturbations(obj,property,'Normal',mean,deviation)` defines the `property` perturbation offset drawn from a normal distribution with specified `mean` and standard `deviation`.

`perturbs = perturbations(obj,property,'TruncatedNormal',mean,deviation,lowerLimit,upperLimit)` defines the `property` perturbation offset drawn from a normal distribution with specified `mean`, standard `deviation`, lower limit, and upper limit.

`perturbs = perturbations(obj,property,'Uniform',minVal,maxVal)` defines the `property` perturbation offset drawn from a uniform distribution on an interval [`minVal`, `maxValue`].

`perturbs = perturbations(obj,property,'Custom',perturbFcn)` enables you to define a custom function, `perturbFcn`, that draws the perturbation offset value.

## Examples

### Default Perturbation Properties of `waypointTrajectory`

Create a `waypointTrajectory` object.

```
traj = waypointTrajectory;
```

Show the default perturbation properties using the `perturbations` method.

```
perturbs = perturbations(traj)
```

```
perturbs=2×3 table
       Property          Type            Value
    _______________    ______    __________________

    "Waypoints"        "None"    {[NaN]}    {[NaN]}
    "TimeOfArrival"    "None"    {[NaN]}    {[NaN]}
```

### Perturb Accuracy of insSensor

Create an `insSensor` object.

```
sensor = insSensor
```

```
sensor = 
  insSensor with properties:

           MountingLocation: [0 0 0]            m
               RollAccuracy: 0.2                deg
              PitchAccuracy: 0.2                deg
                YawAccuracy: 1                  deg
           PositionAccuracy: [1 1 1]            m
           VelocityAccuracy: 0.05               m/s
       AccelerationAccuracy: 0                  m/s²
    AngularVelocityAccuracy: 0                  deg/s
                  TimeInput: 0
               RandomStream: 'Global stream'
```

Define the perturbation on the `RollAccuracy` property as three values with an equal possibility each.

```
values = {0.1 0.2 0.3}
```

```
values=1×3 cell array
    {[0.1000]}    {[0.2000]}    {[0.3000]}
```

```
probabilities = [1/3 1/3 1/3]
```

```
probabilities = 1×3

    0.3333    0.3333    0.3333
```

```
perturbations(sensor,'RollAccuracy','Selection',values,probabilities)
```

```
ans=7×3 table
           Property                  Type                        Value
    _________________________    ___________    ______________________________________

    "RollAccuracy"               "Selection"    {1x3 cell}    {[0.3333 0.3333 0.3333]}
    "PitchAccuracy"              "None"         {[   NaN]}    {[                 NaN]}
    "YawAccuracy"                "None"         {[   NaN]}    {[                 NaN]}
    "PositionAccuracy"           "None"         {[   NaN]}    {[                 NaN]}
    "VelocityAccuracy"           "None"         {[   NaN]}    {[                 NaN]}
    "AccelerationAccuracy"       "None"         {[   NaN]}    {[                 NaN]}
    "AngularVelocityAccuracy"    "None"         {[   NaN]}    {[                 NaN]}
```

Perturb the `sensor` object using the perturb function.

```
rng(2020)
perturb(sensor);
sensor
```

```
sensor = 
  insSensor with properties:

           MountingLocation: [0 0 0]            m        
               RollAccuracy: 0.5                deg      
              PitchAccuracy: 0.2                deg      
                YawAccuracy: 1                  deg      
           PositionAccuracy: [1 1 1]            m        
           VelocityAccuracy: 0.05               m/s      
       AccelerationAccuracy: 0                  m/s²     
    AngularVelocityAccuracy: 0                  deg/s    
                  TimeInput: 0                           
               RandomStream: 'Global stream'
```

The `RollAccuracy` is perturbed to `0.5` deg.

### Perturb Waypoint Trajectory

Define a waypoint trajectory. By default, this trajectory contains two waypoints.

```
traj = waypointTrajectory
```

```
traj = 
  waypointTrajectory with properties:

         SampleRate: 100
    SamplesPerFrame: 1
          Waypoints: [2x3 double]
      TimeOfArrival: [2x1 double]
         Velocities: [2x3 double]
             Course: [2x1 double]
        GroundSpeed: [2x1 double]
          ClimbRate: [2x1 double]
        Orientation: [2x1 quaternion]
          AutoPitch: 0
           AutoBank: 0
```

```
     ReferenceFrame: 'NED'
```

Define perturbations on the `Waypoints` property and the `TimeOfArrival` property.

```
rng(2020);
perturbs1 = perturbations(traj,'Waypoints','Normal',1,1)
```

```
perturbs1=2×3 table
       Property          Type            Value        
    _______________    ________    __________________

    "Waypoints"        "Normal"    {[  1]}    {[  1]}
    "TimeOfArrival"    "None"      {[NaN]}    {[NaN]}
```

```
perturbs2 = perturbations(traj,'TimeOfArrival','Selection',{[0;1],[0;2]})
```

```
perturbs2=2×3 table
       Property           Type                   Value               
    _______________    ___________    _______________________________

    "Waypoints"        "Normal"       {[     1]}    {[            1]}
    "TimeOfArrival"    "Selection"    {1x2 cell}    {[0.5000 0.5000]}
```

Perturb the trajectory.

```
offsets = perturb(traj)
```

```
offsets=2×1 struct array with fields:
    Property
    Offset
    PerturbedValue
```

The `Waypoints` property and the `TimeOfArrival` property have changed.

```
traj.Waypoints
```

```
ans = 2×3

    1.8674    1.0203    0.7032
    2.3154   -0.3207    0.0999
```

```
traj.TimeOfArrival
```

```
ans = 2×1

     0
     2
```

#### Perturb `imuSensor` Parameters

Create an `imuSensor` object and show its perturbable properties.

```
imu = imuSensor;
perturbations(imu)
```

```
ans=17×3 table
                  Property                        Type           Value      
    ______________________________________    ______    _____________________

    "Accelerometer.MeasurementRange"          "None"    {[NaN]}    {[NaN]}
    "Accelerometer.Resolution"                "None"    {[NaN]}    {[NaN]}
    "Accelerometer.ConstantBias"              "None"    {[NaN]}    {[NaN]}
    "Accelerometer.NoiseDensity"              "None"    {[NaN]}    {[NaN]}
    "Accelerometer.BiasInstability"           "None"    {[NaN]}    {[NaN]}
    "Accelerometer.RandomWalk"                "None"    {[NaN]}    {[NaN]}
    "Accelerometer.TemperatureBias"           "None"    {[NaN]}    {[NaN]}
    "Accelerometer.TemperatureScaleFactor"    "None"    {[NaN]}    {[NaN]}
    "Gyroscope.MeasurementRange"              "None"    {[NaN]}    {[NaN]}
    "Gyroscope.Resolution"                    "None"    {[NaN]}    {[NaN]}
    "Gyroscope.ConstantBias"                  "None"    {[NaN]}    {[NaN]}
    "Gyroscope.NoiseDensity"                  "None"    {[NaN]}    {[NaN]}
    "Gyroscope.BiasInstability"               "None"    {[NaN]}    {[NaN]}
    "Gyroscope.RandomWalk"                    "None"    {[NaN]}    {[NaN]}
    "Gyroscope.TemperatureBias"               "None"    {[NaN]}    {[NaN]}
    "Gyroscope.TemperatureScaleFactor"        "None"    {[NaN]}    {[NaN]}
      ⋮
```

Specify the perturbation for the `NoiseDensity` property of the accelerometer as a uniform distribution.

```
perturbations(imu,'Accelerometer.NoiseDensity', ...
    'Uniform',1e-5,1e-3);
```

Specify the perturbation for the `RandomWalk` property of the gyroscope as a truncated normal distribution.

```
 perts = perturbations(imu,'Gyroscope.RandomWalk', ...
    'TruncatedNormal',2,1e-5,0,Inf);
```

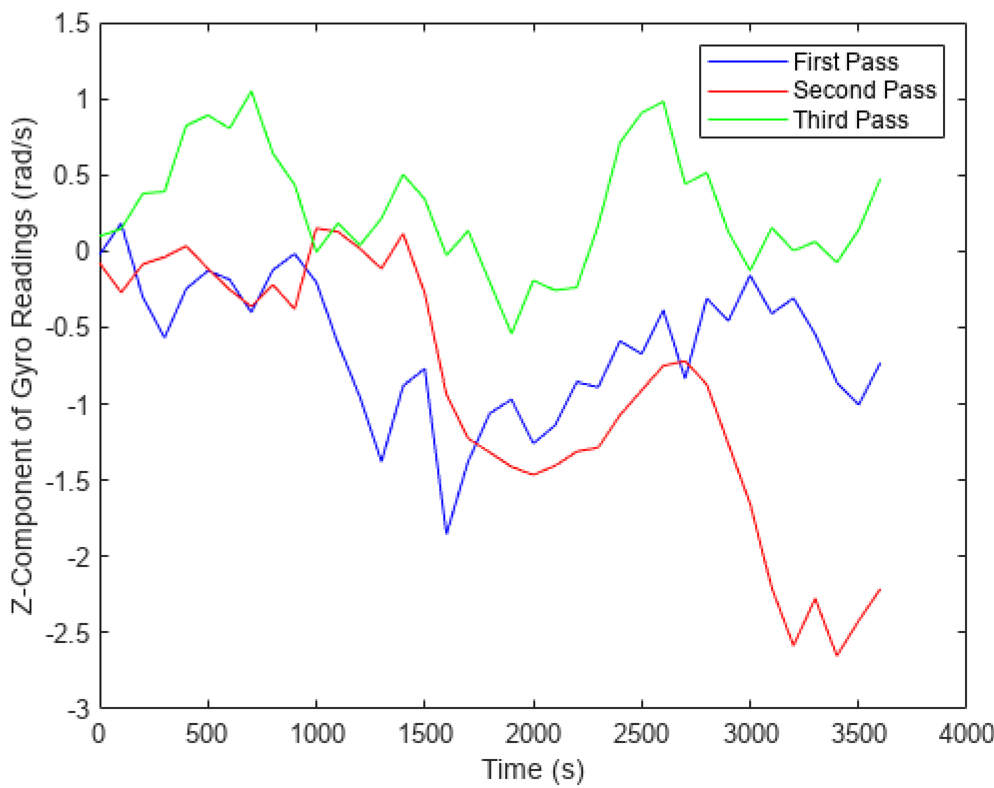
Load prerecorded IMU data.

```
load imuSensorData.mat 
numSamples = size(orientations);
```

Simulate the `imuSensor` three times with different perturbation realizations.

```
rng(2021); % For repeatable results
numRuns = 3;
colors = ['b' 'r' 'g'];
for idx = 1:numRuns

    % Clone IMU to maintain original values
    imuCopy = clone(imu);

    % Perturb noise values
    offsets = perturb(imuCopy);

    % Obtain the measurements
    [accelReadings,gyroReadings] = imuCopy(accelerations,angularVelocities,orientations);
```

```
    % Plot the results
    plot(times,gyroReadings(:,3),colors(idx));
    hold on;
end
xlabel('Time (s)')
ylabel('Z-Component of Gyro Readings (rad/s)')
legend("First Pass","Second Pass","Third Pass");
hold off
```




## Input Arguments

**obj — Object to be perturbed**
objects

Object to be perturbed, specified as an object. The objects that you can perturb include:

- `waypointTrajectory`
- `kinematicTrajectory`
- `insSensor`
- `imuSensor`

**property — Perturbable property**
property name

Perturbable property, specified as a property name. Use `perturbations` to obtain a full list of perturbable properties for the specified `obj`.

For the `imuSensor` System object, you can perturb properties of its accelerometer, gyroscope, and magnetometer components. For more details, see the “Perturb imuSensor Parameters” on page 2-1812 example.

**`values` — Perturbation offset values**
*n*-element cell array of property values

Perturbation offset values, specified as an *n*-element cell array of property values. The function randomly draws the perturbation value for the property from the cell array based on the values' corresponding probabilities specified in the `probabilities` input.

**`probabilities` — Drawing probabilities for each perturbation value**
*n*-element array of nonnegative scalar

Drawing probabilities for each perturbation value, specified as an *n*-element array of nonnegative scalars, where *n* is the number of perturbation values provided in the `values` input. The sum of all elements must be equal to one.

For example, you can specify a series of perturbation value-probability pair as {`x1`,`x2`,…,`xn`} and {`p1`,`p2`,…,`pn`}, where the probability of drawing `xi` is `pi` (`i` = 1, 2, …,n).

**`mean` — Mean of normal or truncated normal distribution**
scalar | vector | matrix

Mean of normal or truncated normal distribution, specified as a scalar, vector, or matrix. The dimension of `mean` must be compatible with the corresponding property that you perturb.

**`deviation` — Standard deviation of normal or truncated normal distribution**
nonnegative scalar | vector of nonnegative scalar | matrix of nonnegative scalar

Standard deviation of normal or truncated normal distribution, specified as a nonnegative scalar, vector of nonnegative scalars, or matrix of nonnegative scalars. The dimension of `deviation` must be compatible with the corresponding property that you perturb.

**`lowerLimit` — Lower limit of truncated normal distribution**
scalar | vector | matrix

Lower limit of the truncated normal distribution, specified as a scalar, vector, or matrix. The dimension of `lowerLimit` must be compatible with the corresponding property that you perturb.

**`upperLimit` — Upper limit of truncated normal distribution**
scalar | vector | matrix

Upper limit of the truncated normal distribution, specified as a scalar, vector, or matrix. The dimension of `upperLimit` must be compatible with the corresponding property that you perturb.

**`minVal` — Minimum value of uniform distribution interval**
scalar | vector | matrix

Minimum value of the uniform distribution interval, specified as a scalar, vector, or matrix. The dimension of `minVal` must be compatible with the corresponding property that you perturb.

**maxVal — Maximum value of uniform distribution interval**
scalar | vector | matrix

Maximum value of the uniform distribution interval, specified as a scalar, vector, or matrix. The dimension of `maxVal` must be compatible with the corresponding property that you perturb.

**perturbFcn — Perturbation function**
function handle

Perturbation function, specified as a function handle. The function must have this syntax:

```
offset = myfun(propVal)
```

where `propVal` is the value of the `property` and `offset` is the perturbation offset for the property.

## Output Arguments

**perturbs — Perturbations defined on object**
table of perturbation property

Perturbations defined on the object, returned as a table of perturbation properties. The table has three columns:

- `Property` — Property names.
- `Type` — Type of perturbations, returned as `"None"`, `"Selection"`, `"Normal"`, `"TruncatedNormal"`, `"Uniform"`, or `"Custom"`.
- `Value` — Perturbation values, returned as a cell array.

## More About

### Specify Perturbation Distributions

You can specify the distribution for the perturbation applied to a specific property.

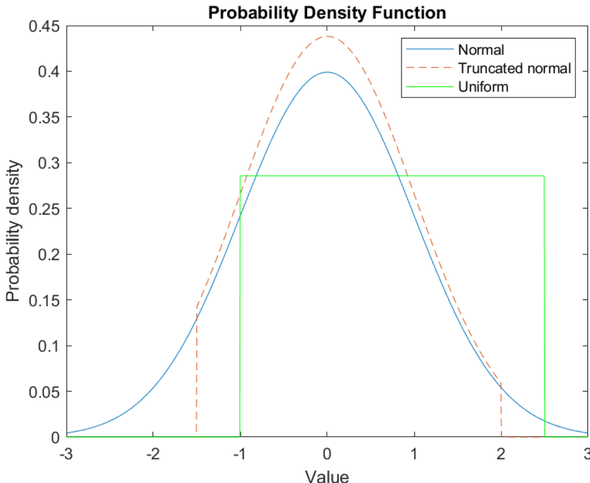
- Selection distribution — The function defines the perturbation offset as one of the specified values with the associated probability. For example, if you specify the values as `[1 2]` and specify the probabilities as `[0.7 0.3]`, then the `perturb` function adds an offset value of `1` to the property with a probability of `0.7` and add an offset value of `2` to the property with a probability of `0.3`. Use selection distribution when you only want to perturb the property with a number of discrete values.
- Normal distribution — The function defines the perturbation offset as a value drawn from a normal distribution with the specified mean and standard deviation (or covariance). Normal distribution is the most commonly used distribution since it mimics the natural perturbation of parameters in most cases.
- Truncated normal distribution — The function defines the perturbation offset as a value drawn from a truncated normal distribution with the specified mean, standard deviation (or covariance), lower limit, and upper limit. Different from the normal distribution, the values drawn from a truncated normal distribution are truncated by the lower and upper limit. Use truncated normal distribution when you want to apply a normal distribution, but the valid values of the property are confined in an interval.

- Uniform distribution — The function defines the perturbation offset as a value drawn from a uniform distribution with the specified minimum and maximum values. All the values in the interval (specified by the minimum and maximum values) have the same probability of realization.
- Custom distribution — Customize your own perturbation function. The function must have this syntax:

  ```
  offset = myfun(propVal)
  ```

  where `propVal` is the value of the `property` and `offset` is the perturbation offset for the property.

This figure shows probability density functions for a normal distribution, a truncated normal distribution, and a uniform distribution, respectively.




## Version History

**Introduced in R2020b**

## See Also

`perturb`

# wheelEncoderAckermann

Simulate wheel encoder sensor readings for Ackermann vehicle

## Description

The `wheelEncoderAckermann` System object computes wheel encoder tick readings based on the pose input of an Ackermann vehicle.

To obtain the encoder tick readings:

1. Create the `wheelEncoderAckermann` object and set its properties.
2. Call the object with arguments, as if it were a function.

To learn more about how System objects work, see What Are System Objects?

# Creation

## Syntax

```
encoder = wheelEncoderAckermann
encoder= wheelEncoderAckermann(Name,Value)
```

### Description

`encoder = wheelEncoderAckermann` creates a `wheelEncoderAckermann` System object, `encoder`.

`encoder= wheelEncoderAckermann(Name,Value)` sets properties for the encoder using one or more name-value pairs. For example, `wheelAckermann('SampleRate',120)` sets the sample rate of the encoder to 120 Hz. Unspecified properties have default values. Enclose each property name in quotes.

## Properties

Unless otherwise indicated, properties are *nontunable*, which means you cannot change their values after calling the object. Objects lock when you call them, and the `release` function unlocks them.

If a property is *tunable*, you can change its value at any time.

For more information on changing property values, see System Design in MATLAB Using System Objects.

**`SampleRate` — Sample rate of encoder**
`100` (default) | positive scalar

Sample rate of the encoder, specified as a positive scalar in Hz.

Example: `'SampleRate',100`

Data Types: `double`

**`TicksPerRevolution` — Number of encoder ticks per wheel revolution**
`[2048 2048 2048 2048]` (default) | four-element vector of positive integers

Number of encoder ticks per wheel revolution, specified as a four-element vector of positive integers. The first, second, third, and fourth elements are for the back-left, back-right, front-left, and front-right wheels, respectively.

Data Types: `double`

**`WheelRadius` — Wheel radius**
`[0.35 0.35 0.35 0.35]` (default) | four-element vector of positive scalars

Wheel radius, specified as a four-element vector of positive scalars in meters. The first, second, third, and fourth elements are for the back-left, back-right, front-left, and front-right wheels, respectively.

Data Types: `double`

**`WheelRadiusBias` — Bias of wheel radius**
`[0 0 0 0]` (default) | four-element vector of scalars

Bias of the wheel radius, specified as a four-element vector of scalars in meters. The first, second, third, and fourth elements are for the back-left, back-right, front-left, and front-right wheels, respectively.

Data Types: `double`

**`WheelPositionAccuracy` — Standard deviation of wheel position error**
`[0 0 0 0]` (default) | four-element vector of nonnegative scalars

Standard deviation of wheel position error, specified as a four-element vector of nonnegative scalars in radians. The first, second, third, and fourth elements are for the back-left, back-right, front-left, and front-right wheels, respectively.

Data Types: `double`

**`SlipRatio` — Slip or skid ratio of wheel**
`[0 0 0 0]` (default) | four-element vector of scalars

Slip or skid ratio of the wheel, specified as a four-element vector of scalars in which each scalar is larger than or equal to –1. The first, second, third, and fourth elements are for the back-left, back-right, front-left, and front-right wheels, respectively.

- For a wheel that slips (over rotation), specify it as a positive value. A higher value denotes more slipping.
- For a wheel that skids (under rotation), specify it as a negative value larger than or equal to –1. A lower value denotes more skidding. For a wheel that does not rotate, specify it as –1.

Data Types: `double`

**`TrackWidth` — Distance between wheel axles**
`[1.572 1.572]` (default) | two-element vector of positive scalars

Distance between the wheel axles, specified as a two-element vector of positive scalars in meters. The first element is for the back track, and the second element is for the front track.

Data Types: `double`

**`TrackWidthBias` — Bias of track width**
`0` (default) | two-element vector of scalars

Bias of track width, specified as a two-element vector of scalars in meters. The first element is for the back track, and the second element is for the front track.

Data Types: `double`

**`WheelBase` — Distance between front and rear axles**
`2.818` (default) | positive scalar

Distance between the front and the rear axles, specified as a positive scalar in meters.

Data Types: `double`

**`RandomStream` — Random number source**
`'Global stream'` (default) | `'mt19937ar with seed'`

Random number source, specified as a character vector or string:

- `'Global stream'` –– Random numbers are generated using the current global random number stream.
- `'mt19937ar with seed'` –– Random numbers are generated using the mt19937ar algorithm with the seed specified by the `Seed` property.

Data Types: `char` | `string`

**Seed — Initial seed**
`67` (default) | nonnegative integer

Initial seed of an mt19937ar random number generator algorithm, specified as a nonnegative integer.

#### Dependencies

To enable this property, set `RandomStream` to `'mt19937ar with seed'`.

## Usage

## Syntax

`ticks = encoder(velocity,angularVelocity,orientation)`

### Description

`ticks = encoder(velocity,angularVelocity,orientation)` return the wheel tick readings, `ticks`, form velocity, angular velocity, and orientation information.

### Input Arguments

**`velocity` — Velocity of vehicle**
*N*-by-3 matrix of scalars

Velocity of the vehicle in the local navigation frame, specified as an *N*-by-3 matrix of scalars in m/s. *N* is the number of samples.

**`angularVelocity` — Angular velocity of vehicle**
*N*-by-3 matrix of scalars

Angular velocity of the vehicle in the local navigation frame, specified as an *N*-by-3 matrix of scalars in rad/s. *N* is the number of samples.

**`orientation` — orientation of vehicle**
*N*-element vector of quaternion | 3-by-3-by-*N* array of rotation matrices

Orientation of the vehicle in the local navigation frame, specified as an *N*-element vector of `quaternion` or a 3-by-3-by-*N* array of rotation matrices. *N* is the number of samples. Each quaternion or rotation matrix is a frame rotation from the local navigation coordinate system to the current vehicle body coordinate system.

### Output Arguments

**`ticks` — Number of wheel ticks per time step**
*N*-by-4 matrix of nonnegative integers

Number of wheel ticks the vehicle moved per time step, returned as an *N*-by-4 matrix of nonnegative integers. *N* is the number of samples. The first, second, third, and fourth columns are for the back-left, back-right, front-left, and front-right wheels, respectively.

## Object Functions

To use an object function, specify the System object as the first input argument. For example, to release system resources of a System object named `obj`, use this syntax:

```
release(obj)
```

## Common to All System Objects

| | |
|---|---|
| clone | Create duplicate System object |
| step | Run System object algorithm |
| release | Release resources and allow changes to System object property values and input characteristics |
| reset | Reset internal states of System object |
| isLocked | Determine if System object is in use |

## Examples

### Generate Wheel Ticks from Ackermann Vehicle Pose

Create the wheel encoder sensor.

```
encoder = wheelEncoderAckermann;
```

Define poses of the vehicle.

```
orient = [quaternion([60 0 0],'eulerd','ZYX','frame'); quaternion([45 0 0], 'eulerd', 'ZYX', 'fra
vel = [1 0 0; 0 1 0];
angvel = [0 0 0.2; 0 0 0.1];
```

Generate wheel ticks from the poses.

```
ticks = encoder(vel,angvel,orient)
```

```
ticks = 2×4

     3     6     6     8
     6     7     6     7
```

# Version History

**Introduced in R2020b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

Usage notes and limitations:

See "System Objects in MATLAB Code Generation" (MATLAB Coder).

# wheelEncoderBicycle

Simulate wheel encoder sensor readings for bicycle vehicle

## Description

The `wheelEncoderBicycle` System object computes wheel encoder tick readings based on the pose input for a bicycle vehicle.

To obtain the encoder tick readings:

1. Create the `wheelEncoderBicycle` object and set its properties.
2. Call the object with arguments, as if it were a function.

To learn more about how System objects work, see What Are System Objects?

# Creation

## Syntax

```
encoder = wheelEncoderBicycle
encoder= wheelEncoderBicycle(Name,Value)
```

### Description

`encoder = wheelEncoderBicycle` creates a `wheelEncoderBicycle` System object, `encoder`.

`encoder= wheelEncoderBicycle(Name,Value)` sets properties for the encoder using one or more name-value pairs. For example, `wheelEncoderBicycle('SampleRate',120)` sets the sample rate of the encoder to 120 Hz. Unspecified properties have default values. Enclose each property name in quotes.

## Properties

Unless otherwise indicated, properties are *nontunable*, which means you cannot change their values after calling the object. Objects lock when you call them, and the `release` function unlocks them.

If a property is *tunable*, you can change its value at any time.

For more information on changing property values, see System Design in MATLAB Using System Objects.

**`SampleRate` — Sample rate of encoder**
`100` (default) | positive scalar

Sample rate of the encoder, specified as a positive scalar in Hz.

Data Types: `double`

**`TicksPerRevolution` — Number of encoder ticks per wheel revolution**
`[2048 2048]` (default) | two-element vector of positive integers

Number of encoder ticks per wheel revolution, specified as a two-element vector of positive integers. The first element is for the back wheel, and the second element is for the front wheel.

Data Types: `double`

**`WheelRadius` — Wheel radius**
`[0.35 0.35]` (default) | two-element vector of positive scalars

Wheel radius, specified as a two-element vector of positive scalars in meters. The first element is for the back wheel, and the second element is for the front wheel.

Data Types: `double`

**`WheelRadiusBias` — Bias of wheel radius**
`[0 0]` (default) | two-element vector of scalars

Bias of the wheel radius, specified as a two-element vector of scalars in meters. The first element is for the back wheel, and the second element is for the front wheel.

Data Types: `double`

**`WheelPositionAccuracy` — Standard deviation of wheel position error**
`[0 0]` (default) | two-element vector of nonnegative scalars

Standard deviation of wheel position error, specified as a two-element vector of nonnegative scalars in radians. The first element is for the back wheel, and the second element is for the front wheel.

Data Types: `double`

**`SlipRatio` — Slip or skid ratio of wheel**
`[0 0]` (default) | two-element vector of scalar

Slip or skid ratio of the wheel, specified as a two-element vector of scalars in which each scalar is larger than or equal to –1. The first element is for the back wheel, and the second element is for the front wheel.

- For a wheel that slips (over rotation), specify it as a positive value. A higher value denotes more slipping.
- For a wheel that skids (under rotation), specify it as a negative value larger than or equal to –1. A lower value denotes more skidding. For a wheel that does not rotate, specify it as –1.

Data Types: `double`

**`WheelBase` — Distance between front and rear wheels**
`2.818` (default) | positive scalar

Distance between the front and the rear wheels, specified as a positive scalar in meters.

Data Types: `double`

**`RandomStream` — Random number source**
`'Global stream'` (default) | `'mt19937ar with seed'`

Random number source, specified as a character vector or string:

- `'Global stream'` –– Random numbers are generated using the current global random number stream.
- `'mt19937ar with seed'` –– Random numbers are generated using the mt19937ar algorithm with the seed specified by the `Seed` property.

Data Types: `char` | `string`

**Seed — Initial seed of mt19937ar random number generator**
67 (default) | nonnegative integer

Initial seed of an mt19937ar random number generator algorithm, specified as a nonnegative integer.

#### Dependencies

To enable this property, set `RandomStream` to `'mt19937ar with seed'`.

## Usage

## Syntax

`ticks = encoder(velocity,angularVelocity,orientation)`

### Description

`ticks = encoder(velocity,angularVelocity,orientation)` return the wheel tick readings, `ticks`, from velocity, angular velocity, and orientation information.

### Input Arguments

**`velocity` — Velocity of vehicle**
*N*-by-3 matrix of scalars

Velocity of the vehicle in the local navigation frame, specified as an *N*-by-3 matrix of scalars in m/s. *N* is the number of samples.

**`angularVelocity` — Angular velocity of vehicle**
*N*-by-3 matrix of scalars

Angular velocity of the vehicle in the local navigation frame, specified as an *N*-by-3 matrix of scalars in rad/s. *N* is the number of samples.

**`orientation` — orientation of vehicle**
*N*-element vector of quaternion | 3-by-3-by-*N* array of rotation matrices

Orientation of the vehicle in the local navigation frame, specified as an *N*-element vector of `quaternion` or a 3-by-3-by-*N* array of rotation matrices. *N* is the number of samples. Each quaternion or rotation matrix is a frame rotation from the local navigation coordinate system to the current vehicle body coordinate system.

### Output Arguments

**`ticks` — Number of wheel ticks per time step**
*N*-by-2 matrix of integer

Number of wheel ticks the vehicle moved per time step, returned as an *N*-by-2 matrix of integers. *N* is the number of samples. The first column is for the back wheel, and the second column is for the front wheel.

## Object Functions

To use an object function, specify the System object as the first input argument. For example, to release system resources of a System object named `obj`, use this syntax:

```
release(obj)
```

### Common to All System Objects

| | |
|---|---|
| clone | Create duplicate System object |
| step | Run System object algorithm |
| release | Release resources and allow changes to System object property values and input characteristics |
| reset | Reset internal states of System object |
| isLocked | Determine if System object is in use |

## Examples

### Generate Wheel Ticks from Bicycle Vehicle Pose

Create the wheel encoder sensor.

```
encoder = wheelEncoderBicycle;
```

Define poses of the vehicle.

```
orient = [quaternion([90 0 0],'eulerd','ZYX','frame'); quaternion([45 0 0], 'eulerd', 'ZYX', 'fra
vel = [1 0 0; 0 1 0];
angvel = [0 0 0.2; 0 0 0.1];
```

Generate wheel ticks from the poses.

```
ticks = encoder(vel,angvel,orient)
```

```
ticks = 2×2

     0     5
     6     7
```

# Version History

**Introduced in R2020b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

Usage notes and limitations:

See “System Objects in MATLAB Code Generation” (MATLAB Coder).

# wheelEncoderDifferentialDrive

Simulate wheel encoder sensor readings for differential drive vehicle

## Description

The `wheelEncoderDifferentialDrive` System object computes wheel encoder tick readings based on the pose input of a differential drive vehicle.

To obtain the encoder tick readings:

1. Create the `wheelEncoderDifferentialDrive` object and set its properties.
2. Call the object with arguments, as if it were a function.

To learn more about how System objects work, see What Are System Objects?

# Creation

## Syntax

```
encoder = wheelEncoderDifferentialDrive
encoder= wheelEncoderDifferentialDrive(Name,Value)
```

### Description

`encoder = wheelEncoderDifferentialDrive` creates a `wheelEncoderDifferentialDrive` System object, `encoder`.

`encoder= wheelEncoderDifferentialDrive(Name,Value)` sets properties for the encoder using one or more name-value pairs. For example, `wheelEncoderDifferentialDrive('SampleRate',120)` sets the sample rate of the encoder to 120 Hz. Unspecified properties have default values. Enclose each property name in quotes.

## Properties

Unless otherwise indicated, properties are *nontunable*, which means you cannot change their values after calling the object. Objects lock when you call them, and the `release` function unlocks them.

If a property is *tunable*, you can change its value at any time.

For more information on changing property values, see System Design in MATLAB Using System Objects.

**`SampleRate` — Sample rate of encoder**
`100` (default) | positive scalar

Sample rate of the encoder, specified as a positive scalar in Hz.

Data Types: `double`

**`TicksPerRevolution` — Number of encoder ticks per wheel revolution**
`[2048 2048]` (default) | two-element vector of positive integers

Number of encoder ticks per wheel revolution, specified as a two-element vector of positive integers. The first element is for the left wheel, and the second element is for the right wheel.

Data Types: `double`

**`WheelRadius` — Wheel radius**
`[0.35 0.35]` (default) | two-element vector of positive scalars

Wheel radius, specified as a two-element vector of positive scalars in meters. The first element is for the left wheel, and the second element is for the right wheel.

Data Types: `double`

**`WheelRadiusBias` — Bias of wheel radius**
`[0 0]` (default) | two-element vector of scalars

Bias of the wheel radius, specified as a two-element vector of scalars in meters. The first element is for the left wheel, and the second element is for the right wheel.

Data Types: `double`

**`WheelPositionAccuracy` — Standard deviation of wheel position error**
`[0 0]` (default) | two-element vector of nonnegative scalar

Standard deviation of wheel position error, specified as a two-element vector of nonnegative scalars in radians. The first element is for the left wheel, and the second element is for the right wheel.

Data Types: `double`

**`SlipRatio` — Slip or skid ratio of wheel**
`[0 0]` (default) | two-element vector of scalar

Slip or skid ratio of the wheel, specified as a two-element vector of scalars in which each scalar is larger than or equal to –1. The first element is for the left wheel, and the second element is for the right wheel.

- For a wheel that slips (over rotation), specify it as a positive value. A higher value denotes more slipping.
- For a wheel that skids (under rotation), specify it as a negative value larger than or equal to –1. A lower value denotes more skidding. For a wheel that does not rotate, specify it as –1.

Data Types: `double`

**`TrackWidth` — Distance between wheel axles**
`1.572` (default) | positive scalar

Distance between the wheel axles, specified as a positive scalar in meters.

Data Types: `double`

**`TrackWidthBias` — Bias of track width**
`0` (default) | scalar

Bias of track width, specified as a scalar in meters.

Data Types: `double`

**`RandomStream` — Random number source**
`'Global stream'` (default) | `'mt19937ar with seed'`

Random number source, specified as a character vector or string:

- `'Global stream'` –– Random numbers are generated using the current global random number stream.
- `'mt19937ar with seed'` –– Random numbers are generated using the mt19937ar algorithm with the seed specified by the `Seed` property.

Data Types: `char` | `string`

**Seed — Initial seed**
`67` (default) | nonnegative integer

Initial seed of an mt19937ar random number generator algorithm, specified as a nonnegative integer.

#### Dependencies

To enable this property, set `RandomStream` to `'mt19937ar with seed'`.

## Usage

## Syntax

```
ticks = encoder(velocity,angularVelocity,orientation)
```

### Description

`ticks = encoder(velocity,angularVelocity,orientation)` return the wheel tick readings, `ticks`, form velocity, angular velocity, and orientation information.

### Input Arguments

**`velocity` — Velocity of vehicle**
*N*-by-3 matrix of scalars

Velocity of the vehicle in the local navigation frame, specified as an *N*-by-3 matrix of scalars in m/s. *N* is the number of samples.

**`angularVelocity` — Angular velocity of vehicle**
*N*-by-3 matrix of scalars

Angular velocity of the vehicle in the local navigation frame, specified as an *N*-by-3 matrix of scalars in rad/s. *N* is the number of samples.

**`orientation` — orientation of vehicle**
*N*-element vector of quaternion | 3-by-3-by-*N* array of rotation matrices

Orientation of the vehicle in the local navigation frame, specified as an *N*-element vector of `quaternion` or a 3-by-3-by-*N* array of rotation matrices. *N* is the number of samples. Each quaternion or rotation matrix is a frame rotation from the local navigation coordinate system to the current vehicle body coordinate system.

#### Output Arguments

**`ticks` — Number of wheel ticks per time step**
*N*-by-2 matrix of nonnegative integers

Number of wheel ticks the vehicle moved per time step, returned as an *N*-by-2 matrix of integers. *N* is the number of samples. The first column is for the left wheel, and the second column is for the right wheel.

## Object Functions

To use an object function, specify the System object as the first input argument. For example, to release system resources of a System object named `obj`, use this syntax:

```
release(obj)
```

### Common to All System Objects

| | |
|---|---|
| clone | Create duplicate System object |
| step | Run System object algorithm |
| release | Release resources and allow changes to System object property values and input characteristics |
| reset | Reset internal states of System object |
| isLocked | Determine if System object is in use |

## Examples

#### Generate Wheel Ticks from Differential Drive Vehicle Pose

Create the wheel encoder sensor.

```
encoder = wheelEncoderDifferentialDrive;
```

Define poses of the vehicle.

```
orient = [quaternion([60 0 0],'eulerd','ZYX','frame'); quaternion([45 0 0], 'eulerd', 'ZYX', 'fra
vel = [1 0 0; 0 1 0];
angvel = [0 0 0.2; 0 0 0.1];
```

Generate wheel ticks from the poses.

```
ticks = encoder(vel,angvel,orient)
```

```
ticks = 2×2

     3     6
     6     7
```

# Version History

**Introduced in R2020b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

Usage notes and limitations:

See “System Objects in MATLAB Code Generation” (MATLAB Coder).

# wheelEncoderUnicycle

Simulate wheel encoder sensor readings for unicycle vehicle

## Description

The `wheelEncoderUnicycle` System object computes wheel encoder tick readings based on the pose input of a unicycle vehicle.

To obtain the encoder tick readings:

1. Create the `wheelEncoderUnicycle` object and set its properties.
2. Call the object with arguments, as if it were a function.

To learn more about how System objects work, see What Are System Objects?

# Creation

## Syntax

```
encoder = wheelEncoderUnicycle
encoder = wheelEncoderUnicycle(Name,Value)
```

### Description

`encoder = wheelEncoderUnicycle` creates a `wheelEncoderUnicycle` System object `encoder`.

`encoder = wheelEncoderUnicycle(Name,Value)` sets properties for the encoder using one or more name-value pairs. For example, `wheelEncoderUnicycle('SampleRate',120)` sets the sample rate of the encoder to 120 Hz. Unspecified properties have default values. Enclose each property name in quotes.

## Properties

Unless otherwise indicated, properties are *nontunable*, which means you cannot change their values after calling the object. Objects lock when you call them, and the `release` function unlocks them.

If a property is *tunable*, you can change its value at any time.

For more information on changing property values, see System Design in MATLAB Using System Objects.

**`SampleRate` — Sample rate of encoder**
`100` (default) | positive scalar

Sample rate of the encoder, specified as a positive scalar in Hz.

Data Types: `double`

**`TicksPerRevolution` — Number of encoder ticks per wheel revolution**
`2048` (default) | positive integer

Number of encoder ticks per wheel revolution, specified as a positive integer.

Data Types: `double`

**`WheelRadius` — Wheel radius**
`0.35` (default) | positive scalar

Wheel radius, specified as a positive scalar in meters.

Data Types: `double`

**`WheelRadiusBias` — Bias of wheel radius**
`0` (default) | scalar

Bias of the wheel radius, specified as a scalar in meters.

Data Types: `double`

**`WheelPositionAccuracy` — Standard deviation of wheel position error**
`0` (default) | nonnegative scalar

Standard deviation of wheel position error, specified as a nonnegative scalar in radians.

Data Types: `double`

**`SlipRatio` — Slip or skid ratio of wheel**
`0` (default) | scalar

Slip or skid ratio of the wheel, specified as a scalar larger than or equal to –1.

- For a wheel that slips (over rotation), specify it as a positive value. A higher value denotes more slipping.
- For a wheel that skids (under rotation), specify it as a negative value larger than or equal to –1. A lower value denotes more skidding. For a wheel that does not rotate, specify it as –1.

Data Types: `double`

**`RandomStream` — Random number source**
`'Global stream'` (default) | `'mt19937ar with seed'`

Random number source, specified as a character vector or string:

- `'Global stream'` –– Random numbers are generated using the current global random number stream.
- `'mt19937ar with seed'` –– Random numbers are generated using the mt19937ar algorithm with the seed specified by the `Seed` property.

Data Types: `char` | `string`

**Seed — Initial seed of mt19937ar random number generator algorithm**
`67` (default) | nonnegative integer

Initial seed of an mt19937ar random number generator algorithm, specified as a nonnegative integer.

#### Dependencies

To enable this property, set `RandomStream` to `'mt19937ar with seed'`.

## Usage

## Syntax

```
ticks = encoder(velocity,angularVelocity,orientation)
```

### Description

`ticks = encoder(velocity,angularVelocity,orientation)` return the wheel tick readings `ticks` from the specified velocity, angular velocity, and orientation information.

### Input Arguments

**`velocity` — Velocity of vehicle**
*N*-by-3 matrix of scalars

Velocity of the vehicle in the local navigation frame, specified as an *N*-by-3 matrix of scalars in m/s. *N* is the number of samples.

**`angularVelocity` — Angular velocity of vehicle**
*N*-by-3 matrix of scalars

Angular velocity of the vehicle in the local navigation frame, specified as an *N*-by-3 matrix of scalars in rad/s. *N* is the number of samples.

**`orientation` — orientation of vehicle**
*N*-element vector of quaternion | 3-by-3-by-*N* array of rotation matrices

Orientation of the vehicle in the local navigation frame, specified as an *N*-element vector of `quaternion` or a 3-by-3-by-*N* array of rotation matrices. *N* is the number of samples. Each quaternion or rotation matrix is a frame rotation from the local navigation coordinate system to the current vehicle body coordinate system.

### Output Arguments

**`ticks` — Number of wheel ticks per time step**
*N*-element vector of nonnegative integers

Number of wheel ticks the vehicle moved per time step, returned as an *N*-element vector of nonnegative integers. *N* is the number of samples.

## Object Functions

To use an object function, specify the System object as the first input argument. For example, to release system resources of a System object named `obj`, use this syntax:

```
release(obj)
```

## Common to All System Objects

clone — Create duplicate System object
step — Run System object algorithm
release — Release resources and allow changes to System object property values and input characteristics
reset — Reset internal states of System object
isLocked — Determine if System object is in use

## Examples

### Generate Wheel Ticks from Unicycle Vehicle Pose

Create the wheel encoder sensor.

```
encoder = wheelEncoderUnicycle;
```

Define poses of the vehicle.

```
orient = [quaternion([90 0 0],'eulerd','ZYX','frame'); quaternion([45 0 0], 'eulerd', 'ZYX', 'fra
vel = [1 0 0; 0 1 0];
angvel = [0 0 0.2; 0 0 0.1];
```

Generate wheel ticks from the poses.

```
ticks = encoder(vel,angvel,orient)
```

```
ticks = 2×1

     0
     6
```

# Version History

**Introduced in R2020b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

Usage notes and limitations:

See “System Objects in MATLAB Code Generation” (MATLAB Coder).

# wheelEncoderOdometryAckermann

Compute Ackermann vehicle odometry using wheel encoder ticks and steering angle

## Description

The `wheelEncoderOdometryAckermann` System object computes Ackermann vehicle odometry using the wheel encoder ticks and steering angle of the vehicle.

To compute Ackermann vehicle odometry:

1. Create the `wheelEncoderOdometryAckermann` object and set its properties.
2. Call the object with arguments, as if it were a function.

To learn more about how System objects work, see What Are System Objects?

# Creation

## Syntax

```
whlEncOdom = wheelEncoderOdometryAckermann
whlEncOdom = wheelEncoderOdometryAckermann(encoder)
whlEncOdom = wheelEncoderOdometryAckermann(Name,Value)
```

### Description

`whlEncOdom = wheelEncoderOdometryAckermann` creates a `wheelEncoderOdometryAckermann` System object with default property values.

`whlEncOdom = wheelEncoderOdometryAckermann(encoder)` creates a `wheelEncoderOdometryAckermann` System object using the specified `wheelEncoderAckermann` System object, `encoder`, to set properties.

`whlEncOdom = wheelEncoderOdometryAckermann(Name,Value)` sets properties using one or more name-value pairs. Unspecified properties have default values. Enclose each property name in quotes.

For example, `whlEncOdom = wheelEncoderOdometryAckermann('SampleRate',100)` sets the sample rate of the sensor to 100 Hz.

## Properties

Unless otherwise indicated, properties are *nontunable*, which means you cannot change their values after calling the object. Objects lock when you call them, and the `release` function unlocks them.

If a property is *tunable*, you can change its value at any time.

For more information on changing property values, see System Design in MATLAB Using System Objects.

**SampleRate — Sample rate of sensor**
100 (default) | positive scalar

Sample rate of sensor, specified as a positive scalar in hertz.

Example: 'SampleRate',100

Data Types: double

**TicksPerRevolution — Number of encoder ticks per wheel revolution**
[2048 2048] (default) | positive integer | two-element vector of positive integers

Number of encoder ticks per wheel revolution, specified as a positive integer or two-element vector of positive integers.

When specifying this value as a two-element vector, the first element corresponds to the back left wheel and the second to the back right wheel.

Example: 'TicksPerRevolution',[2048 2048]

Data Types: double

**WheelRadius — Wheel radius**
[0.35 0.35] (default) | positive scalar | two-element vector of positive numbers

Wheel radius, specified as a positive scalar or two-element vector of positive numbers in meters.

When specifying this value as a two-element vector, the first element corresponds to the back left wheel and the second to the back right wheel.

Example: 'WheelRadius',[0.35 0.35]

Data Types: double

**TrackWidth — Distance between wheels on axle**
1.572 (default) | positive scalar

Distance between the wheels on the axle, specified as a positive scalar in meters.

Example: 'TrackWidth',1.572

Data Types: double

**WheelBase — Distance between front and rear axle**
2.818 (default) | positive scalar

Distance between the front and rear axle, specified as a positive scalar in meters.

Example: 'WheelBase',2.818

Data Types: double

**InitialPose — Initial pose of vehicle**
[0 0 0] (default) | three-element vector

Initial pose of the vehicle, specified as three-element vector of the form [*X Y Yaw*]. *X* and *Y* specify the vehicle position in meters. *Yaw* specifies the vehicle orientation in radians. All values are in the local navigation coordinate system.

Example: 'InitialPose',[0 0 0]

Data Types: `double`

## Usage

## Syntax

```
pose = whlEncOdom(ticks,steer)
[pose,velocity] = whlEncOdom(ticks,steer)
```

### Description

`pose = whlEncOdom(ticks,steer)` computes the odometry of an Ackermann vehicle using the specified wheel encoder ticks `ticks` and steering angle `steer`, and returns the position and orientation of the vehicle in the local navigation coordinate system.

`[pose,velocity] = whlEncOdom(ticks,steer)` additionally returns the linear and angular velocity of the vehicle in the local navigation coordinate system.

### Input Arguments

**`ticks` — Number of wheel encoder ticks**
*n*-by-2 matrix

Number of wheel encoder ticks, specified as an *n*-by-2 matrix. *n* is the number of samples in the current frame.

Each row of the matrix specifies wheel encoder ticks in the form [*ticksBackLeft ticksBackRight*], where *ticksBackLeft* and *ticksBackRight* specify the number of ticks for the back left and back right wheels, respectively.

Example: `[5 5; 2 2]`

Data Types: `single` | `double`

**`steer` — Steering angle of vehicle**
*n*-element column vector

Steering angle of the vehicle, specified as an *n*-element column vector in radians. *n* is the number of samples in the current frame.

Example: `[0.2; 0.2]`

Data Types: `single` | `double`

### Output Arguments

**`pose` — Position and orientation of vehicle**
*n*-by-3 matrix

Position and orientation of the vehicle, returned as an *n*-by-3 matrix. *n* is the number of samples in the current frame. Each row of the matrix specifies the position and orientation of a sample in the form [*X Y Yaw*]. *X* and *Y* specify the vehicle position in meters. *Yaw* specifies the vehicle orientation in radians. All values are in the local navigation coordinate system.

Data Types: `single` | `double`

**`velocity` — Linear and angular velocity of vehicle**
*n*-by-3 matrix

Linear and angular velocity of the vehicle, returned as an *n*-by-3 matrix. *n* is the number of samples in the current frame. Each row of the matrix specifies the linear and angular velocity of a sample in the form [*velX velY yawRate*]. *velX* and *velY* specify the linear velocity of the vehicle in meters per second. *yawRate* specifies the angular velocity of the vehicle in radians per second. All values are in the local navigation coordinate system.

Data Types: `single` | `double`

## Object Functions

To use an object function, specify the System object as the first input argument. For example, to release system resources of a System object named `obj`, use this syntax:

```
release(obj)
```

## Common to All System Objects

| | |
|---|---|
| clone | Create duplicate System object |
| step | Run System object algorithm |
| release | Release resources and allow changes to System object property values and input characteristics |
| reset | Reset internal states of System object |
| isLocked | Determine if System object is in use |

## Examples

### Compute Ackermann Vehicle Odometry Using Wheel Encoder Ticks and Steering Angle

Create a `wheelEncoderOdometryAckermann` System object.

```
whlEncOdom = wheelEncoderOdometryAckermann;
```

Specify the number of wheel encoder ticks and the steering angle.

```
ticks = [5 5; 2 2];
steer = [0.2; 0.2];
```

Compute the Ackermann vehicle odometry.

```
[pose,vel] = whlEncOdom(ticks,steer)
```

```
pose = 2×3

    0.0054    0.0000    0.0004
    0.0075    0.0000    0.0005


vel = 2×3

    0.5369    0.0002    0.0386
    0.2148    0.0001    0.0154
```

# Version History

**Introduced in R2020b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`wheelEncoderAckermann` | `wheelEncoderOdometryBicycle` | `wheelEncoderOdometryDifferentialDrive` | `wheelEncoderOdometryUnicycle`

# wheelEncoderOdometryBicycle

Compute bicycle odometry using wheel encoder ticks and steering angle

## Description

The `wheelEncoderOdometryBicycle` System object computes bicycle odometry using the wheel encoder ticks and steering angle of the vehicle.

To compute bicycle odometry:

1. Create the `wheelEncoderOdometryBicycle` object and set its properties.
2. Call the object with arguments, as if it were a function.

To learn more about how System objects work, see What Are System Objects?

# Creation

## Syntax

```
whlEncOdom = wheelEncoderOdometryBicycle
whlEncOdom = wheelEncoderOdometryBicycle(encoder)
whlEncOdom = wheelEncoderOdometryBicycle(Name,Value)
```

### Description

`whlEncOdom = wheelEncoderOdometryBicycle` creates a `wheelEncoderOdometryBicycle` System object with default property values.

`whlEncOdom = wheelEncoderOdometryBicycle(encoder)` creates a `wheelEncoderOdometryBicycle` System object using the specified `wheelEncoderBicycle` System object, `encoder`, to set properties.

`whlEncOdom = wheelEncoderOdometryBicycle(Name,Value)` sets properties using one or more name-value pairs. Unspecified properties have default values. Enclose each property name in quotes.

For example, `whlEncOdom = wheelEncoderOdometryBicycle('SampleRate',100)` sets the sample rate of the sensor to 100 Hz.

## Properties

Unless otherwise indicated, properties are *nontunable*, which means you cannot change their values after calling the object. Objects lock when you call them, and the `release` function unlocks them.

If a property is *tunable*, you can change its value at any time.

For more information on changing property values, see System Design in MATLAB Using System Objects.

**`SampleRate` — Sample rate of sensor**
`100` (default) | positive scalar

Sample rate of sensor, specified as a positive scalar in hertz.

Example: `'SampleRate',100`

Data Types: `double`

**`TicksPerRevolution` — Number of encoder ticks per wheel revolution**
`2048` (default) | positive integer

Number of encoder ticks per wheel revolution, specified as a positive integer. This value corresponds to the rear wheel of the bicycle.

Example: `'TicksPerRevolution',2048`

Data Types: `double`

**`WheelRadius` — Wheel radius**
`0.35` (default) | positive scalar

Wheel radius, specified as a positive scalar in meters.

Example: `'WheelRadius',0.35`

Data Types: `double`

**`WheelBase` — Distance between front and rear axle**
`2.818` (default) | positive scalar

Distance between front and rear axle, specified as a positive scalar in meters.

Example: `'WheelBase',2.818`

Data Types: `double`

**`InitialPose` — Initial pose of vehicle**
`[0 0 0]` (default) | three-element vector

Initial pose of the vehicle, specified as three-element vector of the form [*X Y Yaw*]. *X* and *Y* specify the vehicle position in meters. *Yaw* specifies the vehicle orientation in radians. All values are in the local navigation coordinate system.

Example: `'InitialPose',[0 0 0]`

**Tunable:** No

Data Types: `double`

## Usage

## Syntax

```
pose = whlEncOdom(ticks,steer)
[pose,velocity] = whlEncOdom(ticks,steer)
```

### Description

`pose = whlEncOdom(ticks,steer)` computes the odometry of a bicycle using the specified wheel encoder ticks `ticks` and steering angle `steer`, and returns the position and orientation of the vehicle in the local navigation coordinate system.

`[pose,velocity] = whlEncOdom(ticks,steer)` additionally returns the linear and angular velocity of the vehicle in the local navigation coordinate system.

### Input Arguments

**`ticks` — Number of wheel encoder ticks**
*n*-element column vector

Number of wheel encoder ticks, specified as an *n*-element column vector. *n* is the number of samples in the current frame. Each element is the number of ticks for the rear wheel of the bicycle in the corresponding sample.

Example: `[5; 2]`

Data Types: `single` | `double`

**`steer` — Steering angle of vehicle**
*n*-element column vector

Steering angle of the vehicle, specified as an *n*-element column vector in radians. *n* is the number of samples in the current frame.

Example: `[0.2; 0.2]`

Data Types: `single` | `double`

### Output Arguments

**`pose` — Position and orientation of vehicle**
*n*-by-3 matrix

Position and orientation of the vehicle, returned as an *n*-by-3 matrix. *n* is the number of samples in the current frame. Each row of the matrix specifies the position and orientation of a sample in the form [*X Y Yaw*]. *X* and *Y* specify the vehicle position in meters. *Yaw* specifies the vehicle orientation in radians. All values are in the local navigation coordinate system.

Data Types: `single` | `double`

**`velocity` — Linear and angular velocity of vehicle**
*n*-by-3 matrix

Linear and angular velocity of the vehicle, returned as an *n*-by-3 matrix. *n* is the number of samples in the current frame. Each row of the matrix specifies the linear and angular velocity of a sample in the form [*velX velY yawRate*]. *velX* and *velY* specify the linear velocity of the vehicle in meters per second. *yawRate* specifies the angular velocity of the vehicle in radians per second. All values are in the local navigation coordinate system.

Data Types: `single` | `double`

## Object Functions

To use an object function, specify the System object as the first input argument. For example, to release system resources of a System object named `obj`, use this syntax:

```
release(obj)
```

### Common to All System Objects

| | |
|---|---|
| clone | Create duplicate System object |
| step | Run System object algorithm |
| release | Release resources and allow changes to System object property values and input characteristics |
| reset | Reset internal states of System object |
| isLocked | Determine if System object is in use |

## Examples

#### Compute Bicycle Odometry Using Wheel Encoder Ticks and Steering Angle

Create a `wheelEncoderOdometryBicycle` System object.

```
whlEncOdom = wheelEncoderOdometryBicycle;
```

Specify the number of wheel encoder ticks and the steering angle.

```
ticks = [5; 2];
steer = [0.2; 0.2];
```

Compute the bicycle odometry.

```
[pose,vel] = whlEncOdom(ticks,steer)
```

```
pose = 2×3

    0.0054    0.0000    0.0004
    0.0075    0.0000    0.0005


vel = 2×3

    0.5369    0.0002    0.0386
    0.2148    0.0001    0.0154
```

# Version History

**Introduced in R2020b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

wheelEncoderBicycle | wheelEncoderOdometryAckermann | wheelEncoderOdometryDifferentialDrive | wheelEncoderOdometryUnicycle

# wheelEncoderOdometryDifferentialDrive

Compute differential-drive vehicle odometry using wheel encoder ticks

## Description

The `wheelEncoderOdometryDifferentialDrive` System object computes differential-drive vehicle odometry using the wheel encoder ticks.

To compute differential-drive vehicle odometry:

1. Create the `wheelEncoderOdometryDifferentialDrive` object and set its properties.
2. Call the object with arguments, as if it were a function.

To learn more about how System objects work, see What Are System Objects?

# Creation

## Syntax

```
whlEncOdom = wheelEncoderOdometryDifferentialDrive
whlEncOdom = wheelEncoderOdometryDifferentialDrive(encoder)
whlEncOdom = wheelEncoderOdometryDifferentialDrive(Name,Value)
```

### Description

`whlEncOdom = wheelEncoderOdometryDifferentialDrive` creates a `wheelEncoderOdometryDifferentialDrive` System object with default property values.

`whlEncOdom = wheelEncoderOdometryDifferentialDrive(encoder)` creates a `wheelEncoderOdometryDifferentialDrive` System object using the specified `wheelEncoderDifferentialDrive` System object, `encoder`, to set properties.

`whlEncOdom = wheelEncoderOdometryDifferentialDrive(Name,Value)` sets properties using one or more name-value pairs. Unspecified properties have default values. Enclose each property name in quotes.

For example, `whlEncOdom = wheelEncoderOdometryDifferentialDrive('SampleRate',100)` sets the sample rate of the sensor to 100 Hz.

## Properties

Unless otherwise indicated, properties are *nontunable*, which means you cannot change their values after calling the object. Objects lock when you call them, and the `release` function unlocks them.

If a property is *tunable*, you can change its value at any time.

For more information on changing property values, see System Design in MATLAB Using System Objects.

**SampleRate — Sample rate of sensor**
100 (default) | positive scalar

Sample rate of sensor, specified as a positive scalar in hertz.

Example: 'SampleRate',100

Data Types: double

**TicksPerRevolution — Number of encoder ticks per wheel revolution**
[2048 2048] (default) | positive integer | two-element vector of positive integers

Number of encoder ticks per wheel revolution, specified as a positive integer or two-element vector of positive integers.

When specifying this value as a two-element vector, the first element corresponds to the left wheel and the second to the right wheel.

Example: 'TicksPerRevolution',[2048 2048]

Data Types: double

**WheelRadius — Wheel radius**
[0.35 0.35] (default) | positive scalar | two-element vector of positive numbers

Wheel radius, specified as a positive scalar or two-element vector of positive numbers in meters.

When specifying this value as a two-element vector, the first element corresponds to the left wheel and the second to the right wheel.

Example: 'WheelRadius',[0.35 0.35]

Data Types: double

**TrackWidth — Distance between wheels on axle**
1.572 (default) | positive scalar

Distance between the wheels on the axle, specified as a positive scalar in meters.

Example: 'TrackWidth',1.572

Data Types: double

**InitialPose — Initial pose of vehicle**
[0 0 0] (default) | three-element vector

Initial pose of the vehicle, specified as three-element vector of the form [*X Y Yaw*]. *X* and *Y* specify the vehicle position in meters. *Yaw* specifies the vehicle orientation in radians. All values are in the local navigation coordinate system.

Example: 'InitialPose',[0 0 0]

Data Types: double

## Usage

## Syntax

```
pose = whlEncOdom(ticks)
[pose,velocity] = whlEncOdom(ticks)
```

### Description

`pose = whlEncOdom(ticks)` computes the odometry of a differential-drive vehicle using the specified wheel encoder ticks `ticks`, and returns the position and orientation of the vehicle in the local navigation coordinate system.

`[pose,velocity] = whlEncOdom(ticks)` additionally returns the linear and angular velocity of the vehicle in the local navigation coordinate system.

### Input Arguments

**`ticks` — Number of wheel encoder ticks**
*n*-by-2 matrix

Number of wheel encoder ticks, specified as an *n*-by-2 matrix. *n* is the number of samples in the current frame.

Each row of the matrix specifies wheel encoder ticks in the form [*ticksLeft ticksRight*], where *ticksLeft* and *ticksRight* specify the number of ticks for the left and right wheels, respectively.

Example: `[5 5; 2 2]`

Data Types: `single` | `double`

### Output Arguments

**`pose` — Position and orientation of vehicle**
*n*-by-3 matrix

Position and orientation of the vehicle, returned as an *n*-by-3 matrix. *n* is the number of samples in the current frame. Each row of the matrix specifies the position and orientation of a sample in the form [*X Y Yaw*]. *X* and *Y* specify the vehicle position in meters. *Yaw* specifies the vehicle orientation in radians. All values are in the local navigation coordinate system.

Data Types: `single` | `double`

**`velocity` — Linear and angular velocity of vehicle**
*n*-by-3 matrix

Linear and angular velocity of the vehicle, returned as an *n*-by-3 matrix. *n* is the number of samples in the current frame. Each row of the matrix specifies the linear and angular velocity of a sample in the form [*velX velY yawRate*]. *velX* and *velY* specify the linear velocity of the vehicle in meters per second. *yawRate* specifies the angular velocity of the vehicle in radians per second. All values are in the local navigation coordinate system.

Data Types: `single` | `double`

## Object Functions

To use an object function, specify the System object as the first input argument. For example, to release system resources of a System object named `obj`, use this syntax:

```
release(obj)
```

### Common to All System Objects

| | |
|---|---|
| clone | Create duplicate System object |
| step | Run System object algorithm |
| release | Release resources and allow changes to System object property values and input characteristics |
| reset | Reset internal states of System object |
| isLocked | Determine if System object is in use |

## Examples

#### Compute Differential-Drive Vehicle Odometry Using Wheel Encoder Ticks

Create a `wheelEncoderOdometryDifferentialDrive` System object.

```
whlEncOdom = wheelEncoderOdometryDifferentialDrive;
```

Specify the number of wheel encoder ticks.

```
ticks = [5 5; 2 2];
```

Compute the differential-drive vehicle odometry.

```
[pose,vel] = whlEncOdom(ticks)
```

```
pose = 2×3

    0.0054         0         0
    0.0075         0         0


vel = 2×3

    0.5369         0         0
    0.2148         0         0
```

# Version History

**Introduced in R2020b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`wheelEncoderDifferentialDrive` | `wheelEncoderOdometryAckermann` | `wheelEncoderOdometryBicycle` | `wheelEncoderOdometryUnicycle`

# wheelEncoderOdometryUnicycle

Compute unicycle odometry using wheel encoder ticks and angular velocity

## Description

The `wheelEncoderOdometryUnicycle` System object computes unicycle odometry using the wheel encoder ticks and angular velocity.

To compute unicycle odometry:

1. Create the `wheelEncoderOdometryUnicycle` object and set its properties.
2. Call the object with arguments, as if it were a function.

To learn more about how System objects work, see What Are System Objects?

# Creation

## Syntax

```
whlEncOdom = wheelEncoderOdometryUnicycle
whlEncOdom = wheelEncoderOdometryUnicycle(encoder)
whlEncOdom = wheelEncoderOdometryUnicycle(Name,Value)
```

### Description

`whlEncOdom = wheelEncoderOdometryUnicycle` creates a `wheelEncoderOdometryUnicycle` System object with default property values.

`whlEncOdom = wheelEncoderOdometryUnicycle(encoder)` creates a `wheelEncoderOdometryUnicycle` System object using the specified `wheelEncoderUnicycle` System object, `encoder`, to set properties.

`whlEncOdom = wheelEncoderOdometryUnicycle(Name,Value)` sets properties using one or more name-value pairs. Unspecified properties have default values. Enclose each property name in quotes.

For example, `whlEncOdom = wheelEncoderOdometryUnicycle('SampleRate',100)` sets the sample rate of the sensor to 100 Hz.

## Properties

Unless otherwise indicated, properties are *nontunable*, which means you cannot change their values after calling the object. Objects lock when you call them, and the `release` function unlocks them.

If a property is *tunable*, you can change its value at any time.

For more information on changing property values, see System Design in MATLAB Using System Objects.

#### `SampleRate` — Sample rate of sensor
`100` (default) | positive scalar

Sample rate of sensor, specified as a positive scalar in hertz.

Example: `'SampleRate',100`

Data Types: `double`

#### `TicksPerRevolution` — Number of encoder ticks per wheel revolution
`2048` (default) | positive integer

Number of encoder ticks per wheel revolution, specified as a positive integer.

Example: `'TicksPerRevolution',2048`

Data Types: `double`

#### `WheelRadius` — Wheel radius
`0.35` (default) | positive scalar

Wheel radius, specified as a positive scalar in meters.

Example: `'WheelRadius',0.35`

Data Types: `double`

#### `InitialPose` — Initial pose of vehicle
`[0 0 0]` (default) | three-element vector

Initial pose of the vehicle, specified as three-element vector of the form [*X Y Yaw*]. *X* and *Y* specify the vehicle position in meters. *Yaw* specifies the vehicle orientation in radians. All values are in the local navigation coordinate system.

Example: `'InitialPose',[0 0 0]`

**Tunable:** No

Data Types: `double`

## Usage

## Syntax

```
pose = whlEncOdom(ticks,angVel)
[pose,velocity] = whlEncOdom(ticks,angVel)
```

### Description

`pose = whlEncOdom(ticks,angVel)` computes the odometry of a unicycle using the specified wheel encoder ticks `ticks` and angular velocity `angVel`, and returns the position and orientation of the vehicle in the local navigation coordinate system.

`[pose,velocity] = whlEncOdom(ticks,angVel)` additionally returns the linear and angular velocity of the vehicle in the local navigation coordinate system.

#### Input Arguments

**`ticks` — Number of wheel encoder ticks**
*n*-element column vector

Number of wheel encoder ticks, specified as an *n*-element column vector. *n* is the number of samples in the current frame.

Example: `[5; 2]`

Data Types: `single` | `double`

**`angVel` — Angular velocity of vehicle in vehicle body coordinate system**
*n*-element column vector

Angular velocity of the vehicle in the vehicle body coordinate system, specified as an *n*-element column vector in radians per second. *n* is the number of samples in the current frame.

Example: `[0.2; 0.2]`

Data Types: `single` | `double`

#### Output Arguments

**`pose` — Position and orientation of vehicle**
*n*-by-3 matrix

Position and orientation of the vehicle, returned as an *n*-by-3 matrix. *n* is the number of samples in the current frame. Each row of the matrix specifies the position and orientation of a sample in the form [*X Y Yaw*]. *X* and *Y* specify the vehicle position in meters. *Yaw* specifies the vehicle orientation in radians. All values are in the local navigation coordinate system.

Data Types: `single` | `double`

**`velocity` — Linear and angular velocity of vehicle**
*n*-by-3 matrix

Linear and angular velocity of the vehicle, returned as an *n*-by-3 matrix. *n* is the number of samples in the current frame. Each row of the matrix specifies the linear and angular velocity of a sample in the form [*velX velY yawRate*]. *velX* and *velY* specify the linear velocity of the vehicle in meters per second. *yawRate* specifies the angular velocity of the vehicle in radians per second. All values are in the local navigation coordinate system.

Data Types: `single` | `double`

## Object Functions

To use an object function, specify the System object as the first input argument. For example, to release system resources of a System object named `obj`, use this syntax:

```
release(obj)
```

## Common to All System Objects

| | |
|---|---|
| clone | Create duplicate System object |
| step | Run System object algorithm |

| | |
|---|---|
| release | Release resources and allow changes to System object property values and input characteristics |
| reset | Reset internal states of System object |
| isLocked | Determine if System object is in use |

## Examples

### Compute Unicycle Odometry Using Wheel Encoder Ticks and Angular Velocity

Create a `wheelEncoderOdometryUnicycle` System object.

```
whlEncOdom = wheelEncoderOdometryUnicycle;
```

Specify the number of wheel encoder ticks and angular velocity.

```
ticks = [5; 2];
angVel = [0.2; 0.2];
```

Compute the unicycle odometry.

```
[pose,vel] = whlEncOdom(ticks,angVel)
```

```
pose = 2×3

    0.0054    0.0000    0.0020
    0.0075    0.0000    0.0040


vel = 2×3

    0.5369    0.0011    0.2000
    0.2148    0.0009    0.2000
```

# Version History

**Introduced in R2020b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

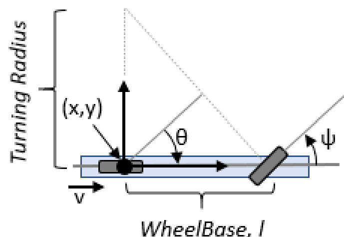
`wheelEncoderUnicycle` | `wheelEncoderOdometryAckermann` | `wheelEncoderOdometryBicycle` | `wheelEncoderOdometryDifferentialDrive`

# bicycleKinematics

Bicycle vehicle model

## Description

`bicycleKinematics` creates a bicycle vehicle model to simulate simplified car-like vehicle dynamics. This model represents a vehicle with two axles separated by a distance, `WheelBase`. The state of the vehicle is defined as a three-element vector, [*x y theta*], with a global *xy*-position, specified in meters, and a vehicle heading angle, *theta*, specified in radians. The front wheel can be turned with steering angle *psi*. The vehicle heading, *theta*, is defined at the center of the rear axle. To compute the time derivative states of the model, use the `derivative` function with input commands and the current robot state.




## Creation

### Syntax

`kinematicModel = bicycleKinematics`

`kinematicModel = bicycleKinematics(Name,Value)`

#### Description

`kinematicModel = bicycleKinematics` creates a bicycle kinematic model object with default property values.

`kinematicModel = bicycleKinematics(Name,Value)` sets additional properties to the specified values. You can specify multiple properties in any order.

## Properties

**`WheelBase` — Distance between front and rear axles**
`1` (default) | positive numeric scalar

The wheel base refers to the distance between the front and rear vehicle axles, specified in meters.

**`VehicleSpeedRange` — Range of vehicle speeds**
`[-Inf Inf]` (default) | positive numeric scalar

The vehicle speed range is a two-element vector that provides the minimum and maximum vehicle speeds, [*MinSpeed MaxSpeed*], specified in meters per second.

**`MaxSteeringAngle` — Maximum steering angle**
`pi/4` (default) | numeric scalar

The maximum steering angle, *psi*, refers to the maximum angle the vehicle can be steered to the right or left, specified in radians. A value of `pi/2` provides the vehicle with a minimum turning radius of 0. This property is used to validate the user-provided state input.

**`MinimumTurningRadius` — Minimum vehicle turning radius**
`1.0000` (default) | numeric scalar

This read-only property returns the minimum vehicle turning radius in meters. The minimum radius is computed using the wheel base and the maximum steering angle.

**`VehicleInputs` — Type of motion inputs for vehicle**
`"VehicleSpeedSteeringAngle"` (default) | character vector | string scalar

The `VehicleInputs` property specifies the format of the model input commands when using the `derivative` function. The property has two valid options, specified as a string or character vector:

- `"VehicleSpeedSteeringAngle"` — Vehicle speed and steering angle
- `"VehicleSpeedHeadingRate"` — Vehicle speed and heading angular velocity

## Object Functions

derivative    Time derivative of bicycle vehicle model

## Examples

### Plot Path of Bicycle Kinematic Robot

Create a robot and set its initial starting position and orientation.

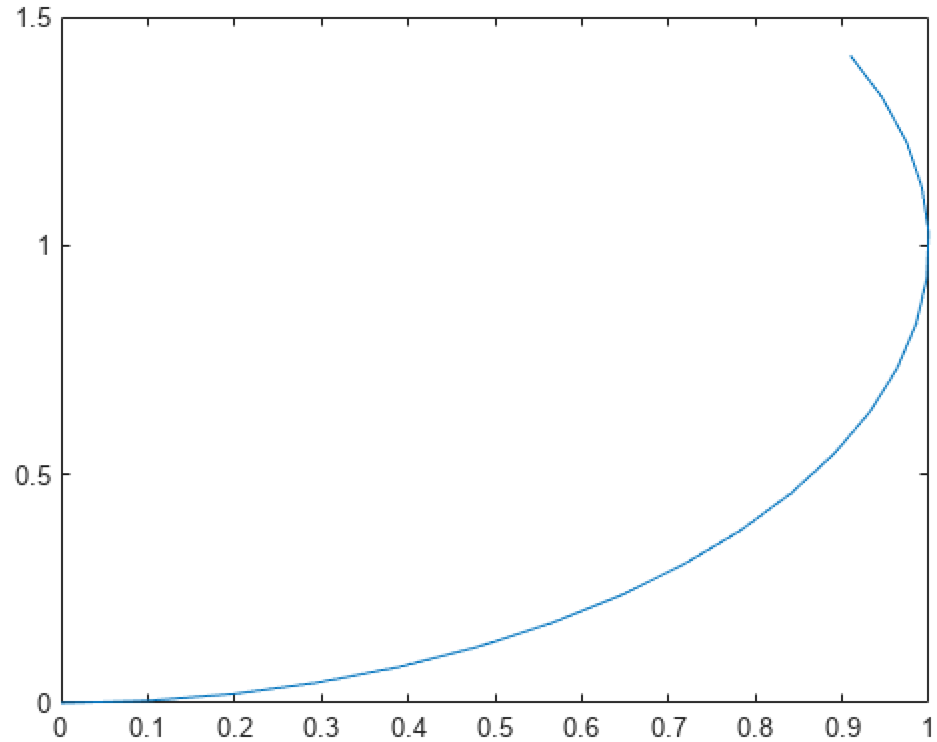
```
kinematicModel = bicycleKinematics;
initialState = [0 0 0];
```

Set the timespan of the simulation to 1 s with 0.05 s time steps and the input commands to 2 m/s for the vehicle speed and `pi/4` rad for the steering angle to create a left turn. Simulate the motion of the robot by using the `ode45` solver on the `derivative` function.

```
tspan = 0:0.05:1;
inputs = [2 pi/4]; %Turn left
[t,y] = ode45(@(t,y)derivative(kinematicModel,y,inputs),tspan,initialState);
```

Plot the path.

```
figure
plot(y(:,1),y(:,2))
```




# Version History

**Introduced in R2021b**

## References

[1] Lynch, Kevin M., and Frank C. Park. *Modern Robotics: Mechanics, Planning, and Control* 1st ed. Cambridge, MA: Cambridge University Press, 2017.

[2] Corke, Peter I. *Robotics, Vision and Control: Fundamental Algorithms in MATLAB*. Springer, 2011.

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Topics**
"Mobile Robot Kinematics Equations" (Robotics System Toolbox)

# derivative

Time derivative of bicycle vehicle model

## Syntax

```
stateDot = derivative(kinematicModel,state,cmds)
```

## Description

`stateDot = derivative(kinematicModel,state,cmds)` returns the current state derivative, `stateDot`, as a three-element vector [*xDot yDot thetaDot*] for a bicycle kinematics vehicle motion model, `kinematicModel`. *xDot* and *yDot* refer to the vehicle velocity, specified in meters per second. *thetaDot* is the angular velocity of the vehicle heading, specified in radians per second.

## Examples

### Plot Path of Bicycle Kinematic Robot

Create a robot and set its initial starting position and orientation.

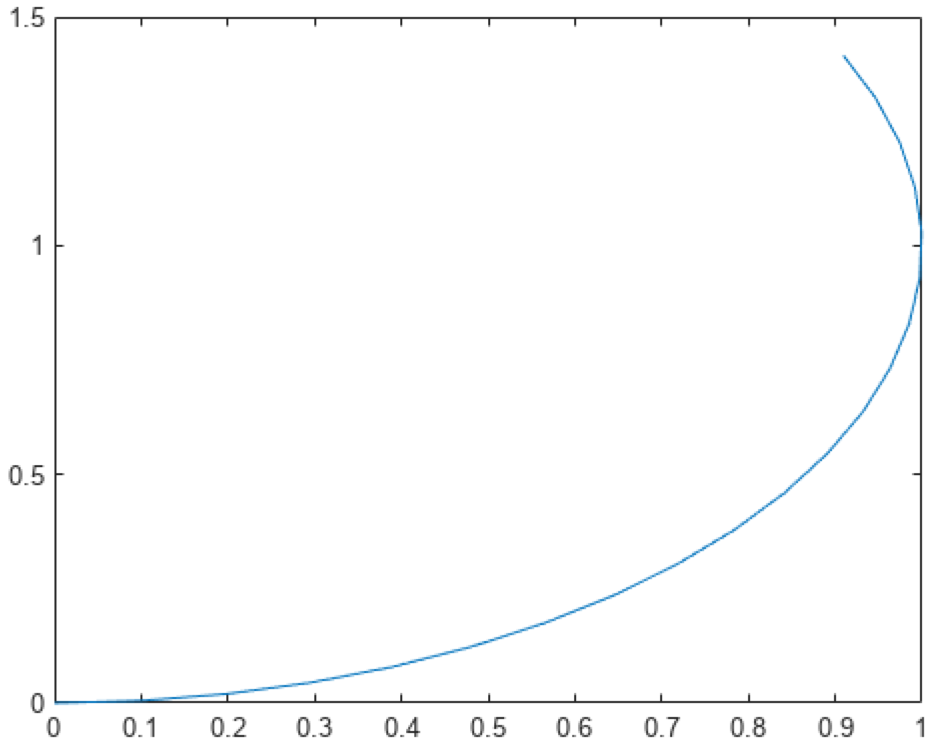
```
kinematicModel = bicycleKinematics;
initialState = [0 0 0];
```

Set the timespan of the simulation to 1 s with 0.05 s time steps and the input commands to 2 m/s for the vehicle speed and `pi/4` rad for the steering angle to create a left turn. Simulate the motion of the robot by using the `ode45` solver on the `derivative` function.

```
tspan = 0:0.05:1;
inputs = [2 pi/4]; %Turn left
[t,y] = ode45(@(t,y)derivative(kinematicModel,y,inputs),tspan,initialState);
```

Plot the path.

```
figure
plot(y(:,1),y(:,2))
```




## Input Arguments

**kinematicModel — Bicycle kinematic motion model**
bicycleKinematics object

Bicycle kinematic motion model, specified as a bicycleKinematics object.

**state — Current vehicle state**
three-element vector | four-element vector

Current vehicle state returned as a three-element vector of the form [*x* *y* *theta*].

*x* and *y* refer to the vehicle position, specified in meters per second. *theta* is the vehicle heading, specified in radians per second.

**cmds — Input commands to motion model**
two-element vector

Input commands to the motion model, specified as a two-element vector. The VehicleInputs property value of motionModel determines the format of this command vector. These are the valid VehicleInputs values for a bicycleKinematics object:

- "VehicleSpeedSteeringAngle" -- [*v* *psiDot*]
- "VehicleSpeedHeadingRate" -- [*v* *omegaDot*]

*v* is the vehicle velocity in the direction of motion in meters per second. *psiDot* is the steering angle rate in radians per second. *omegaDot* is the angular velocity at the rear axle.

### Output Arguments

**`stateDot` — Derivative of current state**
three-element vector of form [*xDot yDot thetaDot*]

Derivative of current state, returned as a three-element vector of the form [*xDot yDot thetaDot*]. *xDot* and *yDot* refer to the vehicle velocity, returned in meters per second. *thetaDot* is the angular velocity of the vehicle heading, returned in radians per second.

## Version History

**Introduced in R2021b**

### References

[1] Lynch, Kevin M., and Frank C. Park. *Modern Robotics: Mechanics, Planning, and Control*. 1st ed. Cambridge, MA: Cambridge University Press, 2017.

### Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

### See Also

`bicycleKinematics`

# insEKF

Inertial Navigation Using Extended Kalman Filter

## Description

The `insEKF` object creates a continuous-discrete extended Kalman Filter (EKF), in which the state prediction uses a continuous-time model and the state correction uses a discrete-time model. The filter uses data from inertial sensors to estimate platform states such as position, velocity, and orientation. The toolbox provides a few sensor models, such as `insAccelerometer`, `insGyroscope`, `insGPS`, and `insMagnetometer`, that you can use to enable the corresponding measurements in the EKF. You can also customize your own sensor models by inheriting from the `positioning.insSensorModel` interface class. The toolbox also provides motion models, such as `insMotionOrientation` and `insMotionPose`, that you can use to enable the corresponding state propagation in the EKF. You can also customize your own motion models by inheriting from the `positioning.insMotionModel` interface class.

## Creation

### Syntax

```
filter = insEKF
filter = insEKF(sensor1,sensor2,...,sensorN)
filter = insEKF( ___ ,motionModel)
filter = insEKF( ___ ,options)
```

#### Description

`filter = insEKF` creates an `insEKF` filter object with default property values. With the default settings, the filter can estimate orientation by fusing accelerometer and gyroscope data.

`filter = insEKF(sensor1,sensor2,...,sensorN)` configures the filter to accept and fuse data from one or more sensors. The filter saves these sensors in its `Sensors` property.

`filter = insEKF( ___ ,motionModel)` configures the filter to use the motion model to predict and estimate state, in addition to any combination of input arguments from previous syntaxes. The filter saves the specified motion model in the `MotionModel` property.

`filter = insEKF( ___ ,options)` configures the filter using the `insOptions` object `options`.

### Properties

**`State` — State vector of extended Kalman filter**
*N*-element real-valued vector

State vector of the extended Kalman filter, specified as an *N*-element real-valued vector. *N* is the dimension of the filter state, determined by the specific sensors and motion model used to construct the filter.

---

**Note** In the `State` property, if a state variable named `Orientation` has a length of four, the object assumes it is a `quaternion`. In that case, the filter renormalizes the quaternion and ensures that the real part of the quaternion is always positive.

---

Data Types: `single` | `double`

**`StateCovariance` — State error covariance of extended Kalman filter**
*N*-by-*N* real-valued positive-definite matrix

State error covariance for the extended Kalman filter, specified as an *N*-by-*N* real-valued positive-definite matrix. *N* is the dimension of the state, specified in the `State` property of the filter.

Data Types: `single` | `double`

**`AddtiveProcessNoise` — Additive process noise for extended Kalman filter**
*N*-by-*N* real-valued positive definite matrix

Additive process noise for the extended Kalman filter, specified as an *N*-by-*N* real-valued positive definite matrix. *N* is the dimension of the state, specified in the `State` of the filter.

Data Types: `single` | `double`

**`MotionModel` — Motion model used in extended Kalman filter**
`insMotionOrientation` object | `insMotionPose` object | object inheriting from `positioning.INSMotionModel` class

This property is read-only.

Motion model used in the extended Kalman filter, specified as an `insMotionOrientation` object , an `insMotionPose` object, or an object inheriting from the `positioning.INSMotionModel` interface class. Specify a motion model using the `motionModel` input argument.

Data Types: `object`

**`Sensors` — Sensors fused in extended Kalman filter**
`{insAccelerometer,insGyroscope}` (default) | cell array of inertial sensor objects

This property is read-only.

Sensors fused in the extended Kalman filter, specified as a cell array of inertial sensor objects. An inertial sensor object is one of these objects:

- An `insAccelerometer` object
- An `insMagnetometer` object
- An `insGPS` object
- An `insGyroscope` object
- An object inheriting from the `positioning.INSSensorModel` interface class

Data Types: `cell`

**`SensorNames` — Names of sensors**
cell array of character vectors

This property is read-only.

Names of the sensors, specified as a cell array of character vectors. By default, the filter names the sensors using the format `'sensorname_n'`, where `sensorname` is the name of the sensor, such as `Accelerometer`, and `n` is the index for additional sensors of the same type.

To customize the sensor names, specify the `options` input when constructing the filter.

Example: `{'Accelerometer' 'Accelerometer_1' 'Accelerometer_2' 'Gyroscope'}`

Data Types: `cell`

**`ReferenceFrame` — Reference frame of extended Kalman filter**
`"NED"` (default) | `"ENU"`

This property is read-only.

Reference frame of the extended Kalman filter, specified as `"NED"` for the north-east-down frame or `"ENU"` for the east-north-up frame.

To specify the reference frame as `"ENU"`, specify the `options` input when constructing the filter.

Data Types: `char` | `string`

## Object Functions

| | |
|---|---|
| predict | Predict state estimates forward in time for insEKF |
| fuse | Fuse sensor data for state estimation in insEKF |
| residual | Residual and residual covariance from state measurement for insEKF |
| correct | Correct state estimates in insEKF using direct state measurements |
| stateparts | Get and set part of state vector in insEKF |
| statecovparts | Get and set part of state covariance matrix in insEKF |
| stateinfo | State vector information for insEKF |
| estimateStates | Batch fusion and smoothing of sensor data |
| tune | Tune insEKF parameters to reduce estimation error |
| createTunerCostTemplate | Create template of tuner cost function |
| tunerCostFcnParam | First parameter example for tuning cost function |
| copy | Create copy of insEKF |
| reset | Reset states for insEKF |

## Examples

### Create `insEKF` with Different Configurations

Create a default `insEKF` object. By default, the filter fuses the measurement data from an accelerometer and a gyroscope assuming orientation-only motion.

```
filter1 = insEKF
```

```
filter1 = 
  insEKF with properties:

                  State: [13x1 double]
        StateCovariance: [13x13 double]
    AdditiveProcessNoise: [13x13 double]
            MotionModel: [1x1 insMotionOrientation]
                Sensors: {[1x1 insAccelerometer]  [1x1 insGyroscope]}
```

```
           SensorNames: {'Accelerometer'  'Gyroscope'}
         ReferenceFrame: 'NED'
```

Create a second `insEKF` object that fuses data from an accelerometer, a gyroscope, and a magnetometer, as well as models both rotational motion and translational motion.

```
filter2 = insEKF(insAccelerometer,insGyroscope,insMagnetometer,insMotionPose)
```

```
filter2 = 
  insEKF with properties:

                  State: [28x1 double]
        StateCovariance: [28x28 double]
    AdditiveProcessNoise: [28x28 double]
            MotionModel: [1x1 insMotionPose]
                Sensors: {[1x1 insAccelerometer]  [1x1 insGyroscope]  [1x1 insMagnetometer]}
            SensorNames: {'Accelerometer'  'Gyroscope'  'Magnetometer'}
         ReferenceFrame: 'NED'
```

Create a third `insEKF` object that fuses data from a gyroscope and a GPS. Specify the reference frame of the filter as the east-north-up (ENU) frame. Note that the motion model that the filter uses is the `insMotionPose` object because a GPS measures platform positions.

```
option = insOptions(ReferenceFrame="ENU");
filter3 = insEKF(insGyroscope,insGPS,option)
```

```
filter3 = 
  insEKF with properties:

                  State: [19x1 double]
        StateCovariance: [19x19 double]
    AdditiveProcessNoise: [19x19 double]
            MotionModel: [1x1 insMotionPose]
                Sensors: {[1x1 insGyroscope]  [1x1 insGPS]}
            SensorNames: {'Gyroscope'  'GPS'}
         ReferenceFrame: 'ENU'
```

#### Sequential Fusion of Accelerometer and Gyroscope Data Using insEKF

Load measurement data from an accelerometer and a gyroscope.

```
load("accelGyroINSEKFData.mat");
```

Create an `insEKF` filter object. Specify the orientation part of the state in the filter using the initial orientation from the measurement data. Specify the diagonal elements of the state estimate error covariance matrix corresponding to the orientation state as `0.01`.

```
accel = insAccelerometer;
gyro = insGyroscope;
filt = insEKF(accel,gyro);
stateparts(filt,"Orientation",compact(ld.initOrient));
statecovparts(filt,"Orientation",1e-2);
```

Specify the measurement noise and the additive process noise. You can obtain these values by using the `tune` object function of the filter object.

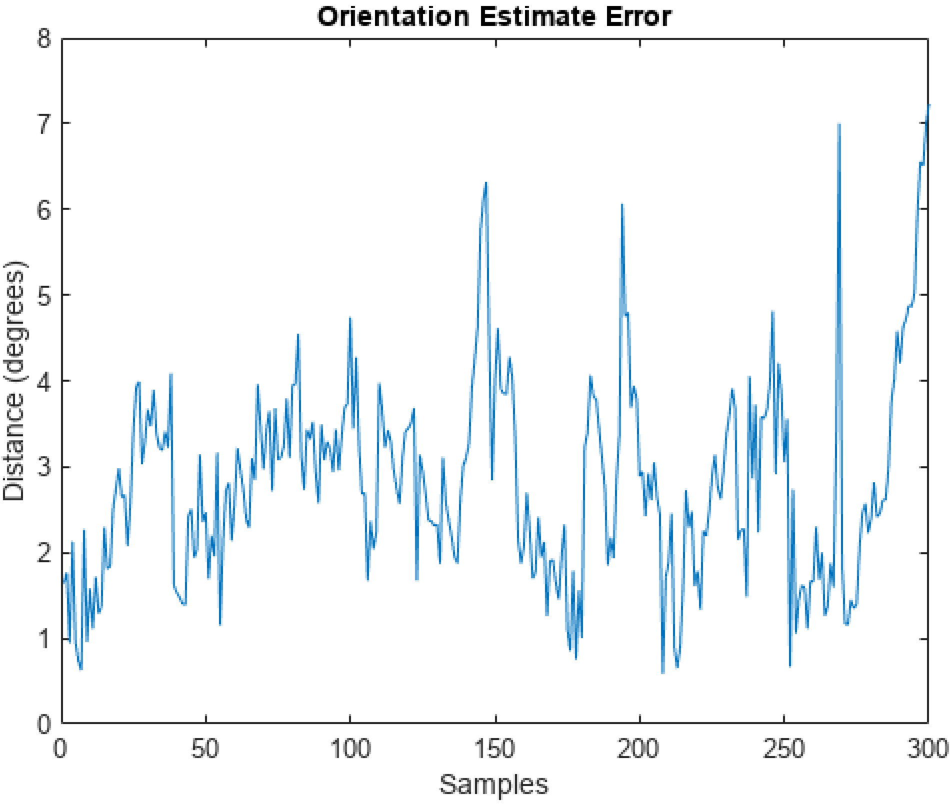
```
accNoise = 0.1739;
gyroNoise = 1.1129;
processNoise = diag([ ...
    2.8586 1.3718 0.8956 3.2148 4.3574 2.5411 3.2148 0.5465 0.2811 ...
    1.7149 0.1739 0.7752 0.1739]);
filt.AdditiveProcessNoise = processNoise;
```

Sequentially fuse the measurement data using the `predict` and `fuse` object functions of the filter object.

```
N = size(ld.sensorData,1);
estOrient = quaternion.zeros(N,1);
dt = seconds(diff(ld.sensorData.Properties.RowTimes));
for ii = 1:N
    if ii ~= 1
        % Step forward in time.
        predict(filt,dt(ii-1));
    end
    % Fuse accelerometer data.
    fuse(filt,accel,ld.sensorData.Accelerometer(ii,:),accNoise);
    % Fuse gyroscope data.
    fuse(filt,gyro,ld.sensorData.Gyroscope(ii,:),gyroNoise);
    % Extract the orientation state estimate using the stateparts object
    % function.
    estOrient(ii) = quaternion(stateparts(filt,"Orientation"));
end
```

Visualize the estimate error, in quaternion distance, using the `dist` object function of the `quaternion` object.

```
figure
plot(rad2deg(dist(estOrient,ld.groundTruth.Orientation)))
xlabel("Samples")
ylabel("Distance (degrees)")
title("Orientation Estimate Error")
```




### Batch Fusion and State Smoothing Using `insEKF`

Load measurement data from an accelerometer and a gyroscope.

```
load("accelGyroINSEKFData.mat");
```

Create an `insEKF` filter object. Specify the orientation part of the state in the filter using the initial orientation from the measurement data. Specify the diagonal elements of the state estimate error covariance matrix corresponding to the orientation state as `0.01`.

```
filt = insEKF;
stateparts(filt,"Orientation",compact(ld.initOrient));
statecovparts(filt,"Orientation",1e-2);
```

Specify the measurement noise and the additive process noise. You can obtain these values by using the `tune` object function of the filter object.

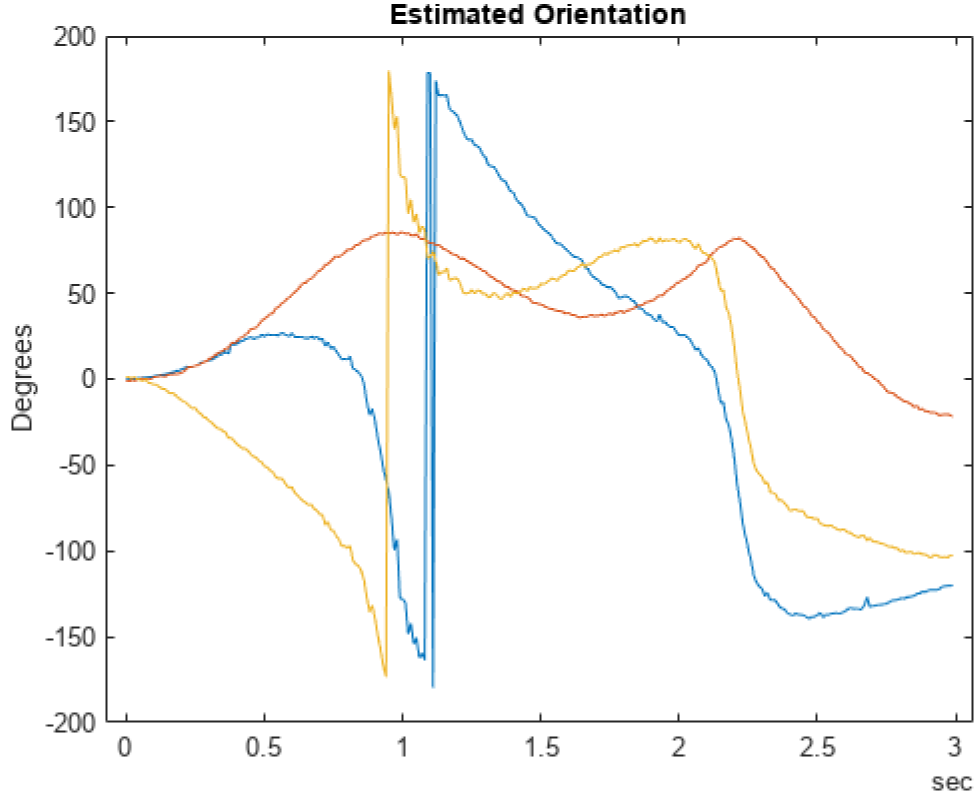
```
measureNoise = struct("AccelerometerNoise", 0.1739, ...
    "GyroscopeNoise", 1.1129);
processNoise = diag([ ...
    2.8586 1.3718 0.8956 3.2148 4.3574 2.5411 3.2148 0.5465 0.2811 ...
    1.7149 0.1739 0.7752 0.1739]);
filt.AdditiveProcessNoise = processNoise;
```

Batch-estimate the states using the `estimateStates` object function. Also, obtain the estimates after smoothing.

```
[estimates,smoothEstimates] = estimateStates(filt,ld.sensorData,measureNoise);
```

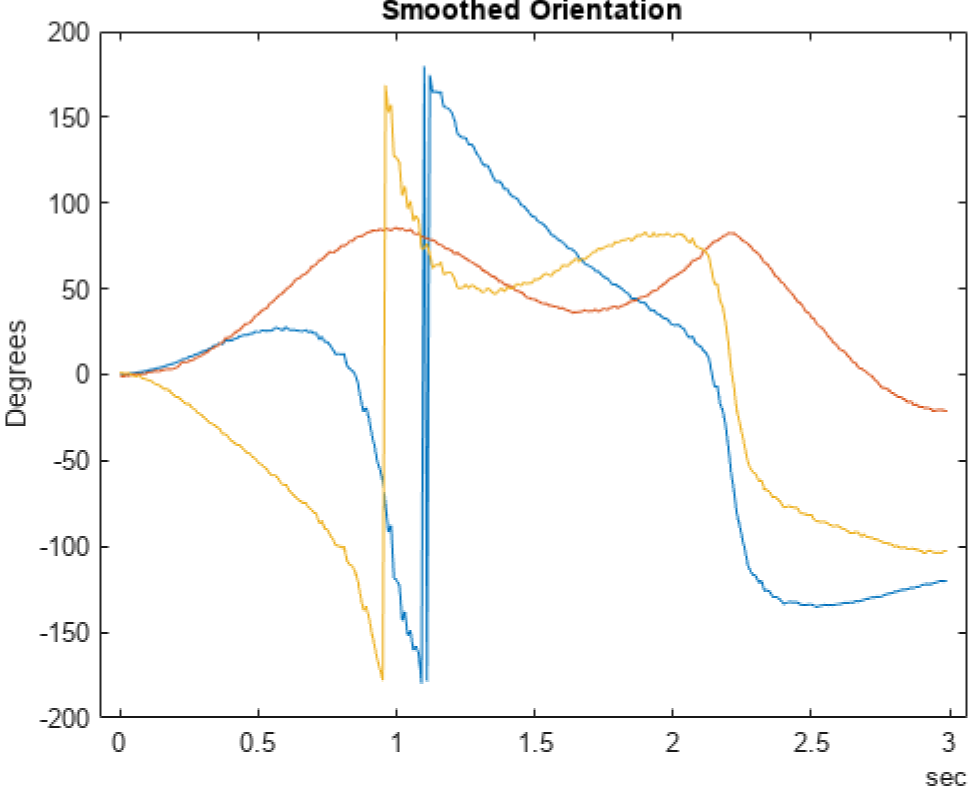
Visualize the estimated orientation in Euler angles.

```
figure
t = estimates.Properties.RowTimes;
plot(t,eulerd(estimates.Orientation,"ZYX","frame"));
title("Estimated Orientation");
ylabel("Degrees")
```



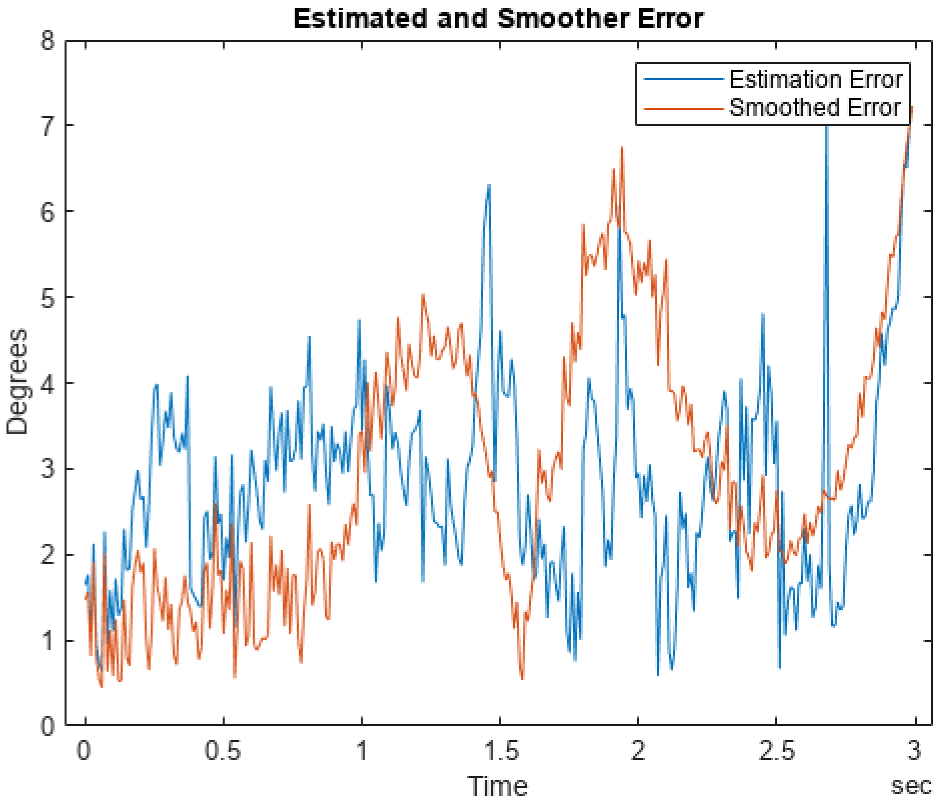

Visualize the estimated orientation after smoothing in Euler angles.

```
figure
plot(t,eulerd(smoothEstimates.Orientation,"ZYX","frame"));
title("Smoothed Orientation");
ylabel("Degrees")
```




Visualize the estimate error, in quaternion distance, using the `dist` object function of the `quaternion` object.

```
trueOrient = ld.groundTruth.Orientation;
plot(t,rad2deg(dist(estimates.Orientation, trueOrient)), ...
     t,rad2deg(dist(smoothEstimates.Orientation, trueOrient)));
title("Estimated and Smoother Error");
legend("Estimation Error","Smoothed Error")
xlabel("Time");
ylabel("Degrees")
```




## Version History

**Introduced in R2022a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`insOptions` | `insAccelerometer` | `insGPS` | `insGyroscope` | `insMagnetometer` | `insMotionOrientation` | `insMotionPose` | `positioning.INSMotionModel` | `positioning.INSSensorModel` | `tunerconfig` | `tunernoise` | `tunerPlotPose`

# predict

Predict state estimates forward in time for `insEKF`

## Syntax

```
[state,stateCovariance] = predict(filter,dt)
[___] = predict(___,varargin)
```

## Description

`[state,stateCovariance] = predict(filter,dt)` predicts the state estimates forward in time by `dt` seconds based on the motion model of the filter and returns the predicted state and state estimate error covariance.

`[___] = predict(___,varargin)` specifies arguments used in the state transition functions or state transition Jacobian functions of the sensor models or the motion model used in the filter, in addition to all arguments from the previous syntax.

## Examples

### Predict insEKF Filter Object

Create an `insEKF` filter object. Specify the angular velocity of filter as `[.1 0 0]` rad/s.

```
filter = insEKF;
stateparts(filter,"AngularVelocity",[.1 0 0]);
```

Show the orientation quaternion at time t = 0 seconds.

```
orientation0 = quaternion(stateparts(filter,"Orientation"))
```

```
orientation0 = quaternion
     1 + 0i + 0j + 0k
```

Predict the filter by 1 second and show the orientation quaternion.

```
[state, statecov] = predict(filter,1);
orientation1 = quaternion(stateparts(filter,"Orientation"))
```

```
orientation1 = quaternion
      0.99875 + 0.049938i +        0j +        0k
```

## Input Arguments

**`filter` — INS filter**
`insEKF` object

INS filter, specified as an `insEKF` object.

**dt — Time step of prediction**
positive scalar

Time step of prediction, specified as a positive scalar.

Data Types: single | double

**varargin — Additional arguments**
any data type

Additional arguments passed to the state transition functions and state transition Jacobian functions of the motion model and sensor models used in the filter, specified as any data type accepted by the two functions. You can use these arguments to simulate control or drive inputs, such as a throttle.

Data Types: single | double

## Output Arguments

**state — Predicted state vector**
*N*-element real-valued vector

Predicted state vector, returned as an *N*-element real-valued vector, where *N* is the dimension of the filter state.

Data Types: single | double

**stateCovariance — State estimate error covariance**
*N*-by-*N* real-valued positive definite matrix

State estimate error covariance, returned as an *N*-by-*N* real-valued positive definite matrix, where *N* is the dimension of the state.

Data Types: single | double

# Version History

**Introduced in R2022a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

fuse | residual | correct | stateparts | statecovparts | stateinfo | estimateStates | tune | createTunerCostTemplate | tunerCostFcnParam

# fuse

Fuse sensor data for state estimation in `insEKF`

## Syntax

`[state,stateCovariance] = fuse(filter,sensor,measurement,measurementNoise)`

## Description

`[state,stateCovariance] = fuse(filter,sensor,measurement,measurementNoise)` fuses the measurement from a sensor, based on the measurement noise, for state estimation.

## Examples

### Fuse Gyroscope Data Using insEKF

Create an `insAccelerometer` sensor object and `insGyroscope` sensor object.

```
acc = insAccelerometer;
gyro = insGyroscope;
```

Construct an `insEKF` object using the two sensor objects.

```
filter = insEKF(acc,gyro);
```

Fuse a gyroscope measurement of `[0.1 0.2 –0.04]` rad/*s* with a measurement noise covariance of `diag([0.2 0.2 0.2])` $(\text{deg}/s)^2$.

```
[state,stateCov] = fuse(filter,gyro,[0.1 0.2 -0.04],diag([0.2 0.2 0.2]));
```

Show the fused state.

```
state
```

```
state = 13×1

    1.0000
         0
         0
         0
    0.0455
    0.0909
   -0.0182
         0
         0
         0
      ⋮
```

## Input Arguments

**`filter` — INS filter**
`insEKF` object

INS filter, specified as an `insEKF` object.

**`sensor` — Inertial sensor**
`insAccelerometer` object | `insGyroscope` object | `insMagnetometer` object | `insGPS` object | object inheriting from `positioning.insSensorModel` interface class

Inertial sensor, specified as one of these objects used to construct the `insEKF` filter object:

- An `insAccelerometer` object
- An `insGyroscope` object
- An `insMagnetometer` object
- An `insGPS` object
- An object inheriting from the `positioning.insSensorModel` interface class

**`measurement` — Measurement from sensor**
*M*-element real-valued vector

Measurement from the sensor, specified as an *M*-element real-valued vector, where *M* is the dimension of the measurement from the `sensor` object.

Data Types: `single` | `double`

**`measurementNoise` — Measurement noise**
*M*-by-*M* real-valued positive-definite matrix | *M*-element vector of positive values | positive scalar

Measurement noise, specified as an *M*-by-*M* real-valued positive-definite matrix, an *M*-element vector of positive values, or a positive scalar. *M* is the dimension of the measurement from the `sensor` object. When specified as a vector, the vector expands to the diagonal of an *M*-by-*M* diagonal matrix. When specified as a scalar, the value of the property is the product of the scalar and an *M*-by-*M* identity matrix.

Data Types: `single` | `double`

## Output Arguments

**`state` — State vector after measurement fusion**
*N*-element real-valued vector

State vector after measurement fusion, returned as an *N*-element real-valued vector, where *N* is the dimension of the filter state.

Data Types: `single` | `double`

**`stateCovariance` — State estimate error covariance after measurement fusion**
*N*-by-*N* real-valued positive definite matrix

State estimate error covariance after measurement fusion, returned as an *N*-by-*N* real-valued positive definite matrix, where *N* is the dimension of the state.

Data Types: `single` | `double`

## Version History

**Introduced in R2022a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`predict` | `residual` | `correct` | `stateparts` | `statecovparts` | `stateinfo` | `estimateStates` | `tune` | `createTunerCostTemplate` | `tunerCostFcnParam`

# residual

Residual and residual covariance from state measurement for `insEKF`

## Syntax

```
[residual,residualCovariance] = residual(filter,sensor,measurement,
measurementNoise)
```

## Description

`[residual,residualCovariance] = residual(filter,sensor,measurement,
measurementNoise)` computes the residual and the residual covariance based on the measurement from the sensor and the measurement covariance.

## Examples

### Obtain Gyroscope Measurement Residuals Using insEKF

Create an `insAccelerometer` sensor object and `insGyroscope` sensor object.

```
acc = insAccelerometer;
gyro = insGyroscope;
```

Construct an `insEKF` object using the two sensor objects. Specify the angular velocity as `[0.1 0.1 0.1]` rad/*s*.

```
filter = insEKF(acc,gyro);
stateparts(filter,"AngularVelocity",[0.1 0.1 0.1]);
```

Obtain the residuals for a gyroscope measurement of `[0.1 0.2 -0.04]` rad/*s* with a measurement noise covariance of `diag([0.2 0.2 0.2])` $(\text{deg}/s)^2$.

```
[residual,residualCov] = residual(filter,gyro,[0.1 0.2 -0.04],diag([0.2 0.2 0.2]))
```

```
residual = 3×1

         0
    0.1000
   -0.1400


residualCov = 3×3

    2.2000         0         0
         0    2.2000         0
         0         0    2.2000
```

## Input Arguments

**`filter` — INS filter**
`insEKF` object

INS filter, specified as an `insEKF` object.

**`sensor` — Inertial sensor**
`insAccelerometer` object | `insGyroscope` object | `insMagnetometer` object | `insGPS` object | object inheriting from `positioning.insSensorModel` interface class

Inertial sensor, specified as one of these objects used to construct the `insEKF` filter object:

- An `insAccelerometer` object
- An `insGyroscope` object
- An `insMagnetometer` object
- An `insGPS` object
- An object inheriting from the `positioning.insSensorModel` interface class

**`measurement` — Measurement from sensor**
*M*-element real-valued vector

Measurement from the sensor, specified as an *M*-element real-valued vector, where *M* is the dimension of the measurement from the `sensor` object.

Data Types: `single` | `double`

**`measurementNoise` — Measurement noise**
*M*-by-*M* real-valued positive-definite matrix | *M*-element vector of positive values | positive scalar

Measurement noise, specified as an *M*-by-*M* real-valued positive-definite matrix, an *M*-element vector of positive values, or a positive scalar. *M* is the dimension of the measurement from the `sensor` object. When specified as a vector, the vector expands to the diagonal of an *M*-by-*M* diagonal matrix. When specified as a scalar, the value of the property is the product of the scalar and an *M*-by-*M* identity matrix.

Data Types: `single` | `double`

## Output Arguments

**`residual` — Measurement residual**
*M*-element real-valued vector

Measurement residual, returned as an *M*-element real-valued vector, where *M* is the dimension of the measurement.

Data Types: `single` | `double`

**`residualCovariance` — Residual covariance**
*M*-by-*M* real-valued positive definite matrix

Residual covariance, returned as an *M*-by-*M* real-valued positive definite matrix, where *M* is the dimension of the measurement.

Data Types: `single` | `double`

# Version History

**Introduced in R2022a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`predict` | `fuse` | `correct` | `stateparts` | `statecovparts` | `stateinfo` | `estimateStates` | `tune` | `createTunerCostTemplate` | `tunerCostFcnParam`

# correct

Correct state estimates in `insEKF` using direct state measurements

## Syntax

```
[state,stateCovariance] = correct(filter,indices,measurement,
measurementNoise)
```

## Description

`[state,stateCovariance] = correct(filter,indices,measurement,
measurementNoise)` corrects filter estimates based on a measurement, the associated index of the measurement, and the measurement noise. The measurement must be a direct measurement of the state vector. For fusing indirect measurements, use the `fuse` object function.

## Examples

### Correct Angular Velocity State in insEKF

Create a default `insEKF` object and show its state.

```
filter = insEKF;
filter.State
```

```
ans = 13×1

     1
     0
     0
     0
     0
     0
     0
     0
     0
     0
       ⋮
```

Obtain the indices corresponding to the angular velocity state.

```
idx = stateinfo(filter,"AngularVelocity");
```

Correct the angular velocity state and show the corrected state.

```
state = correct(filter,idx,[1 1 1], diag([0.1 0.1 0.1]))
```

```
state = 13×1

    1.0000
         0
```

```
        0
        0
   0.9091
   0.9091
   0.9091
        0
        0
        0
       ⋮
```

## Input Arguments

**filter — INS filter**
insEKF object

INS filter, specified as an `insEKF` object.

**indices — State indices**
*M*-element vector of state indices

State indices of the measurement, specified as an *M*-element vector of state indices, where *M* is the dimension of the measurement. For example, if the measurement is the first and third elements in the state vector of the filter, then specify `indices` as `[1 3]`.

**measurement — Direct state measurement**
*M*-element real-valued vector

Direct state measurement, specified as an *M*-element real-valued vector, where *M* is the dimension of the measurement.

Data Types: single | double

**measurementNoise — Measurement noise**
*M*-by-*M* real-valued positive-definite matrix | *M*-element vector of positive values | positive scalar

Measurement noise, specified as an *M*-by-*M* real-valued positive-definite matrix, an *M*-element vector of positive values, or a positive scalar. *M* is the dimension of the measurement. When specified as a vector, the vector expands to the diagonal of an *M*-by-*M* diagonal matrix. When specified as a scalar, the value of the property is the product of the scalar and an *M*-by-*M* identity matrix.

Data Types: single | double

## Output Arguments

**state — Corrected state vector**
*N*-element real-valued vector

Corrected state vector, returned as an *N*-element real-valued vector, where *N* is the dimension of the filter state.

Data Types: single | double

**stateCovariance — Corrected state estimate error covariance**
*N*-by-*N* real-valued positive definite matrix

Corrected state estimate error covariance, returned as an *N*-by-*N* real-valued positive definite matrix, where *N* is the dimension of the state.

Data Types: `single` | `double`

# Version History

**Introduced in R2022a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`predict` | `fuse` | `residual` | `stateparts` | `stateinfo` | `estimateStates` | `tune` | `createTunerCostTemplate` | `tunerCostFcnParam`

# stateparts

Get and set part of state vector in insEKF

## Syntax

```
part = stateparts(filter,stateName)
part = stateparts(filter,sensor,stateName)
stateparts(filter,stateName,value)
stateparts(filter,sensor,stateName,value)
```

## Description

`part = stateparts(filter,stateName)` returns the components of the state vector corresponding to the specified state name of the filter.

`part = stateparts(filter,sensor,stateName)` returns the components of the state vector corresponding to the specified state name of the specified sensor.

`stateparts(filter,stateName,value)` sets the components of the state vector corresponding to the specified state name of the filter to the specified value.

`stateparts(filter,sensor,stateName,value)` sets the components of the state vector corresponding to the specified state name of the specified sensor to the specified value.

## Examples

### Set and Get Accelerometer Biases in insEKF

Create an `insAccelerometer` sensor object and `insGyroscope` sensor object.

```
acc = insAccelerometer;
gyro = insGyroscope;
```

Construct an `insEKF` object using the two sensor objects.

```
filter = insEKF(acc,gyro);
```

Set the bias of the accelerometer to `[10 0 1]` m/s$^2$.

```
stateparts(filter,acc,"Bias",[10 0 1])
```

Get the bias of the accelerometer via the sensor.

```
accBias = stateparts(filter,acc,"Bias")
```

```
accBias = 1×3

    10     0     1
```

Get the bias of the accelerometer via the filter.

```
accBias2 = stateparts(filter,"Accelerometer_Bias")
```

```
accBias2 = 1×3

    10     0     1
```

Set the bias of the accelerometer back to `[0 0 0]`.

```
stateparts(filter,"Accelerometer_Bias",[0 0 0])
```

## Input Arguments

**filter — INS filter**
insEKF object

INS filter, specified as an `insEKF` object.

**stateName — Name of part of state**
string scalar | character vector

Name of a part of the state for the filter or the sensor, specified as a string scalar or character vector.

Use the `stateinfo` object function to find the names of state parts in the filter.

Example: `"AngularVelocity"`

Example: `"Bias"`

Data Types: `char` | `string`

**sensor — Inertial sensor**
`insAccelerometer` object | `insGyroscope` object | `insMagnetometer` object | `insGPS` object | object inheriting from `positioning.insSensorModel` interface class

Inertial sensor, specified as one of these objects used to construct the `insEKF` filter object:

- An `insAccelerometer` object
- An `insGyroscope` object
- An `insMagnetometer` object
- An `insGPS` object
- An object inheriting from the `positioning.insSensorModel` interface class

**value — Value for filter state or sensor state part**
$N$-element real-valued vector

Value for the filter state or sensor state part, specified as an $N$-element real-valued vector, where $N$ is the number of elements in the state part.

Example: `[.2 .3]`

Data Types: `single` | `double`

## Output Arguments

**`part` — Part of state vector**
*N*-element real-valued vector

Part of the state vector, returned as a real-valued vector, where *N* is the number of elements in the state part.

# Version History

**Introduced in R2022a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

# statecovparts

Get and set part of state covariance matrix in `insEKF`

## Syntax

```
covparts = statecovparts(filter,stateName)
covparts = statecovparts(filter,sensor,stateName)
statecovparts(filter,stateName,value)
statecovparts(filter,sensor,stateName,value)
```

## Description

`covparts = statecovparts(filter,stateName)` returns the covariance submatrix corresponding to the specified state name of the filter. The returned submatrix is a square matrix extracted from along the main diagonal of the full state covariance matrix of the filter.

`covparts = statecovparts(filter,sensor,stateName)` returns the covariance submatrix corresponding to the specified state name of the sensor.

`statecovparts(filter,stateName,value)` sets the covariance submatrix corresponding to the specified state name of the filter to the specified value.

`statecovparts(filter,sensor,stateName,value)` sets the covariance submatrix corresponding to the specified state name of the specified sensor to the specified value.

## Examples

### Set and Get Accelerometer Bias Covariances in `insEKF`

Create an `insAccelerometer` sensor object.

```
acc = insAccelerometer;
```

Construct an `insEKF` object using the two sensor objects.

```
filter = insEKF(acc);
```

View the state covariance matrix of the filter. By default, the state covariance matrix is a 10-by-10 identity matrix.

```
filter.StateCovariance
```

```
ans = 10×10

     1     0     0     0     0     0     0     0     0     0
     0     1     0     0     0     0     0     0     0     0
     0     0     1     0     0     0     0     0     0     0
     0     0     0     1     0     0     0     0     0     0
     0     0     0     0     1     0     0     0     0     0
     0     0     0     0     0     1     0     0     0     0
```

```
     0     0     0     0     0     0     1     0     0     0
     0     0     0     0     0     0     0     1     0     0
     0     0     0     0     0     0     0     0     1     0
     0     0     0     0     0     0     0     0     0     1
```

Set the diagonal of the covariance submatrix corresponding to the accelerometer to `3`, and show the submatrix.

```
statecovparts(filter,acc,"Bias",3);
statecovparts(filter,acc,"Bias")
```

```
ans = 3×3

     3     0     0
     0     3     0
     0     0     3
```

Set the diagonal of the covariance submatrix corresponding to the accelerometer to `[1 2 3]`, and show the submatrix.

```
statecovparts(filter,acc,"Bias",[1 2 3]);
statecovparts(filter,acc,"Bias")
```

```
ans = 3×3

     1     0     0
     0     2     0
     0     0     3
```

Set the covariance submatrix corresponding to the accelerometer to `magic(3)`, and show the submatrix.

```
statecovparts(filter,acc,"Bias",magic(3));
statecovparts(filter,acc,"Bias")
```

```
ans = 3×3

     8     1     6
     3     5     7
     4     9     2
```

Show the covariance submatrix corresponding to the accelerometer directly through the filter.

```
statecovparts(filter,"Accelerometer_Bias")
```

```
ans = 3×3

     8     1     6
     3     5     7
     4     9     2
```

View the altered state covariance matrix.

```
filter.StateCovariance
```

```
ans = 10×10

     1     0     0     0     0     0     0     0     0     0
     0     1     0     0     0     0     0     0     0     0
     0     0     1     0     0     0     0     0     0     0
     0     0     0     1     0     0     0     0     0     0
     0     0     0     0     1     0     0     0     0     0
     0     0     0     0     0     1     0     0     0     0
     0     0     0     0     0     0     1     0     0     0
     0     0     0     0     0     0     0     8     1     6
     0     0     0     0     0     0     0     3     5     7
     0     0     0     0     0     0     0     4     9     2
```

## Input Arguments

**`filter` — INS filter**
`insEKF` object

INS filter, specified as an `insEKF` object.

**`stateName` — Name of part of state**
string scalar | character vector

Name of a part of the state for the filter or the sensor, specified as a string scalar or character vector.

Use the `stateinfo` object function to find the names of state parts in the filter.

Example: `"AngularVelocity"`

Example: `"Bias"`

Data Types: `char` | `string`

**`sensor` — Inertial sensor**
`insAccelerometer` object | `insGyroscope` object | `insMagnetometer` object | `insGPS` object | object inheriting from `positioning.insSensorModel` interface class

Inertial sensor, specified as one of these objects used to construct the `insEKF` filter object:

- An `insAccelerometer` object
- An `insGyroscope` object
- An `insMagnetometer` object
- An `insGPS` object
- An object inheriting from the `positioning.insSensorModel` interface class

**`value` — Value for filter or sensor state part covariance matrix**
scalar | *N*-element real-valued vector | *N*-by-*N* real-valued matrix

Value for filter or sensor state part covariance matrix, specified as one of these options:

- Real scalar — The diagonal elements of the resulting state part covariance matrix are all equal to the scalar.

- *N*-element real-valued vector — The diagonal of the resulting state part covariance matrix is equal to the vector, where *N* is the dimension of the state corresponding to the `stateName` argument.
- *N*-by-*N* real-valued matrix — The resulting state part covariance matrix is equal to the matrix, where *N* is the dimension of the state corresponding to the `stateName` argument.

Data Types: `single` | `double`

## Output Arguments

**`covparts` — Covariance matrix corresponding to state name**
*N*-by-*N* real-valued matrix

Covariance matrix corresponding to the state name, returned as an *N*-by-*N* real-valued matrix.

# Version History

**Introduced in R2022a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

`predict` | `fuse` | `residual` | `correct` | `stateparts` | `stateinfo` | `estimateStates` | `tune` | `createTunerCostTemplate` | `tunerCostFcnParam`

# stateinfo

State vector information for `insEKF`

## Syntax

```
info = stateinfo(filter)
indices = stateinfo(filter,stateName)
indices = stateinfo(filter,sensor,stateName)
```

## Description

`info = stateinfo(filter)` returns a structure whose fields contain descriptions of the elements of the state vector in the filter.

`indices = stateinfo(filter,stateName)` returns the indices of the components of the filter state vector corresponding to the specified state name.

`indices = stateinfo(filter,sensor,stateName)` returns the indices of the components of the sensor state vector corresponding to the specified state name.

## Examples

### Obtain State Information of insEKF

Create an `insGyroscope` object and use it to construct an `insEKF` object.

```
sensor = insGyroscope;
filt = insEKF(sensor);
```

Show the information for all the state components.

```
stateinfo(filt)
```

```
ans = struct with fields:
        Orientation: [1 2 3 4]
    AngularVelocity: [5 6 7]
     Gyroscope_Bias: [8 9 10]
```

Obtain the indices for the `orientation` state.

```
stateinfo(filt,"Orientation")
```

```
ans = 1×4

     1     2     3     4
```

Obtain the indices for the sensor bias by using the sensor object input.

```
stateinfo(filt,sensor,"Bias")
```

```
ans = 1×3

     8     9    10
```

Obtain the indices for the sensor bias directly from the filter.

```
stateinfo(filt,"Gyroscope_Bias")
```

```
ans = 1×3

     8     9    10
```

## Input Arguments

### `filter` — INS filter
`insEKF` object

INS filter, specified as an `insEKF` object.

### `stateName` — Name of part of state
string scalar | character vector

Name of a part of the state for the filter or the sensor, specified as a string scalar or character vector.

Use the `stateinfo` object function to find the names of state parts in the filter.

Example: `"AngularVelocity"`

Example: `"Bias"`

Data Types: `char` | `string`

### `sensor` — Inertial sensor
`insAccelerometer` object | `insGyroscope` object | `insMagnetometer` object | `insGPS` object | object inheriting from `positioning.insSensorModel` interface class

Inertial sensor, specified one of these objects used to construct the `insEKF` filter object:

- An `insAccelerometer` object
- An `insGyroscope` object
- An `insMagnetometer`
- An `insGPS` object
- An object inheriting from the `positioning.insSensorModel` interface class

## Output Arguments

### `info` — State information
structure

State information, returned as a structure. The field names of the structure are names of the elements of the state vector in the filter. The values of each field are the corresponding indices of the state vector.

**`indices` — State indices**
*M*-element vector of state indices

State indices, returned as an *M*-element vector of state indices, where *M* is the dimension of the state part corresponding to the `stateName`. For example, if the state name corresponds to the first, second, and third elements in the state vector of the filter, then the function returns `indices` as `[1 2 3]`.

# Version History

**Introduced in R2022a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`predict` | `fuse` | `residual` | `correct` | `stateparts` | `statecovparts` | `estimateStates` | `tune` | `createTunerCostTemplate` | `tunerCostFcnParam`

# estimateStates

Batch fusion and smoothing of sensor data

## Syntax

```
estimates = estimateStates(filter,sensorData,measurementNoise)
[estimates,smoothEstimates] = estimateStates( ___ )
```

## Description

`estimates = estimateStates(filter,sensorData,measurementNoise)` returns the state estimates based on the motion model used in the filter, the sensor data, and the measurement noise. The function predicts the filter state estimates forward in time based on the row times in `sensorData` and fuses data from each column of the table one by one.

`[estimates,smoothEstimates] = estimateStates( ___ )` additionally returns the smoothed state estimates by using the Rach-Tung-Striebel (RTS) nonlinear Kalman smoother. For algorithm details, see "Algorithms" on page 2-1896 and [1].

---

**Tip** Smoothing usually requires considerably more memory and computation time. Use this syntax only when you need the smoothed estimated states.

---

## Examples

### Batch Fusion and State Smoothing Using insEKF

Load measurement data from an accelerometer and a gyroscope.

```
load("accelGyroINSEKFData.mat");
```

Create an `insEKF` filter object. Specify the orientation part of the state in the filter using the initial orientation from the measurement data. Specify the diagonal elements of the state estimate error covariance matrix corresponding to the orientation state as `0.01`.

```
filt = insEKF;
stateparts(filt,"Orientation",compact(ld.initOrient));
statecovparts(filt,"Orientation",1e-2);
```

Specify the measurement noise and the additive process noise. You can obtain these values by using the `tune` object function of the filter object.

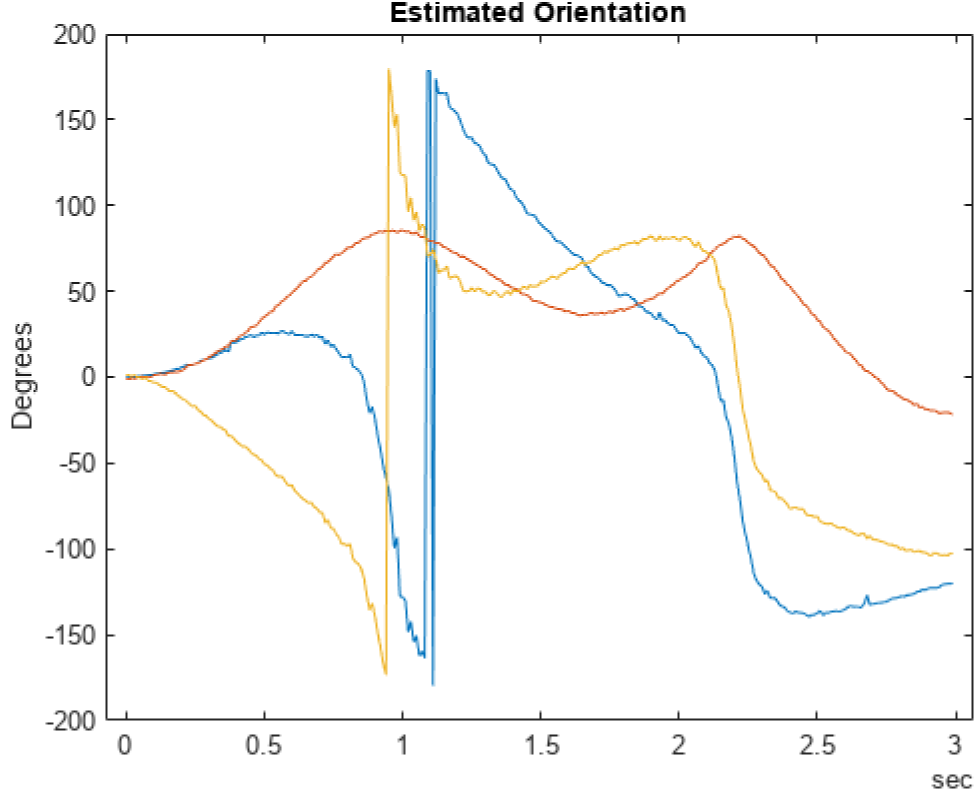
```
measureNoise = struct("AccelerometerNoise", 0.1739, ...
    "GyroscopeNoise", 1.1129);
processNoise = diag([ ...
    2.8586 1.3718 0.8956 3.2148 4.3574 2.5411 3.2148 0.5465 0.2811 ...
    1.7149 0.1739 0.7752 0.1739]);
filt.AdditiveProcessNoise = processNoise;
```

Batch-estimate the states using the `estimateStates` object function. Also, obtain the estimates after smoothing.

```
[estimates,smoothEstimates] = estimateStates(filt,ld.sensorData,measureNoise);
```

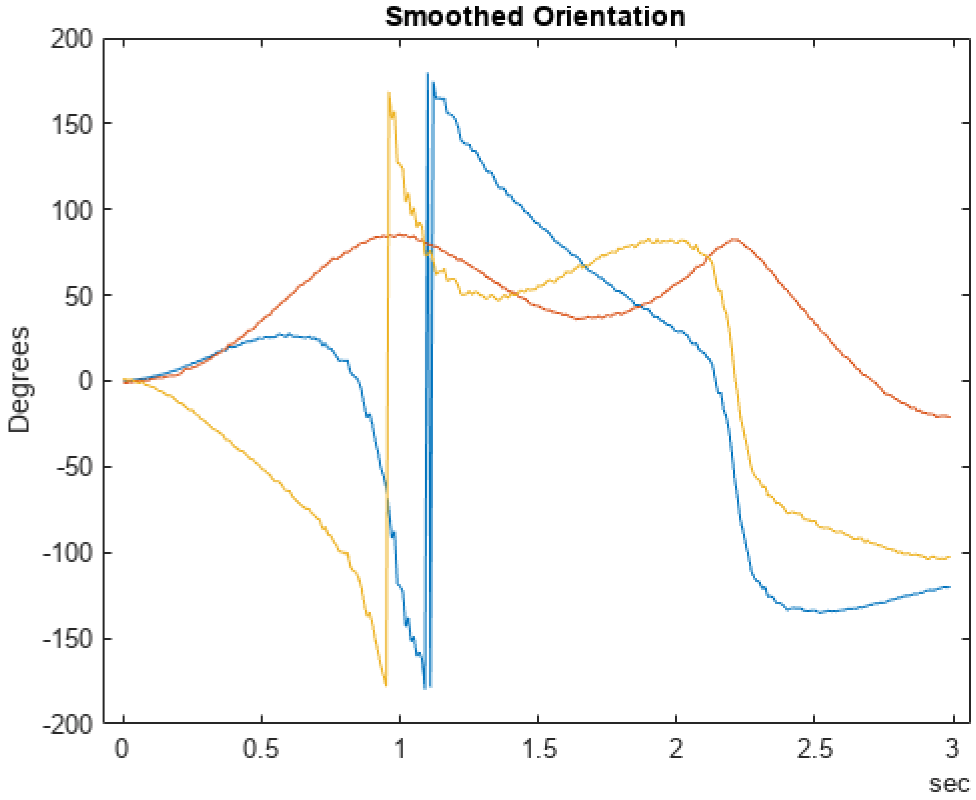
Visualize the estimated orientation in Euler angles.

```
figure
t = estimates.Properties.RowTimes;
plot(t,eulerd(estimates.Orientation,"ZYX","frame"));
title("Estimated Orientation");
ylabel("Degrees")
```



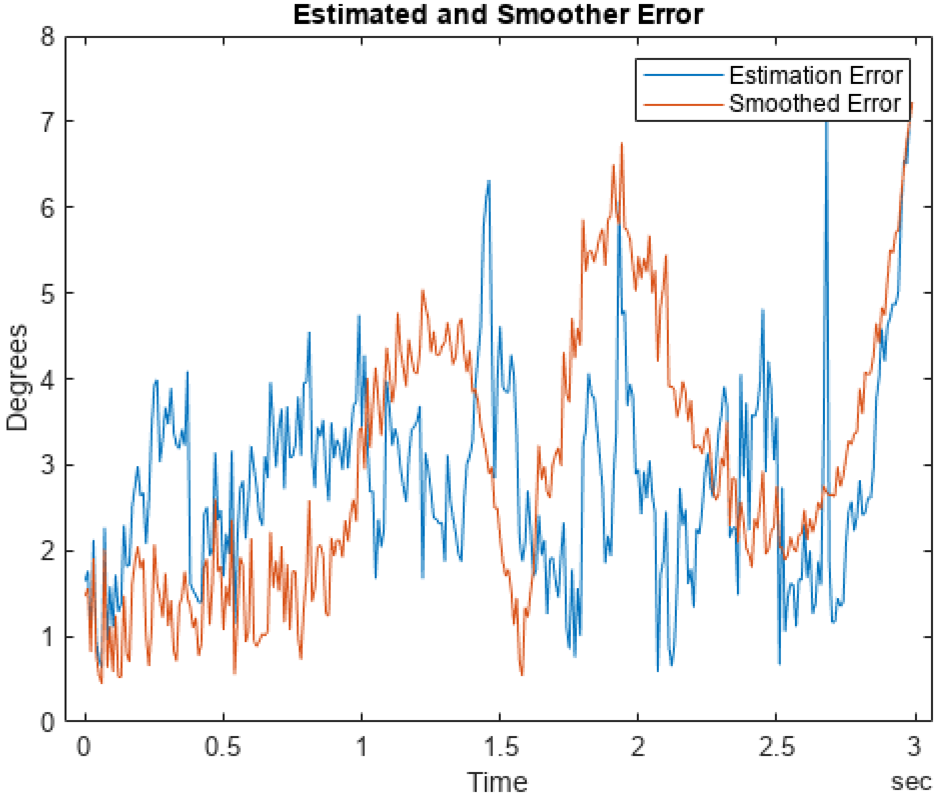

Visualize the estimated orientation after smoothing in Euler angles.

```
figure
plot(t,eulerd(smoothEstimates.Orientation,"ZYX","frame"));
title("Smoothed Orientation");
ylabel("Degrees")
```




Visualize the estimate error, in quaternion distance, using the `dist` object function of the `quaternion` object.

```
trueOrient = ld.groundTruth.Orientation;
plot(t,rad2deg(dist(estimates.Orientation, trueOrient)), ...
     t,rad2deg(dist(smoothEstimates.Orientation, trueOrient)));
title("Estimated and Smoother Error");
legend("Estimation Error","Smoothed Error")
xlabel("Time");
ylabel("Degrees")
```




## Input Arguments

**`filter` — INS filter**
`insEKF` object

INS filter, specified as an `insEKF` object.

**`sensorData` — Sensor data**
`timetable`

Sensor data, specified as a `timetable`. Each variable name (as a column) in the timetable must match one of the sensor names specified in the `SensorNames` property of the `filter`. Each entry in the table is the measurement from the sensor at the corresponding row time.

If a sensor does not produce measurements at a row time, specify the corresponding entry as `NaN`.

**`measurementNoise` — Measurement noise**
structure

Measurement noise of the sensors, specified as a structure. Each field name must match one of the sensor names specified in the `SensorNames` property of the `filter`. The field value is the corresponding measurement noise covariance matrix. If you specify a field value as a scalar, the function extends the scalar to the diagonal of the matrix.

Data Types: `struct`

## Output Arguments

**`estimates` — State estimates**
`timetable`

State estimates, returned as a `timetable`. The name of each variable in the table represents a state. You can obtain the variable names by using the `stateinfo` object function of the filter. The last column in the table is the state estimate error covariance matrix for the complete state vector of the filter at each of the row times.

**`smoothEstimates` — Smoothed state estimates**
`timetable`

Smoothed state estimates, returned as a `timetable`. The name of each variable in the table represents a state. You can obtain the variable names by using the `stateinfo` object function of the filter. The last column in the table is the state estimate error covariance matrix for the complete state vector of the filter at each of the row times.

## Algorithms

### RTS Smoother

Consider a continuous discrete nonlinear model as follows.

$$\frac{d}{dt}x(t) = f(x(t), t) + w(t), \quad w(t) \sim N(0, Q(t))$$
$$y_k = h(x_k) + v_k, \quad v_k \sim N(0, R_k)$$

In the equation, $t$ represents the continuous system time, $x$ is the system state, $f$ is the state equation, and $w$ is process noise that follows a normal distribution of mean 0 and covariance $Q$. $k$ is the discrete time step, $y$ is the measurement, $h$ is the measurement function, $v$ is measurement noise that follows a normal distribution of mean 0 and covariance $R$.

Consider a time period $[0, T]$, where $T$ is the total time considered for smoothing. The smoother first performs forward filtering for $t \in [0, T]$ by using a regular continuous discrete extended Kalman filter. Eventually, the smoother obtains the forward state estimate $x_f(T)$ and forward covariance estimate $P_f(T)$ at the final time. The smoother also saves the state estimates and covariances at intermediate steps when the smoother corrects the estimated state with measurements.

Next, the smoother obtains the smoothed state by using a backward filter. For convenience, define a variable $\tau = T - t$ representing the backward time. The backward filter obtains the smoothed state $x_s$ and covariance $P_s$ at each measurement time by using backward integration with these equations.

$$K_f(t) = QP_f^{-1}(t)$$
$$\frac{d}{d\tau}P_s(t) = -\left[F\left(x_f(t), t\right) + K_f(t)\right]P_f(t) - P_f(t)\left[F\left(x_f(t), t\right) + K_f(t)\right]^T + Q(t), \quad P_s(T) = P_f(T)$$
$$\frac{d}{d\tau}x_s(t) = -\left[F\left(x_f(t), t\right) + K_f(t)\right]\left[x_s(t) - x_f(t)\right] - f(x_f(t), t), \quad x_s(T) = x_f(T)$$

In these equations, $K_f(t)$ is the Kalman gain and $F = \partial f(x,t)/\partial x$ is the Jacobian matrix of the state model.

## Version History

**Introduced in R2022a**

### R2023a: Smooth state estimates using insEKF

You can now obtain smoothed state estimates as the second output from the `estimateStates` function. The function uses the Rauch-Tung-Striebel (RTS) smoothing algorithm to obtain the smoothed state estimates.

## References

[1] Crassidis, John L., and John L. Junkins. "Optimal Estimation of Dynamic Systems". 2nd ed, CRC Press, pp. 349- 352, 2012.

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`predict` | `fuse` | `residual` | `correct` | `stateparts` | `statecovparts` | `stateinfo` | `tune` | `createTunerCostTemplate` | `tunerCostFcnParam`

# tune

Tune insEKF parameters to reduce estimation error

## Syntax

```
tunedMeasureNoise = tune(filter,measureNoise,sensorData,groundTruth)
tunedMeasureNoise = tune( ___ ,config)
```

## Description

`tunedMeasureNoise = tune(filter,measureNoise,sensorData,groundTruth)` tunes the `AdditiveProcessNoise` property of the `insEKF` filter object `filter`, and the measurement noise, to reduce the root-mean-squared (RMS) state estimation error between the fused sensor data and the ground truth. The function also returns the tuned measurement noise `tunedMeasureNoise`. The function uses the property values in the filter and the measurement noise provided in the `measureNoise` structure as the initial estimate for the optimization algorithm.

`tunedMeasureNoise = tune( ___ ,config)` specifies the tuning configuration using a `tunerconfig` object `config`, in addition to all input arguments from the previous syntax.

## Examples

### Tune insEKF to Optimize Orientation Estimation

Load the recorded sensor data and ground truth data.

```
load("accelGyroINSEKFData.mat");
```

Create an `insEKF` filter object. Specify the orientation part of the state in the filter using the initial orientation from the measurement data. Specify the diagonal elements of the state estimate error covariance matrix corresponding to the orientation state as `0.01`.

```
filt = insEKF;
stateparts(filt,"Orientation",compact(ld.initOrient));
statecovparts(filt,"Orientation",1e-2);
```

Obtain a representative measurement noise structure and use it to estimate states before tuning.

```
mnoise = tunernoise(filt);
untunedEst = estimateStates(filt,ld.sensorData,mnoise);
```

Reinitialize the filter, set up a `tunerconfig` object, and tune the filter.

```
stateparts(filt,"Orientation",compact(ld.initOrient));
statecovparts(filt,"Orientation",1e-2);
cfg = tunerconfig(filt,MaxIterations=10,ObjectiveLimit=1e-4);
tunedmn = tune(filt,mnoise,ld.sensorData,ld.groundTruth,cfg);
```

```
    Iteration     Parameter                         Metric
    _________     _________                         ______
```

```
1             AdditiveProcessNoise(1)      0.3787
1             AdditiveProcessNoise(15)     0.3761
1             AdditiveProcessNoise(29)     0.3695
1             AdditiveProcessNoise(43)     0.3655
1             AdditiveProcessNoise(57)     0.3533
1             AdditiveProcessNoise(71)     0.3446
1             AdditiveProcessNoise(85)     0.3431
1             AdditiveProcessNoise(99)     0.3428
1             AdditiveProcessNoise(113)    0.3427
1             AdditiveProcessNoise(127)    0.3426
1             AdditiveProcessNoise(141)    0.3298
1             AdditiveProcessNoise(155)    0.3206
1             AdditiveProcessNoise(169)    0.3200
1             AccelerometerNoise           0.3199
1             GyroscopeNoise               0.3198
2             AdditiveProcessNoise(1)      0.3126
2             AdditiveProcessNoise(15)     0.3098
2             AdditiveProcessNoise(29)     0.3018
2             AdditiveProcessNoise(43)     0.2988
2             AdditiveProcessNoise(57)     0.2851
2             AdditiveProcessNoise(71)     0.2784
2             AdditiveProcessNoise(85)     0.2760
2             AdditiveProcessNoise(99)     0.2744
2             AdditiveProcessNoise(113)    0.2744
2             AdditiveProcessNoise(127)    0.2743
2             AdditiveProcessNoise(141)    0.2602
2             AdditiveProcessNoise(155)    0.2537
2             AdditiveProcessNoise(169)    0.2527
2             AccelerometerNoise           0.2524
2             GyroscopeNoise               0.2524
3             AdditiveProcessNoise(1)      0.2476
3             AdditiveProcessNoise(15)     0.2432
3             AdditiveProcessNoise(29)     0.2397
3             AdditiveProcessNoise(43)     0.2381
3             AdditiveProcessNoise(57)     0.2255
3             AdditiveProcessNoise(71)     0.2226
3             AdditiveProcessNoise(85)     0.2221
3             AdditiveProcessNoise(99)     0.2202
3             AdditiveProcessNoise(113)    0.2201
3             AdditiveProcessNoise(127)    0.2201
3             AdditiveProcessNoise(141)    0.2090
3             AdditiveProcessNoise(155)    0.2070
3             AdditiveProcessNoise(169)    0.2058
3             AccelerometerNoise           0.2052
3             GyroscopeNoise               0.2052
4             AdditiveProcessNoise(1)      0.2051
4             AdditiveProcessNoise(15)     0.2027
4             AdditiveProcessNoise(29)     0.2019
4             AdditiveProcessNoise(43)     0.2000
4             AdditiveProcessNoise(57)     0.1909
4             AdditiveProcessNoise(71)     0.1897
4             AdditiveProcessNoise(85)     0.1882
4             AdditiveProcessNoise(99)     0.1871
4             AdditiveProcessNoise(113)    0.1870
4             AdditiveProcessNoise(127)    0.1870
4             AdditiveProcessNoise(141)    0.1791
4             AdditiveProcessNoise(155)    0.1783
4             AdditiveProcessNoise(169)    0.1751
```

```
4            AccelerometerNoise          0.1748
4            GyroscopeNoise              0.1747
5            AdditiveProcessNoise(1)     0.1742
5            AdditiveProcessNoise(15)    0.1732
5            AdditiveProcessNoise(29)    0.1712
5            AdditiveProcessNoise(43)    0.1712
5            AdditiveProcessNoise(57)    0.1626
5            AdditiveProcessNoise(71)    0.1615
5            AdditiveProcessNoise(85)    0.1598
5            AdditiveProcessNoise(99)    0.1590
5            AdditiveProcessNoise(113)   0.1589
5            AdditiveProcessNoise(127)   0.1589
5            AdditiveProcessNoise(141)   0.1517
5            AdditiveProcessNoise(155)   0.1508
5            AdditiveProcessNoise(169)   0.1476
5            AccelerometerNoise          0.1473
5            GyroscopeNoise              0.1470
6            AdditiveProcessNoise(1)     0.1470
6            AdditiveProcessNoise(15)    0.1470
6            AdditiveProcessNoise(29)    0.1463
6            AdditiveProcessNoise(43)    0.1462
6            AdditiveProcessNoise(57)    0.1367
6            AdditiveProcessNoise(71)    0.1360
6            AdditiveProcessNoise(85)    0.1360
6            AdditiveProcessNoise(99)    0.1350
6            AdditiveProcessNoise(113)   0.1350
6            AdditiveProcessNoise(127)   0.1350
6            AdditiveProcessNoise(141)   0.1289
6            AdditiveProcessNoise(155)   0.1288
6            AdditiveProcessNoise(169)   0.1262
6            AccelerometerNoise          0.1253
6            GyroscopeNoise              0.1246
7            AdditiveProcessNoise(1)     0.1246
7            AdditiveProcessNoise(15)    0.1244
7            AdditiveProcessNoise(29)    0.1205
7            AdditiveProcessNoise(43)    0.1203
7            AdditiveProcessNoise(57)    0.1125
7            AdditiveProcessNoise(71)    0.1122
7            AdditiveProcessNoise(85)    0.1117
7            AdditiveProcessNoise(99)    0.1106
7            AdditiveProcessNoise(113)   0.1104
7            AdditiveProcessNoise(127)   0.1104
7            AdditiveProcessNoise(141)   0.1058
7            AdditiveProcessNoise(155)   0.1052
7            AdditiveProcessNoise(169)   0.1035
7            AccelerometerNoise          0.1024
7            GyroscopeNoise              0.1014
8            AdditiveProcessNoise(1)     0.1014
8            AdditiveProcessNoise(15)    0.1012
8            AdditiveProcessNoise(29)    0.1012
8            AdditiveProcessNoise(43)    0.1005
8            AdditiveProcessNoise(57)    0.0948
8            AdditiveProcessNoise(71)    0.0948
8            AdditiveProcessNoise(85)    0.0938
8            AdditiveProcessNoise(99)    0.0934
8            AdditiveProcessNoise(113)   0.0931
8            AdditiveProcessNoise(127)   0.0931
8            AdditiveProcessNoise(141)   0.0896
```

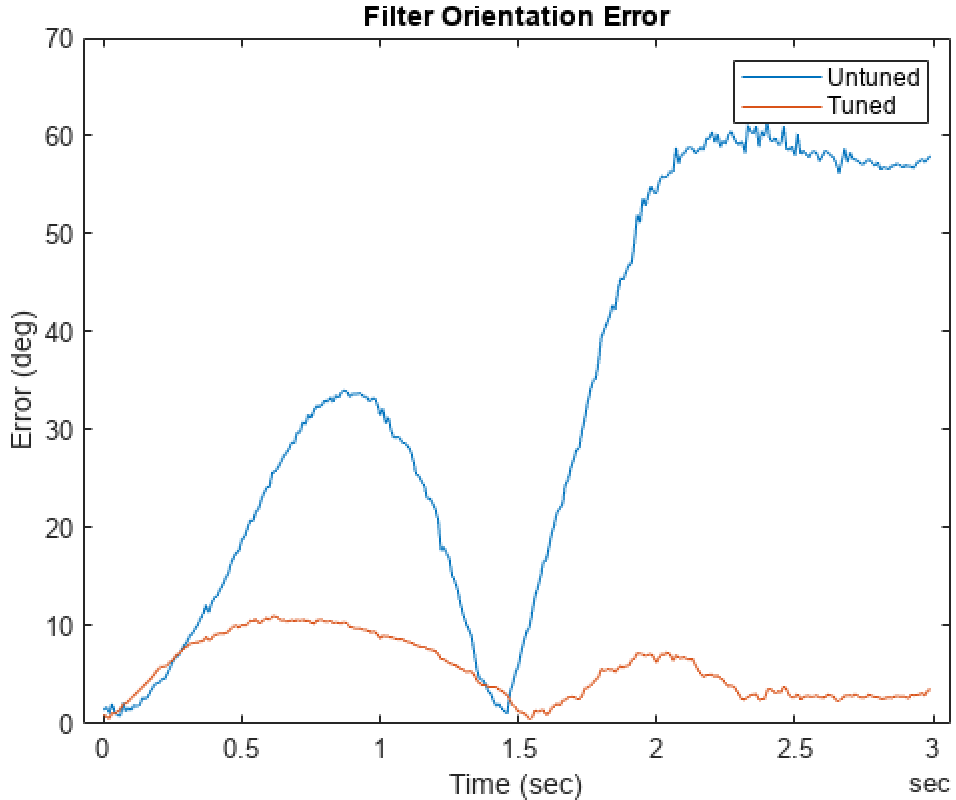
```
    8            AdditiveProcessNoise(155)    0.0889
    8            AdditiveProcessNoise(169)    0.0867
    8            AccelerometerNoise           0.0859
    8            GyroscopeNoise               0.0851
    9            AdditiveProcessNoise(1)      0.0851
    9            AdditiveProcessNoise(15)     0.0850
    9            AdditiveProcessNoise(29)     0.0824
    9            AdditiveProcessNoise(43)     0.0819
    9            AdditiveProcessNoise(57)     0.0771
    9            AdditiveProcessNoise(71)     0.0771
    9            AdditiveProcessNoise(85)     0.0762
    9            AdditiveProcessNoise(99)     0.0759
    9            AdditiveProcessNoise(113)    0.0754
    9            AdditiveProcessNoise(127)    0.0754
    9            AdditiveProcessNoise(141)    0.0734
    9            AdditiveProcessNoise(155)    0.0724
    9            AdditiveProcessNoise(169)    0.0702
    9            AccelerometerNoise           0.0697
    9            GyroscopeNoise               0.0689
    10           AdditiveProcessNoise(1)      0.0689
    10           AdditiveProcessNoise(15)     0.0686
    10           AdditiveProcessNoise(29)     0.0658
    10           AdditiveProcessNoise(43)     0.0655
    10           AdditiveProcessNoise(57)     0.0622
    10           AdditiveProcessNoise(71)     0.0620
    10           AdditiveProcessNoise(85)     0.0616
    10           AdditiveProcessNoise(99)     0.0615
    10           AdditiveProcessNoise(113)    0.0607
    10           AdditiveProcessNoise(127)    0.0606
    10           AdditiveProcessNoise(141)    0.0590
    10           AdditiveProcessNoise(155)    0.0578
    10           AdditiveProcessNoise(169)    0.0565
    10           AccelerometerNoise           0.0562
    10           GyroscopeNoise               0.0557
```

Estimate states again, this time using the tuned filter.

```
tunedEst = estimateStates(filt,ld.sensorData,tunedmn);
```

Compare the tuned and untuned estimates against the ground truth data.

```
times = ld.groundTruth.Properties.RowTimes;
duntuned = rad2deg(dist(untunedEst.Orientation,ld.groundTruth.Orientation));
dtuned = rad2deg(dist(tunedEst.Orientation,ld.groundTruth.Orientation));
plot(times,duntuned,times,dtuned);
xlabel("Time (sec)")
ylabel("Error (deg)")
legend("Untuned","Tuned")
title("Filter Orientation Error")
```




Print the root-mean-squared (RMS) error of both the untuned and the tuned filters.

```
untunedRMSError = sqrt(mean(duntuned.^2));
tunedRMSError = sqrt(mean(dtuned.^2));
fprintf("Untuned RMS error: %.2f degrees\n", ...
    untunedRMSError);
```

```
Untuned RMS error: 39.47 degrees
```

```
fprintf("Tuned RMS error: %.2f degrees\n", ...
    tunedRMSError);
```

```
Tuned RMS error: 6.39 degrees
```

## Input Arguments

### `filter` — INS filter

`insEKF` object

INS filter, specified as an `insEKF` object.

### `measureNoise` — Measurement noise

structure

Measurement noise, specified as a structure. The function uses the measurement noise input as the initial guess for tuning the measurement noise. The structure should contain the measurement noise

for sensor models specified in the `Sensors` property of the INS filter. For example, if the `insEKF` filter object only contains an `insAccelerometer` object and an `insGyroscope` object, you should specify the structure like this:

| Field name | Description |
|---|---|
| `AccelerometerNoise` | Variance of accelerometer noise, specified as a scalar in ($m^2/s$). |
| `GyroscopeNoise` | Variance of gyroscope noise, specified as a scalar in $(rad/s)^2$. |

**Tip** Use the `tunernoise` function to obtain a representative structure for the `measureNoise` structure. For example:

```
filter = insEKF;
mNoise = tunerNoise(filter)
```

**sensorData — Sensor data**
timetable

Sensor data, specified as a `timetable`. Each variable name (as a column) in the time table must match one of the sensor names specified in the `SensorNames` property of the `filter`. Each entry in the table is the measurement from the sensor at the corresponding row time.

If a sensor does not produce measurements at the row time, specify the corresponding entry as `NaN`.

If you set the `Cost` property of the tuner configuration input, `config`, to `Custom`, then you can use other data types for the `sensorData` input based on your choice.

**groundTruth — Ground truth data**
timetable

Ground truth data, specified as a `timetable`. In each row, the table contains the truth data for the row time. Each variable name (as a column) in the table must be one of the filter state names that you can obtain using the `stateinfo` object function.

The function processes each row of the `sensorData` and `groundTruth` tables sequentially to calculate the state estimate and RMS error from the ground truth. State variables not present in `groundTruth` input are ignored for the comparison. The `sensorData` and the `groundTruth` tables must have the same row times.

If you set the `Cost` property of the tuner configuration input, `config`, to `Custom`, then you can use other data types for the `groundTruth` input based on your choice.

**config — Tuner configuration**
`tunerconfig` object

Tuner configuration, specified as a `tunerconfig` object.

## Output Arguments

**`tunedMeasureNoise` — Tuned measurement noise**
structure

Tuned measurement noise, returned as a structure. The structure contains the same fields as the structure specified in the `measureNoise` input.

# Version History

**Introduced in R2022a**

## References

[1] Abbeel, P., Coates, A., Montemerlo, M., Ng, A.Y. and Thrun, S. Discriminative Training of Kalman Filters. In *Robotics: Science and systems*, Vol. 2, pp. 1, 2005.

## See Also

`tunerconfig` | `tunernoise` | `predict` | `fuse` | `residual` | `correct` | `stateparts` | `statecovparts` | `stateinfo` | `estimateStates` | `createTunerCostTemplate` | `tunerCostFcnParam`

# createTunerCostTemplate

Create template of tuner cost function

## Syntax

```
createTunerCostTemplate(filter)
```

## Description

`createTunerCostTemplate(filter)` creates a template of a tuner cost function and shows it in an editor window. The created cost function computes the cost as the root-mean-squared (RMS) error between the estimated states and the ground truth. You can modify the cost function as desired.

When you tune the filter parameters of the `insEKF` object using its `tune` object function, use the function created by `createTunerCostTemplate` to specify the cost in the `tunerconfig` object as an input to the `tune` object function.

## Examples

### Tune `insEKF` with Custom Cost Function

Create an `insEKF` filter object and create a cost function using the `createTunerCostTemplate` object function.

```
filter = insEKF;
createTunerCostTemplate(filter);
```

Save the created function in an m-file.

```
doc = matlab.desktop.editor.getActive;
doc.saveAs(fullfile(pwd,"tunercost.m"));
```

Load prerecorded sensor data and ground truth data.

```
load("accelGyroINSEKFData.mat");
```

Specify an initial orientation state and its covariance.

```
stateparts(filter,"Orientation",compact(ld.initOrient));
statecovparts(filter,"Orientation",1e-2);
```

Create a measurement noise structure using the `tunernoise` function.

```
mnoise = tunernoise(filter);
```

Create a `tunerconfig` object using the created cost function.

```
cfg = tunerconfig(filter,MaxIterations=1, ...
    ObjectiveLimit=1e-4, ...
    Cost="custom", ...
    CustomCostFcn=@tunercost);
```

Tune the filter. Show the tuned measurement noise and process noise in the filter.

```
tunedmn = tune(filter,mnoise,ld.sensorData, ...
    ld.groundTruth,cfg)

    Iteration    Parameter                    Metric
    _________    _________                    ______
    1            AdditiveProcessNoise(1)      0.3413
    1            AdditiveProcessNoise(15)     0.3381
    1            AdditiveProcessNoise(29)     0.3353
    1            AdditiveProcessNoise(43)     0.3334
    1            AdditiveProcessNoise(57)     0.3214
    1            AdditiveProcessNoise(71)     0.3121
    1            AdditiveProcessNoise(85)     0.3110
    1            AdditiveProcessNoise(99)     0.3107
    1            AdditiveProcessNoise(113)    0.3106
    1            AdditiveProcessNoise(127)    0.3105
    1            AdditiveProcessNoise(141)    0.2972
    1            AdditiveProcessNoise(155)    0.2872
    1            AdditiveProcessNoise(169)    0.2855
    1            AccelerometerNoise           0.2852
    1            GyroscopeNoise               0.2851

tunedmn = struct with fields:
    AccelerometerNoise: 0.9000
        GyroscopeNoise: 0.9000
```

```
orientationNoise = statecovparts(filter,"Orientation")

orientationNoise = 4×4

    0.0100         0         0         0
         0    0.0100         0         0
         0         0    0.0100         0
         0         0         0    0.0100
```

## Input Arguments

### filter — INS filter

insEKF object

INS filter, specified as an insEKF object.

# Version History

**Introduced in R2022a**

## See Also

predict | fuse | residual | correct | stateparts | statecovparts | stateinfo | estimateStates | tune | tunerCostFcnParam

# tunerCostFcnParam

First parameter example for tuning cost function

## Syntax

```
tunerCostFcnParam(filter)
```

## Description

`tunerCostFcnParam(filter)` creates a structure that has the fields required for tuning an `insEKF` filter with a custom cost function. The structure is useful when generating C code for a cost function using MATLAB Coder™.

## Examples

### Tune insEKF with MEX-Accelerated Custom Cost Function

Create an `insEKF` filter object. Then create a cost function using the `createTunerCostTemplate` object function.

```
filter = insEKF;
createTunerCostTemplate(filter);
doc = matlab.desktop.editor.getActive;
doc.saveAs(fullfile(pwd,"tunercost.m"));
```

Load prerecorded sensor data and ground truth data.

```
load("accelGyroINSEKFData.mat");
```

Create a MEX cost function using MATLAB Coder.

```
p = tunerCostFcnParam(filter);
disp("Generating MEX-accelerated cost function");
```

```
Generating MEX-accelerated cost function
```

```
codegen tunercost.m -args {p,ld.sensorData,ld.groundTruth};
```

```
Code generation successful.
```

Specify an initial orientation state and its covariance.

```
stateparts(filter,"Orientation",compact(ld.initOrient));
statecovparts(filter,"Orientation",1e-2);
```

Create a measurement noise structure using the `tunernoise` function.

```
mnoise = tunernoise(filter);
```

Create a `tunerconfig` object using the created MEX cost function.

```
cfg = tunerconfig(filter, MaxIterations=1, ...
    ObjectiveLimit=1e-4, ...
```

```
    Cost="custom", ...
    CustomCostFcn=@tunercost_mex);
```

Tune the filter. Show the tuned measurement noise and process noise in the filter.

```
tunedmn = tune(filter,mnoise,ld.sensorData, ...
    ld.groundTruth,cfg)
```

```
    Iteration    Parameter                   Metric
    _________    _________                   ______
    1            AdditiveProcessNoise(1)     0.3413
    1            AdditiveProcessNoise(15)    0.3381
    1            AdditiveProcessNoise(29)    0.3353
    1            AdditiveProcessNoise(43)    0.3334
    1            AdditiveProcessNoise(57)    0.3214
    1            AdditiveProcessNoise(71)    0.3121
    1            AdditiveProcessNoise(85)    0.3110
    1            AdditiveProcessNoise(99)    0.3107
    1            AdditiveProcessNoise(113)   0.3106
    1            AdditiveProcessNoise(127)   0.3105
    1            AdditiveProcessNoise(141)   0.2972
    1            AdditiveProcessNoise(155)   0.2872
    1            AdditiveProcessNoise(169)   0.2855
    1            AccelerometerNoise          0.2852
    1            GyroscopeNoise              0.2851
```

```
tunedmn = struct with fields:
    AccelerometerNoise: 0.9000
        GyroscopeNoise: 0.9000
```

```
orientationNoise = statecovparts(filter,"Orientation")
```

```
orientationNoise = 4×4

    0.0100         0         0         0
         0    0.0100         0         0
         0         0    0.0100         0
         0         0         0    0.0100
```

## Input Arguments

**filter — INS filter**
insEKF object

INS filter, specified as an `insEKF` object.

# Version History

**Introduced in R2022a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

`predict` | `fuse` | `residual` | `correct` | `stateparts` | `statecovparts` | `stateinfo` | `estimateStates` | `tune` | `createTunerCostTemplate`

# copy

Create copy of insEKF

## Syntax

```
newFilter = copy(filter)
```

## Description

newFilter = copy(filter) returns a copy of the insEKF object filter. The new filter object has the exactly the same property values.

## Examples

### Create Copy of insEKF

Create a default insEKF object.

```
filter = insEKF
```

```
filter = 
  insEKF with properties:

                    State: [13x1 double]
          StateCovariance: [13x13 double]
    AdditiveProcessNoise: [13x13 double]
              MotionModel: [1x1 insMotionOrientation]
                  Sensors: {[1x1 insAccelerometer]  [1x1 insGyroscope]}
              SensorNames: {'Accelerometer'  'Gyroscope'}
           ReferenceFrame: 'NED'
```

Create a copy of the insEKF object.

```
newFilter = copy(insEKF)
```

```
newFilter = 
  insEKF with properties:

                    State: [13x1 double]
          StateCovariance: [13x13 double]
    AdditiveProcessNoise: [13x13 double]
              MotionModel: [1x1 insMotionOrientation]
                  Sensors: {[1x1 insAccelerometer]  [1x1 insGyroscope]}
              SensorNames: {'Accelerometer'  'Gyroscope'}
           ReferenceFrame: 'NED'
```

### Input Arguments

**`filter` — INS filter**
`insEKF` object

INS filter, specified as an `insEKF` object.

### Output Arguments

**`newFilter` — Filter copy**
`insEKF` object

Filter copy, returned as an `insEKF` object.

## Version History

**Introduced in R2022b**

### See Also

`insEKF`

# reset

Reset states for insEKF

## Syntax

```
reset(filter)
```

## Description

`reset(filter)` resets the `State` and `StateCovariance` properties of the `insEKF` object `filter` to their default values.

## Examples

### Reset insEKF Filter object

Create an `insEKF` filter object.

```
filter = insEKF
```

```
filter = 
  insEKF with properties:

                    State: [13x1 double]
          StateCovariance: [13x13 double]
    AdditiveProcessNoise: [13x13 double]
              MotionModel: [1x1 insMotionOrientation]
                  Sensors: {[1x1 insAccelerometer]  [1x1 insGyroscope]}
              SensorNames: {'Accelerometer'  'Gyroscope'}
           ReferenceFrame: 'NED'
```

Show the default angular velocity state using the `stateparts` object function.

```
stateparts(filter,"AngularVelocity")
```

```
ans = 1×3

     0     0     0
```

Specify the angular velocity state as [0.1 0.1 0.1] rad/s using the `stateparts` object function.

```
stateparts(filter,"AngularVelocity",[0.1 0.1 0.1])
stateparts(filter,"AngularVelocity")
```

```
ans = 1×3

    0.1000    0.1000    0.1000
```

Reset the filter and show the angular velocity state.

```
reset(filter)
stateparts(filter,"AngularVelocity")
```

```
ans = 1×3

     0     0     0
```

## Input Arguments

**`filter` — INS filter**
`insEKF` object

INS filter, specified as an `insEKF` object.

# Version History

**Introduced in R2022b**

## See Also

`insEKF`

# insOptions

Options for configuration of insEKF object

## Description

The insOptions object specifies properties for an insEKF object.

## Creation

### Syntax

```
options = insOptions
options = insOptions(Name=Value)
```

#### Description

options = insOptions returns an insOptions object with default property values.

options = insOptions(Name=Value) specifies properties using one or more name-value arguments. For example, options = insOptions(ReferenceFrame="ENU") sets the reference frame used in the insEKF object as the east-north-up (ENU) frame. Unspecified properties have default values.

### Properties

**Datatype — Data type of insEKF variables**
"double" (default) | "single"

Data type of insEKF variables, specified as "single" or "double". This data type applies to variables such as state, state covariance, and other internal variables.

Data Types: char | string

**SensorNamesSource — Source for names of sensors fused**
"default" (default) | "property"

Source for the names of the sensors fused in the insEKF object, specified as "default" or "property".

- "default" — The insEKF object names the fused sensors using the default convention. See the SensorNames property of the insEKF object for details on the default names.
- "property" — Specify the names of sensors fused in the insEKF object using the SensorNames property of the insOptions object.

Data Types: char | string

**ReferenceFrame — Reference frame of insEKF object**
"NED" (default) | "ENU"

Reference frame of the insEKF object, specified as "NED" for the north-east-down frame or "ENU" for the east-north-up frame.

Data Types: char | string

**SensorNames — Names of sensors fused in filter**
{''} (default) | cell array of character vectors

Names of sensors fused in the filter, specified as a cell array of character vectors.

Example: {'Sensor1','Accelerometer2'}

Data Types: cell

## Examples

### Create insOptions to Use with insEKF Object

Create an insOptions object, and specify the sensor names as Sensor1 and Sensor2. Specify the data type as single.

```
options = insOptions(SensorNamesSource="Property", ...
    SensorNames={'Sensor1','Sensor2'}, ...
    Datatype="single")
```

```
options = 
  insOptions with properties:

             Datatype: 'single'
    SensorNamesSource: property
       ReferenceFrame: NED
          SensorNames: {'Sensor1'  'Sensor2'}
```

Create an insEKF filter object with one accelerometer and one magnetometer. Specify the properties of the filter using the insOptions object. In the created filter, the sensor names are Sensor1 and Sensor2, respectively. The data type is single.

```
filter = insEKF(insAccelerometer,insMagnetometer,options)
```

```
filter = 
  insEKF with properties:

                   State: [16x1 single]
         StateCovariance: [16x16 single]
    AdditiveProcessNoise: [16x16 single]
             MotionModel: [1x1 insMotionOrientation]
                 Sensors: {[1x1 insAccelerometer]  [1x1 insMagnetometer]}
             SensorNames: {'Sensor1'  'Sensor2'}
          ReferenceFrame: 'NED'
```

# Version History

**Introduced in R2022a**

## See Also

`insEKF`

# insAccelerometer

Model accelerometer readings for sensor fusion

## Description

The `insAccelerometer` object models accelerometer readings for sensor fusion. Passing an `insAccelerometer` object to an `insEKF` object enables the `insEKF` object to fuse accelerometer data. For details on the accelerometer model, see “Algorithms” on page 2-1919.

## Creation

### Syntax

`sensor = insAccelerometer`

#### Description

`sensor = insAccelerometer` creates an `insAccelerometer` object. Passing the created `sensor` to an `insEKF` object enables the `insEKF` object to fuse accelerometer data. When fusing data with the `fuse` object function of `insEKF`, pass `sensor` as the second argument to identify the data as obtained from an accelerometer.

## Examples

#### Create `insAccelerometer` for Use in `insEKF`

Create two `insAccelerometer` objects and pass them to an `insEKF` object.

```
sensor1 = insAccelerometer;
sensor2 = insAccelerometer;
filterOrientation = insEKF(sensor1,sensor2,insMotionOrientation)
```

```
filterOrientation = 
  insEKF with properties:

                    State: [13x1 double]
          StateCovariance: [13x13 double]
    AdditiveProcessNoise: [13x13 double]
              MotionModel: [1x1 insMotionOrientation]
                  Sensors: {[1x1 insAccelerometer]  [1x1 insAccelerometer]}
              SensorNames: {'Accelerometer'  'Accelerometer_1'}
           ReferenceFrame: 'NED'
```

Since the `insMotionOrientation` object does not model linear acceleration, the filter does not estimate acceleration.

```
stateinfo(filterOrientation)
```

```
ans = struct with fields:
            Orientation: [1 2 3 4]
        AngularVelocity: [5 6 7]
     Accelerometer_Bias: [8 9 10]
   Accelerometer_1_Bias: [11 12 13]
```

Create another two `insAccelerometer` objects and pass them to a new `insEKF` object. Since the `insMotionPose` object models linear acceleration, the filter estimates acceleration.

```
sensor3 = insAccelerometer;
sensor4 = insAccelerometer;

filterPose = insEKF(sensor3,sensor4,insMotionPose)
```

```
filterPose = 
  insEKF with properties:

                  State: [22x1 double]
        StateCovariance: [22x22 double]
    AdditiveProcessNoise: [22x22 double]
            MotionModel: [1x1 insMotionPose]
                Sensors: {[1x1 insAccelerometer]  [1x1 insAccelerometer]}
            SensorNames: {'Accelerometer'  'Accelerometer_1'}
         ReferenceFrame: 'NED'
```

```
stateinfo(filterPose)
```

```
ans = struct with fields:
            Orientation: [1 2 3 4]
        AngularVelocity: [5 6 7]
               Position: [8 9 10]
               Velocity: [11 12 13]
           Acceleration: [14 15 16]
     Accelerometer_Bias: [17 18 19]
   Accelerometer_1_Bias: [20 21 22]
```

Fuse a measurement from `sensor3`.

```
fuse(filterPose,sensor3,[1 1 1],eye(3))
```

```
ans = 22×1

    0.9958
    0.0649
   -0.0649
         0
         0
         0
         0
         0
         0
         0
      ⋮
```

## Algorithms

The insAccelerometer object models the accelerometer reading as acceleration in the sensor frame. Depending on whether the insEKF object estimates linear acceleration in the state equations, the measurement equation takes one of two forms:

- If the insEKF object does not estimate the acceleration state, the measurement equation is:

  $$h(x) = g_{sensor} + \Delta$$

  where $h(x)$ is the three-dimensional measurement output, $g_{sensor}$ is the gravitational acceleration expressed in the sensor frame, and $\Delta$ is the three-dimensional bias of the sensor, modeled as a constant vector in the sensor frame.
- If the insEKF object estimates the acceleration state, the equation is:

  $$h(x) = g_{sensor} + a_{sensor} + \Delta$$

  where $a_{sensor}$ is the acceleration, excluding the gravity acceleration, expressed in the sensor frame.

Passing an insAccelerometer object to an insEKF filter object enables the filter object to additionally track the bias of the accelerometer. Internally, the insEKF object decides if the acceleration state is estimated by calling its stateparts object function.

# Version History

**Introduced in R2022a**

## See Also

insEKF | insOptions

# insGyroscope

Model gyroscope readings for sensor fusion

## Description

The `insGyroscope` object models gyroscope readings for sensor fusion. Passing an `insGyroscope` object to an `insEKF` object enables the `insEKF` object to fuse gyroscope data. For details on the gyroscope model, see “Algorithms” on page 2-1921.

## Creation

### Syntax

`sensor = insGyroscope`

#### Description

`sensor = insGyroscope` creates an `insGyroscope` object. Passing the created `sensor` to an `insEKF` object enables the `insEKF` object to fuse gyroscope data. When fusing data with the `fuse` object function of `insEKF`, pass `sensor` as the second argument to identify the data as obtained from a gyroscope.

### Examples

#### Create `insGyroscope` for Use in `insEKF`

Create an `insGyroscope` object and pass it to an `insEKF` object.

```
sensor = insGyroscope;
filterOrientation = insEKF(sensor)
```

```
filterOrientation = 
  insEKF with properties:

                   State: [10x1 double]
         StateCovariance: [10x10 double]
    AdditiveProcessNoise: [10x10 double]
             MotionModel: [1x1 insMotionOrientation]
                 Sensors: {[1x1 insGyroscope]}
             SensorNames: {'Gyroscope'}
          ReferenceFrame: 'NED'
```

Show the state information of the filter. Notice that the state contains the gyroscope bias component.

```
stateinfo(filterOrientation)
```

```
ans = struct with fields:
        Orientation: [1 2 3 4]
```

```
    AngularVelocity: [5 6 7]
     Gyroscope_Bias: [8 9 10]
```

Fuse a gyroscope measurement of `[0.1 0.1 0.1]` rad/s with measurement noise of `diag([0.01 0.01 0.01])`.

```
measure = [0.1 0.1 0.1];
measureNoise = diag([0.01 0.01 0.01]);

state = fuse(filterOrientation,sensor,measure,measureNoise)
```

```
state = 10×1

    1.0000
         0
         0
         0
    0.0498
    0.0498
    0.0498
    0.0498
    0.0498
    0.0498
```

## Algorithms

The `insGyroscope` object models the angular velocity vector expressed in the sensor frame. The measurement equation is:

$$h(x) = \omega_{gyro} + \Delta$$

where $h(x)$ is the three-dimensional measurement output, $\omega_{gyro}$ is the angular velocity of the platform expressed in the sensor frame, and $\Delta$ is the three-dimensional bias of the sensor, modeled as a constant vector in the sensor frame.

Passing an `insGyroscope` object to an `insEKF` filter object enables the filter object to additionally track the bias of the gyroscope.

# Version History

**Introduced in R2022a**

## See Also

`insEKF` | `insOptions`

# insGPS

Model GPS readings for sensor fusion

## Description

The `insGPS` object models GPS readings for sensor fusion. Passing an `insGPS` object to an `insEKF` object enables the `insEKF` object to fuse position and optional velocity data. For details on the GPS model, see “Algorithms” on page 2-1924.

## Creation

### Syntax

`sensor = insGPS`

#### Description

`sensor = insGPS` creates an `insGPS` object. Passing the created `sensor` to an `insEKF` object enables the `insEKF` object to fuse position and optional velocity data. When fusing data with the `fuse` object function of `insEKF`, pass `sensor` as the second argument to identify the data as obtained from a GPS.

To enable position and velocity estimation in `insEKF`, use a motion model that models position and velocity states, such as the `insMotionPose` object.

### Properties

**`ReferenceLocation` — Origin of local navigation reference frame**
`[0 0 0]` (default) | three-element row vector of form `[latitude longitude altitude]`

Origin of the local navigation reference frame, specified as a three 3-element row vector in geodetic coordinates `[latitude longitude altitude]`. Altitude is the height above the reference ellipsoid model, WGS84, in meters. Latitude and longitude are in degrees.

The reference frame is a north-east-down (NED) or east-north-up (ENU) frame, based on the `ReferenceFrame` property of the `insEKF` object.

Data Types: `single` | `double`

## Examples

### Create `insGPS` for Use in `insEKF`

Create an `insGPS` object and pass it to an `insEKF` object.

```
sensor = insGPS;
filter = insEKF(sensor)
```

```
filter = 
  insEKF with properties:

                   State: [16x1 double]
         StateCovariance: [16x16 double]
    AdditiveProcessNoise: [16x16 double]
             MotionModel: [1x1 insMotionPose]
                 Sensors: {[1x1 insGPS]}
             SensorNames: {'GPS'}
          ReferenceFrame: 'NED'
```

Show the state information of the filter. Since the GPS sensor reports position measurements, the filter by default models both rotational and translational motion.

```
stateinfo(filter)
```

```
ans = struct with fields:
        Orientation: [1 2 3 4]
    AngularVelocity: [5 6 7]
           Position: [8 9 10]
           Velocity: [11 12 13]
       Acceleration: [14 15 16]
```

Assume a GPS position measurement of 10 degrees in latitude, 10 degrees in longitude, and 10 meters in altitude. The velocity measurement of the GPS is `[5 5 0]` in m/s.

```
lla = [10 10 10];
vel = [5 5 0];
llaNoise = eye(3);
velNoise = 0.1*eye(3);
```

Fuse the GPS position measurement.

```
state = fuse(filter,sensor,lla,llaNoise)
```

```
state = 16×1
10^5 ×

    0.0000
         0
         0
         0
         0
         0
         0
    5.5013
    5.4542
    0.9585
      ⋮
```

Fuse the GPS position measurement along with the velocity measurement.

```
measure = [lla vel];
measureNoise = blkdiag(llaNoise,velNoise);
state2 = fuse(filter,sensor,measure,measureNoise)
```

```
state2 = 16×1
10^5 ×

    0.0000
         0
         0
         0
         0
         0
         0
    7.3350
    7.2722
    1.2779
      ⋮
```

## Algorithms

The insGPS object models the GPS reading as the longitude, latitude, and altitude (LLA) position, and optional velocity data in the navigation frame.

Depending on whether you include the velocity data when using the fuse object function of insEKF, the measurement equation takes one of two forms:

- If you do not fuse velocity data, the measurement is the latitude in meters, longitude in degrees, and altitude in meters (LLA).
- If you fuse velocity data, the measurement is the LLA measurement, and the velocity of the platform in m/s, expressed in the reference frame defined by the ReferenceLoation property of the insGPS object and the ReferenceFrame property of the insEKF object.

# Version History

**Introduced in R2022a**

## See Also

insEKF | insOptions

# insMagnetometer

Model magnetometer readings for sensor fusion

## Description

The `insMagnetometer` object models magnetometer readings for sensor fusion. Passing an `insMagnetometer` object to an `insEKF` object enables the `insEKF` object to fuse magnetometer data. For details on the magnetometer model, see “Algorithms” on page 2-1926.

## Creation

### Syntax

`sensor = insMagnetometer`

#### Description

`sensor = insMagnetometer` creates an `insMagnetometer` object. Passing the created `sensor` to an `insEKF` object enables the `insEKF` object to fuse magnetometer data. When fusing data with the `fuse` object function of `insEKF`, pass `sensor` as the second argument to identify the data as obtained from a magnetometer.

### Examples

#### Create `insMagnetometer` for Use in `insEKF`

Create an `insMagnetometer` object and pass it to an `insEKF` object.

```
sensor = insMagnetometer;
filterOrientation = insEKF(sensor)
```

```
filterOrientation = 
  insEKF with properties:

                   State: [13x1 double]
         StateCovariance: [13x13 double]
    AdditiveProcessNoise: [13x13 double]
             MotionModel: [1x1 insMotionOrientation]
                 Sensors: {[1x1 insMagnetometer]}
             SensorNames: {'Magnetometer'}
          ReferenceFrame: 'NED'
```

Show the state information of the filter. Notice that the state contains the geomagnetic vector component and the magnetometer bias component.

```
stateinfo(filterOrientation)
```

```
ans = struct with fields:
          Orientation: [1 2 3 4]
      AngularVelocity: [5 6 7]
    GeomagneticVector: [8 9 10]
    Magnetometer_Bias: [11 12 13]
```

Fuse a magnetometer reading of `[27 -2 -16]` μT with a measurement noise of `diag([0.1 0.1 0.1])` $\mu T^2$.

```
measure = [27 -2 -16];
measureNoise = diag([0.1 0.1 0.1]);

fuse(filterOrientation,sensor,measure,measureNoise)
```

```
ans = 13×1

    1.0000
   -0.0032
   -0.0032
   -0.0050
         0
         0
         0
   27.5550
   -2.4168
  -16.0849
      ⋮
```

## Algorithms

The `insMagnetometer` object models the magnetometer reading as the geomagnetic vector in the sensor frame. The measurement equation is:

$$h(x) = g_{mag} + \Delta$$

where $h(x)$ is the three-dimensional measurement output, $g_{mag}$ is the geomagnetic vector expressed in the sensor frame, and $\Delta$ is the three-dimensional bias of the sensor, which is modeled as a constant vector in the sensor frame.

Passing an `insMagnetometer` object to an `insEKF` filter object enables the filter object to additionally track the unique geomagnetic vector, as well as the bias of the magnetometer.

# Version History

**Introduced in R2022a**

## See Also

`insEKF` | `insOptions`

# insMotionOrientation

Motion model for 3-D orientation estimation

## Description

The `insMotionOrientation` object models orientation-only platform motion assuming a constant angular velocity. Passing an `insMotionOrientation` object to an `insEKF` object enables the estimation of 3-D orientation and angular velocity. For details on the motion model, see “Algorithms” on page 2-1928.

## Creation

### Syntax

`model = insMotionOrientation`

#### Description

`model = insMotionOrientation` creates an `insMotionOrientation` object. Passing the created `model` to an `insEKF` object enables the estimation of:

- The orientation quaternion from the navigation frame to the body frame.
- The angular velocity of the platform, expressed in the body frame.

### Examples

#### Create `insMotionOrientation` for Use in `insEKF`

Create an `insMotionOrientation` object and pass it to an `insEKF` object.

```
motionModel = insMotionOrientation
```

```
motionModel = 
  insMotionOrientation with no properties.
```

```
filter = insEKF(motionModel)
```

```
filter = 
  insEKF with properties:

                   State: [7x1 double]
         StateCovariance: [7x7 double]
    AdditiveProcessNoise: [7x7 double]
             MotionModel: [1x1 insMotionOrientation]
                 Sensors: {}
             SensorNames: {1x0 cell}
```

```
        ReferenceFrame: 'NED'
```

Show the state maintained in the filter.

```
stateinfo(filter)
```

```
ans = struct with fields:
        Orientation: [1 2 3 4]
    AngularVelocity: [5 6 7]
```

## Algorithms

The `insMotionOrientation` object models the orientation-only motion of platforms. The state equation of the motion model is:

$$\dot{q} = \frac{1}{2}\omega q$$

$$\dot{\omega} = 0$$

where:

- $q = (q_0, q_1, q_2, q_3)$ is the quaternion from the navigation frame to the body frame.
- $\omega$ is the angular velocity of the platform, expressed in the body frame.

# Version History

**Introduced in R2022a**

## See Also

`insEKF` | `insOptions` | `insMotionPose` | `positioning.insMotionModel`

# insMotionPose

Model for 3-D motion estimation

## Description

The `insMotionPose` object models 3-D motion assuming constant angular velocity and constant linear acceleration. Passing an `insMotionPose` object to an `insEKF` object enables the estimation of 3-D motion, including orientation, angular velocity, position, linear velocity, and linear acceleration. For details on the motion model, see “Algorithms” on page 2-1930.

## Creation

### Syntax

`model = insMotionPose`

#### Description

`model = insMotionPose` creates an `insMotionPose` object. Passing `model` to an `insEKF` object enables the estimation of:

- The orientation quaternion from the navigation frame to the body frame.
- The angular velocity of the platform, expressed in the body frame.
- The position of the platform, expressed in the navigation frame.
- The velocity of the platform, expressed in the navigation frame.
- The acceleration of the platform, expressed in the navigation frame.

### Examples

#### Create `insMotionPose` for Use in `insEKF`

Create an `insMotionPose` object and pass it to an `insEKF` object.

```
motionModel = insMotionPose
```

```
motionModel = 
  insMotionPose with no properties.
```

```
filter = insEKF(motionModel)
```

```
filter = 
  insEKF with properties:

                   State: [16x1 double]
         StateCovariance: [16x16 double]
```

```
    AdditiveProcessNoise: [16x16 double]
             MotionModel: [1x1 insMotionPose]
                 Sensors: {}
             SensorNames: {1x0 cell}
          ReferenceFrame: 'NED'
```

Show the state maintained in the filter.

```
stateinfo(filter)
```

```
ans = struct with fields:
        Orientation: [1 2 3 4]
    AngularVelocity: [5 6 7]
           Position: [8 9 10]
           Velocity: [11 12 13]
       Acceleration: [14 15 16]
```

## Algorithms

The `insMotionPose` object models the orientation-only motion of platforms. The state equation of the motion model is:

$$\dot{q} = \frac{1}{2}\omega q$$
$$\dot{\omega} = 0$$
$$\dot{p} = v$$
$$\dot{v} = a$$
$$\dot{a} = 0$$

where:

- $q = (q_0, q_1, q_2, q_3)$ is the quaternion from the navigation frame to the body frame.
- $\omega$ is the angular velocity of the platform, expressed in the body frame.
- $p$ is the position of the platform, expressed in the navigation frame.
- $v$ is the linear velocity of the platform, expressed in the navigation frame.
- $a$ is the linear acceleration of the platform, expressed in the navigation frame.

# Version History

**Introduced in R2022a**

## See Also

`insEKF` | `insOptions` | `insMotionOrientation` | `positioning.insMotionModel`

# positioning.INSMotionModel class

**Package:** `positioning`

Base class for defining motion models used with `insEKF`

## Description

The `positioning.INSMotionModel` class defines the base class for motion models used with INS filters. Derive from this class to define your own motion model.

To define a new motion model:

- Inherit from this class and implement at least two methods: `modelstates` and `stateTransition`.
- Optionally, if you want a higher fidelity simulation, you can implement a `stateTransitionJacobian` method that returns the Jacobian of the state transition function. If you do not implement this method, the object calculates the Jacobian numerically with lower accuracy and higher computation cost.

As an example of implementing this interface class, see the implementation details of `insMotionOrientation` by typing this in the Command Window:

```
edit insMotionOrientation
```

The `positioning.INSMotionModel` class is a `handle` class.

### Class Attributes

| | |
|---|---|
| `Abstract` | `true` |

For information on class attributes, see “Class Attributes”.

# Creation

## Syntax

`sensor = positioning.INSMotionModel()`

### Description

`sensor = positioning.INSMotionModel()` creates an INS sensor model object. This constructor can only be called from a derived class.

## Methods

### Public Methods

| | |
|---|---|
| modelstates | States for motion model |
| stateTransition | State transition of motion model |

| | |
|---|---|
| stateTransitionJacobian | Jacobian of state transition function |
| copy | Create copy of motion model |

## Examples

### Customize Motion Model Used with insEKF

Customize a 1-D constant velocity motion model used with an `insEKF` object. Customize the motion model by inheriting from the `positioning.INSMotionModel` interface class and implement the `modelstates` and `stateTranistion` methods. You can also optionally implement the `stateTransitionJacobian` method. These sections provide an overview of how the `ConstantVelocityMotion` class implements the `positioning.INSMotionModel` methods, but for more details on their implementation, see the attached `ConstantVelocityMotion.m` file.

#### Implement modelstates method

To model 1-D constant velocity motion, you need to return only the 1-D position and velocity state as a structure. When you add a `ConstantVelocityMotion` object to an `insEKF` filter object, the filter adds the `Position` and `Velocity` components to the state vector of the filter.

#### Implement stateTransition method

The `stateTransition` method returns the derivatives of the state defined by the motion model as a structure. The derivative of the `Position` is the `Velocity`, and the derivative of the `Velocity` is `0`.

#### Implement stateTransitionJacobian method

The `stateTransitionJacobian` method returns the partial derivatives of `stateTransition` method, with respect to the state vector of the filter, as a structure. All the partial derivatives are 0, except the partial derivative of the derivative of the `Position` component, which is the `Velocity`, with respect to the `Velocity` state, is `1`.

#### Create and add inherited object

Create a `ConstantVelocityMotion` object.

```
cvModel = ConstantVelocityMotion
```

```
cvModel = 
  ConstantVelocityMotion with no properties.
```

Create an `insEKF` object with the created `cvModel` object.

```
filter = insEKF(insAccelerometer,cvModel)
```

```
filter = 
  insEKF with properties:

                   State: [5x1 double]
         StateCovariance: [5x5 double]
    AdditiveProcessNoise: [5x5 double]
             MotionModel: [1x1 ConstantVelocityMotion]
                 Sensors: {[1x1 insAccelerometer]}
             SensorNames: {'Accelerometer'}
```

```
         ReferenceFrame: 'NED'
```

The filter state contains the `Position` and `Velocity` components.

```
stateinfo(filter)
```

```
ans = struct with fields:
              Position: 1
              Velocity: 2
    Accelerometer_Bias: [3 4 5]
```

### Show customized `ConstantVelocityMotion` class

```
type ConstantVelocityMotion.m
```

```
classdef ConstantVelocityMotion < positioning.INSMotionModel
% CONSTANTVELOCITYMOTION Constant velocity motion in 1-D

%   Copyright 2021 The MathWorks, Inc.

    methods
        function m = modelstates(~,~)
            % Return the state of motion model (added to the state of the
            % filter) as a structure.
            % Since the motion is 1-D constant velocity motion,
            % retrun only 1-D position and velocity state.
            m = struct('Position',0,'Velocity',0);
        end
        function sdot = stateTransition(~,filter,~, varargin)
            % Return the derivative of each state with respect to time as a
            % structure.

            % Deriviative of position = velocity.
            % Deriviative of velocity = 0 because this model assumes constant
            % velocity.

            % Find the current estimated velocity
            currentVelocityEstimate = stateparts(filter,'Velocity');

            % Return the derivatives
            sdot = struct( ...
                'Position',currentVelocityEstimate, ...
                'Velocity',0);
        end
        function dfdx = stateTransitionJacobian(~,filter,~,varargin)
            % Return the Jacobian of the stateTransition method with
            % respect to the state vector. The output is a structure with the
            % same fields as stateTransition but the value of each field is a
            % vector containing the derivative of that state relative to
            % all other states.

            % First, figure out the number of state components in the filter
            % and the corresponding indices
            N = numel(filter.State);
            idx = stateinfo(filter);
```

```
            % Compute the N partial derivatives of Position with respect to
            % the N states. The partial derivative of the derivative of the
            % Position stateTransition function with respect to Velocity is
            % just 1. All others are 0.
            dpdx = zeros(1,N);
            dpdx(1,idx.Velocity) =  1;

            % Compute the N partial derivatives of Velocity with respect to
            % the N states. In this case all the partial derivatives are 0.
            dvdx = zeros(1,N);

            % Return the partial derivatives as a structure.
            dfdx = struct('Position',dpdx,'Velocity',dvdx);
        end
    end
end
```

## Version History

**Introduced in R2022a**

### See Also

insEKF | insOptions

# modelstates

**Package:** `positioning`

States for motion model

## Syntax

```
s = modelstates(filter,options)
```

## Description

`s = modelstates(filter,options)` returns a structure that describes the motion model states tracked by the `insEKF` filter object.

**Tip** After defining an `insEKF` object with a custom motion model, you can access the model states using the `stateparts` object function of `insEKF`.

## Examples

### Customize Motion Model Used with `insEKF`

Customize a 1-D constant velocity motion model used with an `insEKF` object. Customize the motion model by inheriting from the `positioning.INSMotionModel` interface class and implement the `modelstates` and `stateTranistion` methods. You can also optionally implement the `stateTransitionJacobian` method. These sections provide an overview of how the `ConstantVelocityMotion` class implements the `positioning.INSMotionModel` methods, but for more details on their implementation, see the attached `ConstantVelocityMotion.m` file.

#### Implement `modelstates` method

To model 1-D constant velocity motion, you need to return only the 1-D position and velocity state as a structure. When you add a `ConstantVelocityMotion` object to an `insEKF` filter object, the filter adds the `Position` and `Velocity` components to the state vector of the filter.

#### Implement `stateTransition` method

The `stateTransition` method returns the derivatives of the state defined by the motion model as a structure. The derivative of the `Position` is the `Velocity`, and the derivative of the `Velocity` is `0`.

#### Implement `stateTransitionJacobian` method

The `stateTransitionJacobian` method returns the partial derivatives of `stateTransition` method, with respect to the state vector of the filter, as a structure. All the partial derivatives are 0, except the partial derivative of the derivative of the `Position` component, which is the `Velocity`, with respect to the `Velocity` state, is `1`.

#### Create and add inherited object

Create a `ConstantVelocityMotion` object.

```
cvModel = ConstantVelocityMotion
```

```
cvModel = 
  ConstantVelocityMotion with no properties.
```

Create an `insEKF` object with the created `cvModel` object.

```
filter = insEKF(insAccelerometer,cvModel)
```

```
filter = 
  insEKF with properties:

                   State: [5x1 double]
         StateCovariance: [5x5 double]
    AdditiveProcessNoise: [5x5 double]
             MotionModel: [1x1 ConstantVelocityMotion]
                 Sensors: {[1x1 insAccelerometer]}
             SensorNames: {'Accelerometer'}
          ReferenceFrame: 'NED'
```

The filter state contains the `Position` and `Velocity` components.

```
stateinfo(filter)
```

```
ans = struct with fields:
              Position: 1
              Velocity: 2
    Accelerometer_Bias: [3 4 5]
```

#### Show customized ConstantVelocityMotion class

```
type ConstantVelocityMotion.m
```

```
classdef ConstantVelocityMotion < positioning.INSMotionModel
% CONSTANTVELOCITYMOTION Constant velocity motion in 1-D

%   Copyright 2021 The MathWorks, Inc.

    methods
        function m = modelstates(~,~)
            % Return the state of motion model (added to the state of the
            % filter) as a structure.
            % Since the motion is 1-D constant velocity motion,
            % retrun only 1-D position and velocity state.
            m = struct('Position',0,'Velocity',0);
        end
        function sdot = stateTransition(~,filter,~, varargin)
            % Return the derivative of each state with respect to time as a
            % structure.

            % Deriviative of position = velocity.
            % Deriviative of velocity = 0 because this model assumes constant
            % velocity.

            % Find the current estimated velocity
            currentVelocityEstimate = stateparts(filter,'Velocity');
```

```
            % Return the derivatives
            sdot = struct( ...
                'Position',currentVelocityEstimate, ...
                'Velocity',0);
        end
        function dfdx = stateTransitionJacobian(~,filter,~,varargin)
            % Return the Jacobian of the stateTransition method with
            % respect to the state vector. The output is a structure with the
            % same fields as stateTransition but the value of each field is a
            % vector containing the derivative of that state relative to
            % all other states.

            % First, figure out the number of state components in the filter
            % and the corresponding indices
            N = numel(filter.State);
            idx = stateinfo(filter);


            % Compute the N partial derivatives of Position with respect to
            % the N states. The partial derivative of the derivative of the
            % Position stateTransition function with respect to Velocity is
            % just 1. All others are 0.
            dpdx = zeros(1,N);
            dpdx(1,idx.Velocity) =  1;

            % Compute the N partial derivatives of Velocity with respect to
            % the N states. In this case all the partial derivatives are 0.
            dvdx = zeros(1,N);

            % Return the partial derivatives as a structure.
            dfdx = struct('Position',dpdx,'Velocity',dvdx);
        end
    end
end
```

## Input Arguments

**filter — INS filter**
insEKF object

INS filter, specified as an insEKF object.

**options — Options for INS filter**
insOptions object

Options for the INS filter, specified as an insOptions object.

## Output Arguments

**s — State structure**
structure

State structure, returned as a structure. The field names of the structure are the names of the states that you want estimate. The insEKF filter object uses the value of each field as the default value of its

corresponding state component, and uses the size of the value as the size of the corresponding state component.

**Tip** You can use the `stateparts` object function of the `insEKF` object to access the states, saved in the filter.

## Version History

**Introduced in R2022a**

### See Also

`stateTransition` | `stateTransitionJacobian`

# stateTransition

**Package:** `positioning`

State transition of motion model

## Syntax

```
statedot = stateTransition(model,filter,dt,varargin)
```

## Description

`statedot = stateTransition(model,filter,dt,varargin)` returns the derivatives of the states of the motion model used with the INS filter.

## Examples

### Customize Motion Model Used with `insEKF`

Customize a 1-D constant velocity motion model used with an `insEKF` object. Customize the motion model by inheriting from the `positioning.INSMotionModel` interface class and implement the `modelstates` and `stateTranistion` methods. You can also optionally implement the `stateTransitionJacobian` method. These sections provide an overview of how the `ConstantVelocityMotion` class implements the `positioning.INSMotionModel` methods, but for more details on their implementation, see the attached `ConstantVelocityMotion.m` file.

**Implement `modelstates` method**

To model 1-D constant velocity motion, you need to return only the 1-D position and velocity state as a structure. When you add a `ConstantVelocityMotion` object to an `insEKF` filter object, the filter adds the `Position` and `Velocity` components to the state vector of the filter.

**Implement `stateTransition` method**

The `stateTransition` method returns the derivatives of the state defined by the motion model as a structure. The derivative of the `Position` is the `Velocity`, and the derivative of the `Velocity` is `0`.

**Implement `stateTransitionJacobian` method**

The `stateTransitionJacobian` method returns the partial derivatives of `stateTransition` method, with respect to the state vector of the filter, as a structure. All the partial derivatives are 0, except the partial derivative of the derivative of the `Position` component, which is the `Velocity`, with respect to the `Velocity` state, is `1`.

**Create and add inherited object**

Create a `ConstantVelocityMotion` object.

```
cvModel = ConstantVelocityMotion
```

```
cvModel = 
  ConstantVelocityMotion with no properties.
```

Create an `insEKF` object with the created `cvModel` object.

```
filter = insEKF(insAccelerometer,cvModel)
```

```
filter = 
  insEKF with properties:

                   State: [5x1 double]
         StateCovariance: [5x5 double]
    AdditiveProcessNoise: [5x5 double]
             MotionModel: [1x1 ConstantVelocityMotion]
                 Sensors: {[1x1 insAccelerometer]}
             SensorNames: {'Accelerometer'}
          ReferenceFrame: 'NED'
```

The filter state contains the `Position` and `Velocity` components.

```
stateinfo(filter)
```

```
ans = struct with fields:
              Position: 1
              Velocity: 2
    Accelerometer_Bias: [3 4 5]
```

**Show customized `ConstantVelocityMotion` class**

```
type ConstantVelocityMotion.m
```

```
classdef ConstantVelocityMotion < positioning.INSMotionModel
% CONSTANTVELOCITYMOTION Constant velocity motion in 1-D

%   Copyright 2021 The MathWorks, Inc.

    methods
        function m = modelstates(~,~)
            % Return the state of motion model (added to the state of the
            % filter) as a structure.
            % Since the motion is 1-D constant velocity motion,
            % retrun only 1-D position and velocity state.
            m = struct('Position',0,'Velocity',0);
        end
        function sdot = stateTransition(~,filter,~, varargin)
            % Return the derivative of each state with respect to time as a
            % structure.

            % Deriviative of position = velocity.
            % Deriviative of velocity = 0 because this model assumes constant
            % velocity.

            % Find the current estimated velocity
            currentVelocityEstimate = stateparts(filter,'Velocity');

            % Return the derivatives
```

```
            sdot = struct( ...
                'Position',currentVelocityEstimate, ...
                'Velocity',0);
        end
        function dfdx = stateTransitionJacobian(~,filter,~,varargin)
            % Return the Jacobian of the stateTransition method with
            % respect to the state vector. The output is a structure with the
            % same fields as stateTransition but the value of each field is a
            % vector containing the derivative of that state relative to
            % all other states.

            % First, figure out the number of state components in the filter
            % and the corresponding indices
            N = numel(filter.State);
            idx = stateinfo(filter);


            % Compute the N partial derivatives of Position with respect to
            % the N states. The partial derivative of the derivative of the
            % Position stateTransition function with respect to Velocity is
            % just 1. All others are 0.
            dpdx = zeros(1,N);
            dpdx(1,idx.Velocity) =  1;

            % Compute the N partial derivatives of Velocity with respect to
            % the N states. In this case all the partial derivatives are 0.
            dvdx = zeros(1,N);

            % Return the partial derivatives as a structure.
            dfdx = struct('Position',dpdx,'Velocity',dvdx);
        end
    end
end
```

## Input Arguments

**`model` — Motion model used with INS filter**
object inherited from `positioning.INSMotionModel` class

Motion model used with an INS filter, specified as an object inherited from the `positioning.INSMotionModel` abstract class.

**`filter` — INS filter**
`insEKF` object

INS filter, specified as an `insEKF` object.

**`dt` — Filter time step**
positive scalar

Filter time step, specified as a positive scalar.

Data Types: `single` | `double`

**`varargin` — Additional inputs**
any data type

Additional inputs that are passed as the `varargin` inputs of the `predict` object function of the `insEKF` object.

### Output Arguments

**`statedot` — Derivatives of states**
structure

Derivatives of the states, returned as a structure. The field names must be exactly the same as those of the structure returned by the `modelstates` method of `model`. The field values are the corresponding time derivatives of the sensor states.

## Version History

**Introduced in R2022a**

### See Also

`modelstates` | `stateTransitionJacobian`

# stateTransitionJacobian

**Package:** `positioning`

Jacobian of state transition function

## Syntax

```
jac = stateTransitionJacobian(model,filter,dt,varargin)
```

## Description

`jac = stateTransitionJacobian(model,filter,dt,varargin)` returns the Jacobian matrix for the state transition function of the `model` object inherited from the `positioning.INSMotionModel` abstract class.

**Note** Implementing this method is optional for a subclass of the `positioning.INSMotionModel` abstract class. If you do not implement this method, the subclass uses a Jacobian matrix calculated by numerical differentiation.

## Examples

### Customize Motion Model Used with `insEKF`

Customize a 1-D constant velocity motion model used with an `insEKF` object. Customize the motion model by inheriting from the `positioning.INSMotionModel` interface class and implement the `modelstates` and `stateTranistion` methods. You can also optionally implement the `stateTransitionJacobian` method. These sections provide an overview of how the `ConstantVelocityMotion` class implements the `positioning.INSMotionModel` methods, but for more details on their implementation, see the attached `ConstantVelocityMotion.m` file.

#### Implement `modelstates` method

To model 1-D constant velocity motion, you need to return only the 1-D position and velocity state as a structure. When you add a `ConstantVelocityMotion` object to an `insEKF` filter object, the filter adds the `Position` and `Velocity` components to the state vector of the filter.

#### Implement `stateTransition` method

The `stateTransition` method returns the derivatives of the state defined by the motion model as a structure. The derivative of the `Position` is the `Velocity`, and the derivative of the `Velocity` is `0`.

#### Implement `stateTransitionJacobian` method

The `stateTransitionJacobian` method returns the partial derivatives of `stateTransition` method, with respect to the state vector of the filter, as a structure. All the partial derivatives are 0, except the partial derivative of the derivative of the `Position` component, which is the `Velocity`, with respect to the `Velocity` state, is `1`.

### Create and add inherited object

Create a `ConstantVelocityMotion` object.

```
cvModel = ConstantVelocityMotion
```

```
cvModel = 
  ConstantVelocityMotion with no properties.
```

Create an `insEKF` object with the created `cvModel` object.

```
filter = insEKF(insAccelerometer,cvModel)
```

```
filter = 
  insEKF with properties:

                   State: [5x1 double]
         StateCovariance: [5x5 double]
    AdditiveProcessNoise: [5x5 double]
             MotionModel: [1x1 ConstantVelocityMotion]
                 Sensors: {[1x1 insAccelerometer]}
             SensorNames: {'Accelerometer'}
          ReferenceFrame: 'NED'
```

The filter state contains the `Position` and `Velocity` components.

```
stateinfo(filter)
```

```
ans = struct with fields:
              Position: 1
              Velocity: 2
    Accelerometer_Bias: [3 4 5]
```

### Show customized `ConstantVelocityMotion` class

```
type ConstantVelocityMotion.m
```

```
classdef ConstantVelocityMotion < positioning.INSMotionModel
% CONSTANTVELOCITYMOTION Constant velocity motion in 1-D

%   Copyright 2021 The MathWorks, Inc.

    methods
        function m = modelstates(~,~)
            % Return the state of motion model (added to the state of the
            % filter) as a structure.
            % Since the motion is 1-D constant velocity motion,
            % retrun only 1-D position and velocity state.
            m = struct('Position',0,'Velocity',0);
        end
        function sdot = stateTransition(~,filter,~, varargin)
            % Return the derivative of each state with respect to time as a
            % structure.

            % Deriviative of position = velocity.
            % Deriviative of velocity = 0 because this model assumes constant
```

```
            % velocity.

            % Find the current estimated velocity
            currentVelocityEstimate = stateparts(filter,'Velocity');

            % Return the derivatives
            sdot = struct( ...
                'Position',currentVelocityEstimate, ...
                'Velocity',0);
        end
        function dfdx = stateTransitionJacobian(~,filter,~,varargin)
            % Return the Jacobian of the stateTransition method with
            % respect to the state vector. The output is a structure with the
            % same fields as stateTransition but the value of each field is a
            % vector containing the derivative of that state relative to
            % all other states.

            % First, figure out the number of state components in the filter
            % and the corresponding indices
            N = numel(filter.State);
            idx = stateinfo(filter);


            % Compute the N partial derivatives of Position with respect to
            % the N states. The partial derivative of the derivative of the
            % Position stateTransition function with respect to Velocity is
            % just 1. All others are 0.
            dpdx = zeros(1,N);
            dpdx(1,idx.Velocity) =  1;

            % Compute the N partial derivatives of Velocity with respect to
            % the N states. In this case all the partial derivatives are 0.
            dvdx = zeros(1,N);

            % Return the partial derivatives as a structure.
            dfdx = struct('Position',dpdx,'Velocity',dvdx);
        end
    end
end
```

## Input Arguments

**`model` — Motion model used with INS filter**
object inherited from `positioning.INSMotionModel` class

Motion model used with an INS filter, specified as an object inherited from the `positioning.INSMotionModel` abstract class.

**`filter` — INS filter**
`insEKF` object

INS filter, specified as an `insEKF` object.

**`dt` — Filter time step**
positive scalar

Filter time step, specified as a positive scalar.

Data Types: `single` | `double`

**`varargin` — Additional inputs**
any data type

Additional inputs that are passed as the `varargin` inputs of the `predict` object function of the `insEKF` object.

## Output Arguments

**`jac` — Jacobian matrix for state transition equation**
*S*-by-*N* real-valued matrix

Jacobian matrix for the state transition equation, returned as an *S*-by-*N* real-valued matrix. *S* is the number of fields in the returned structure of the `modelstates` method of the motion model, and *N* is the dimension of the state maintained in the `State` property of the `filter`.

# Version History

**Introduced in R2022a**

## See Also

`modelstates` | `stateTransition`

# copy

**Package:** `positioning`

Create copy of motion model

## Syntax

`newModel=copy(model)`

## Description

`newModel=copy(model)` creates a copy of the motion model.

---

**Note** Implementing this method is optional for a subclass of the `positioning.INSMotionModel` abstract class. You need to implement this method only when both of these conditions are true.

- You need to use the `copy` object function of the `insEKF` object.
- You want to copy at least one non-public property of the implemented motion model.

---

## Examples

### Implement copy Method of positioning.INSMotionModel

Use the `copy` method to copy a private property, `PrivateProp`.

```
classdef myModel < positioning.INSMotionModel
    properties (Access = private)
        PrivateProp % A private property
    end
    % Implement the class as desired.
    methods
        function m = modelstates(~,~)
            m = struct('Position',0,'Velocity',0);
        end
    end
    % Add a public copy method to additionally copy the private property.
        function newObj = copy(obj)
            newObj = obj;
            newObj.PrivateProp = obj.PrivateProp;
        end
    end
end
```

## Input Arguments

**`model` — Motion model used with INS filter**
object inherited from `positioning.INSMotionModel` class

Motion model used with an INS filter, specified as an object inherited from the `positioning.INSMotionModel` abstract class.

### Output Arguments

**`newModel` — Copy of motion model**
object inherited from `positioning.INSMotionModel` class

Copy of the motion model, returned as an object inherited from `positioning.INSMotionModel` class.

## Version History

**Introduced in R2022b**

# positioning.INSSensorModel class

**Package:** `positioning`

Base class for defining sensor models used with `insEKF`

## Description

The positioning.INSSensorModel class defines the base class for sensor models used with INS filters. Derive from this class to define your own sensor model.

To define a new sensor:

- Inherit from this class and implement at least the `measurement` method.
- Optionally, if you want a higher fidelity simulation, you can implement the `measurementJacobian` method that returns the Jacobian of the measurement function. If you do not implement this method, the object calculates a Jacobian numerically with lower accuracy and higher computation cost.

If the sensor model definition requires the use of the tracked state, you must additionally:

- Implement the `sensorStates` method to define the tracked state.
- Optionally, you can implement the `stateTransition` method if the state is not constant over time.
- Optionally, you can implement the `stateTransitionJacobian` method (that returns the Jacobian of the state transition function) for a higher fidelity simulation. If you do not implement this method, the object calculates the Jacobian numerically with lower accuracy and higher computation cost.

As an example of implementing this interface class, see the implementation details of `insAccelerometer` by typing this in the Command Window:

```
edit insGyroscope
```

The `positioning.INSSensorModel` class is a `handle` class.

### Class Attributes

| | |
|---|---|
| `Abstract` | `true` |

For information on class attributes, see "Class Attributes".

# Creation

## Syntax

```
sensor = positioning.INSSensorModel()
```

#### Description

`sensor = positioning.INSSensorModel()` creates an INS sensor model object. This constructor can only be called from a derived class.

## Methods

#### Public Methods

| | |
|---|---|
| measurement | Sensor measurement from states |
| measurementJacobian | Jacobian of measurement function |
| sensorStates | Sensor states |
| stateTransition | State transition of sensor states |
| stateTransitionJacobian | Jacobian of sensor state transition function |
| copy | Create copy of sensor model |

## Examples

### Customize Sensor Model Used with `insEKF`

Customize a sensor model used with the `insEKF` object. The sensor measures the velocity state, including a bias affected by random noise.

Customize the sensor model by inheriting from the `positioning.INSSensorModel` interface class and implementing its methods. Note that only the `measurement` method is required for implementation in the `positioning.INSSensorModel` interface class. These sections provide an overview of how the `BiasSensor` class implements the `positioning.INSSensorModel` methods, but for details on their implementation, see the details of the implementation are in the attached `BiasSensor.m` file.

#### Implement `sensorStates` method

To model bias, the `sensorStates` method needs to return a state, `Bias`, as a structure. When you add a `BiasSensor` object to an `insEKF` filter object, the filter adds the bias component to the state vector of the filter.

#### Implement `measurement` method

The measurement is the velocity component of the filter state, including the bias. Therefore, return the summation of the velocity component from the filter and the bias.

#### Implement `measurementJacobian` method

The `measurementJacobian` method returns the partial derivative of the `measurement` method with respect to the state vector of the filter as a structure. All the partial derivatives are `0`, except the partial derivatives of the measurement with respect to the velocity and bias state components.

#### Implement `stateTransition` method

The `stateTransiton` method returns the derivative of the sensor state defined in the `sensorStates` method. Assume the derivative of the bias is affected by a white noise with a standard deviation of `0.01`. Return the derivative as a structure. Note that this only showcases how to set up the method, and does not correspond to any practical application.

#### Implement `stateTransitionJacobian` method

Since the `stateTransiton` function does not depend on the state of the filter, the Jacobian matrix is 0.

#### Create and add inherited object

Create a `BiasSensor` object.

```
biSensor = BiasSensor
```

```
biSensor = 
  BiasSensor with no properties.
```

Create an `insEKF` object with the `biSensor` object.

```
filter = insEKF(biSensor,insMotionPose)
```

```
filter = 
  insEKF with properties:

                    State: [17x1 double]
          StateCovariance: [17x17 double]
    AdditiveProcessNoise: [17x17 double]
              MotionModel: [1x1 insMotionPose]
                  Sensors: {[1x1 BiasSensor]}
              SensorNames: {'BiasSensor'}
           ReferenceFrame: 'NED'
```

The filter state contains the bias component.

```
stateinfo(filter)
```

```
ans = struct with fields:
        Orientation: [1 2 3 4]
    AngularVelocity: [5 6 7]
           Position: [8 9 10]
           Velocity: [11 12 13]
       Acceleration: [14 15 16]
    BiasSensor_Bias: 17
```

#### Show customized `BiasSensor` class

```
type BiasSensor.m
```

```
classdef BiasSensor < positioning.INSSensorModel
%BIASSENSOR Sensor measuring velocity with bias

%   Copyright 2021 The MathWorks, Inc.

    methods
        function s = sensorstates(~,~)
            % Assume the sensor has a bias. Define a Bias state to enable
            % the filter to estimate the bias.
            s = struct('Bias',0);
        end
```

```
        function z = measurement(sensor,filter)
            % Measurement is the summation of the velocity measurement and
            % the bias.
            velocity = stateparts(filter,'Velocity');
            bias = stateparts(filter,sensor,'Bias');
            z = velocity + bias;
        end
        function dzdx = measurementJacobian(sensor,filter)
            % Compute the Jacobian, which is the partial derivative of the
            % measurement (velocity plus bias) with respect to the filter
            % state vector.
            % Obtain the dimension of the filter state.
            N = numel(filter.State);

            % The partial derviative of the Bias with respect to all the
            % states is zero, except the Bias state itself.
            dzdx = zeros(1,N);

            % Obtain the index for the Bias state component in the filter.
            bidx = stateinfo(filter,sensor,'Bias');
            dzdx(:,bidx) = 1;

            % The partial derivative of the Velocity with respect to all the
            % states is zero, except the Velocity state itself.
            vidx = stateinfo(filter,'Velocity');
            dzdx(:,vidx) = 1;
        end
        function dBias = stateTransition(~,~,dt,~)
            % Assume the derivative of the bias is affected by a zero-mean
            % white noise with a standard deviation of 0.01.
            noise = 0.01*randn*dt;
            dBias = struct('Bias',noise);
        end
        function dBiasdx = stateTransitonJacobian(~,filter,~,~)
            % Since the stateTransiton function does not depend on the
            % state of the filter, the Jacobian is all zero.
            N = numel(filter.State);
            dBiasdx = zeros(1,N);
        end
    end
end
```

## Version History

**Introduced in R2022a**

### See Also

insEKF | insOptions

# measurement

**Package:** `positioning`

Sensor measurement from states

## Syntax

```
z = measurement(sensor,filter)
```

## Description

`z = measurement(sensor,filter)` returns the measurement `z` from the state maintained in the filter object. You must implement this method when you define a sensor object based on the `positioning.INSSensorModel` abstract class.

## Examples

### Customize Sensor Model Used with `insEKF`

Customize a sensor model used with the `insEKF` object. The sensor measures the velocity state, including a bias affected by random noise.

Customize the sensor model by inheriting from the `positioning.INSSensorModel` interface class and implementing its methods. Note that only the `measurement` method is required for implementation in the `positioning.INSSensorModel` interface class. These sections provide an overview of how the `BiasSensor` class implements the `positioning.INSSensorModel` methods, but for details on their implementation, see the details of the implementation are in the attached `BiasSensor.m` file.

#### Implement `sensorStates` method

To model bias, the `sensorStates` method needs to return a state, `Bias`, as a structure. When you add a `BiasSensor` object to an `insEKF` filter object, the filter adds the bias component to the state vector of the filter.

#### Implement `measurement` method

The measurement is the velocity component of the filter state, including the bias. Therefore, return the summation of the velocity component from the filter and the bias.

#### Implement `measurementJacobian` method

The `measurementJacobian` method returns the partial derivative of the `measurement` method with respect to the state vector of the filter as a structure. All the partial derivatives are `0`, except the partial derivatives of the measurement with respect to the velocity and bias state components.

#### Implement `stateTransition` method

The `stateTransiton` method returns the derivative of the sensor state defined in the `sensorStates` method. Assume the derivative of the bias is affected by a white noise with a

standard deviation of `0.01`. Return the derivative as a structure. Note that this only showcases how to set up the method, and does not correspond to any practical application.

#### Implement `stateTransitionJacobian` method

Since the `stateTransiton` function does not depend on the state of the filter, the Jacobian matrix is 0.

#### Create and add inherited object

Create a `BiasSensor` object.

```
biSensor = BiasSensor
```

```
biSensor = 
  BiasSensor with no properties.
```

Create an `insEKF` object with the `biSensor` object.

```
filter = insEKF(biSensor,insMotionPose)
```

```
filter = 
  insEKF with properties:

                    State: [17x1 double]
          StateCovariance: [17x17 double]
    AdditiveProcessNoise: [17x17 double]
              MotionModel: [1x1 insMotionPose]
                  Sensors: {[1x1 BiasSensor]}
              SensorNames: {'BiasSensor'}
           ReferenceFrame: 'NED'
```

The filter state contains the bias component.

```
stateinfo(filter)
```

```
ans = struct with fields:
        Orientation: [1 2 3 4]
    AngularVelocity: [5 6 7]
           Position: [8 9 10]
           Velocity: [11 12 13]
       Acceleration: [14 15 16]
    BiasSensor_Bias: 17
```

#### Show customized `BiasSensor` class

```
type BiasSensor.m
```

```
classdef BiasSensor < positioning.INSSensorModel
%BIASSENSOR Sensor measuring velocity with bias

%   Copyright 2021 The MathWorks, Inc.

    methods
        function s = sensorstates(~,~)
            % Assume the sensor has a bias. Define a Bias state to enable
```

```
            % the filter to estimate the bias.
            s = struct('Bias',0);
        end
        function z = measurement(sensor,filter)
            % Measurement is the summation of the velocity measurement and
            % the bias.
            velocity = stateparts(filter,'Velocity');
            bias = stateparts(filter,sensor,'Bias');
            z = velocity + bias;
        end
        function dzdx = measurementJacobian(sensor,filter)
            % Compute the Jacobian, which is the partial derivative of the
            % measurement (velocity plus bias) with respect to the filter
            % state vector.
            % Obtain the dimension of the filter state.
            N = numel(filter.State);

            % The partial derviative of the Bias with respect to all the
            % states is zero, except the Bias state itself.
            dzdx = zeros(1,N);

            % Obtain the index for the Bias state component in the filter.
            bidx = stateinfo(filter,sensor,'Bias');
            dzdx(:,bidx) = 1;

            % The partial derivative of the Velocity with respect to all the
            % states is zero, except the Velocity state itself.
            vidx = stateinfo(filter,'Velocity');
            dzdx(:,vidx) = 1;
        end
        function dBias = stateTransition(~,~,dt,~)
            % Assume the derivative of the bias is affected by a zero-mean
            % white noise with a standard deviation of 0.01.
            noise = 0.01*randn*dt;
            dBias = struct('Bias',noise);
        end
        function dBiasdx = stateTransitonJacobian(~,filter,~,~)
            % Since the stateTransiton function does not depend on the
            % state of the filter, the Jacobian is all zero.
            N = numel(filter.State);
            dBiasdx = zeros(1,N);
        end
    end
end
```

## Input Arguments

**`sensor` — Sensor model used with INS filter**
object inherited from `positioning.INSSensorModel` class

Sensor model used with an INS filter, specified as an object inherited from the `positioning.INSSensorModel` abstract class.

**`filter` — INS filter**
`insEKF` object

INS filter, specified as an `insEKF` object.

## Output Arguments

**z — Measurement**
*M*-by-1 real-valued vector

Measurement, returned as an *M*-by-1 real-valued vector.

# Version History

**Introduced in R2022a**

## See Also

`measurementJacobian` | `sensorStates` | `stateTransition` | `stateTransitionJacobian`

# measurementJacobian

**Package:** `positioning`

Jacobian of measurement function

## Syntax

`jac = measurementJacobian(sensor,filter)`

## Description

`jac = measurementJacobian(sensor,filter)` returns the Jacobian matrix for the measurement function of the `sensor` object, inherited from the `positioning.INSSensorModel` abstract class.

---

**Note** Implementing this method is optional for a subclass of the `positioning.INSSensorModel` abstract class. If you do not implement this method, the subclass uses a Jacobian matrix calculated by numerical differentiation.

---

## Examples

### Customize Sensor Model Used with `insEKF`

Customize a sensor model used with the `insEKF` object. The sensor measures the velocity state, including a bias affected by random noise.

Customize the sensor model by inheriting from the `positioning.INSSensorModel` interface class and implementing its methods. Note that only the `measurement` method is required for implementation in the `positioning.INSSensorModel` interface class. These sections provide an overview of how the `BiasSensor` class implements the `positioning.INSSensorModel` methods, but for details on their implementation, see the details of the implementation are in the attached `BiasSensor.m` file.

#### Implement `sensorStates` method

To model bias, the `sensorStates` method needs to return a state, `Bias`, as a structure. When you add a `BiasSensor` object to an `insEKF` filter object, the filter adds the bias component to the state vector of the filter.

#### Implement `measurement` method

The measurement is the velocity component of the filter state, including the bias. Therefore, return the summation of the velocity component from the filter and the bias.

#### Implement `measurementJacobian` method

The `measurementJacobian` method returns the partial derivative of the `measurement` method with respect to the state vector of the filter as a structure. All the partial derivatives are `0`, except the partial derivatives of the measurement with respect to the velocity and bias state components.

#### Implement `stateTransition` method

The `stateTransiton` method returns the derivative of the sensor state defined in the `sensorStates` method. Assume the derivative of the bias is affected by a white noise with a standard deviation of `0.01`. Return the derivative as a structure. Note that this only showcases how to set up the method, and does not correspond to any practical application.

#### Implement `stateTransitionJacobian` method

Since the `stateTransiton` function does not depend on the state of the filter, the Jacobian matrix is 0.

#### Create and add inherited object

Create a `BiasSensor` object.

```
biSensor = BiasSensor
```

```
biSensor = 
  BiasSensor with no properties.
```

Create an `insEKF` object with the `biSensor` object.

```
filter = insEKF(biSensor,insMotionPose)
```

```
filter = 
  insEKF with properties:

                   State: [17x1 double]
         StateCovariance: [17x17 double]
    AdditiveProcessNoise: [17x17 double]
             MotionModel: [1x1 insMotionPose]
                 Sensors: {[1x1 BiasSensor]}
             SensorNames: {'BiasSensor'}
          ReferenceFrame: 'NED'
```

The filter state contains the bias component.

```
stateinfo(filter)
```

```
ans = struct with fields:
        Orientation: [1 2 3 4]
    AngularVelocity: [5 6 7]
           Position: [8 9 10]
           Velocity: [11 12 13]
       Acceleration: [14 15 16]
    BiasSensor_Bias: 17
```

### Show customized BiasSensor class

```
type BiasSensor.m
```

```
classdef BiasSensor < positioning.INSSensorModel
%BIASSENSOR Sensor measuring velocity with bias

%   Copyright 2021 The MathWorks, Inc.

    methods
        function s = sensorstates(~,~)
            % Assume the sensor has a bias. Define a Bias state to enable
            % the filter to estimate the bias.
            s = struct('Bias',0);
        end
        function z = measurement(sensor,filter)
            % Measurement is the summation of the velocity measurement and
            % the bias.
            velocity = stateparts(filter,'Velocity');
            bias = stateparts(filter,sensor,'Bias');
            z = velocity + bias;
        end
        function dzdx = measurementJacobian(sensor,filter)
            % Compute the Jacobian, which is the partial derivative of the
            % measurement (velocity plus bias) with respect to the filter
            % state vector.
            % Obtain the dimension of the filter state.
            N = numel(filter.State);

            % The partial derviative of the Bias with respect to all the
            % states is zero, except the Bias state itself.
            dzdx = zeros(1,N);

            % Obtain the index for the Bias state component in the filter.
            bidx = stateinfo(filter,sensor,'Bias');
            dzdx(:,bidx) = 1;

            % The partial derivative of the Velocity with respect to all the
            % states is zero, except the Velocity state itself.
            vidx = stateinfo(filter,'Velocity');
            dzdx(:,vidx) = 1;
        end
        function dBias = stateTransition(~,~,dt,~)
            % Assume the derivative of the bias is affected by a zero-mean
            % white noise with a standard deviation of 0.01.
            noise = 0.01*randn*dt;
            dBias = struct('Bias',noise);
        end
        function dBiasdx = stateTransitonJacobian(~,filter,~,~)
            % Since the stateTransiton function does not depend on the
            % state of the filter, the Jacobian is all zero.
            N = numel(filter.State);
            dBiasdx = zeros(1,N);
        end
```

```
    end
end
```

## Input Arguments

**`sensor` — Sensor model used with INS filter**
object inherited from `positioning.INSSensorModel` class

Sensor model used with an INS filter, specified as an object inherited from the `positioning.INSSensorModel` abstract class.

**`filter` — INS filter**
`insEKF` object

INS filter, specified as an `insEKF` object.

## Output Arguments

**`jac` — Jacobian matrix for measurement equation**
*M*-by-*N* real-valued matrix

Jacobian matrix for the measurement equation, returned as an *M*-by-*N* real-valued matrix. *M* is the dimension of the sensor measurement, and *N* is the dimension of the state maintained in the `State` property of the `filter`.

# Version History

**Introduced in R2022a**

## See Also

`measurement` | `sensorStates` | `stateTransition` | `stateTransitionJacobian`

# sensorStates

**Package:** `positioning`

Sensor states

## Syntax

```
s = sensorStates(filter,options)
```

## Description

`s = sensorStates(filter,options)` returns a structure that describes the states used by the sensor model and tracked by the `insEKF` filter object.

---

**Tip** Implement this method only if you want to estimate sensor-specific states, such as biases, using the filter.

---

## Examples

### Customize Sensor Model Used with `insEKF`

Customize a sensor model used with the `insEKF` object. The sensor measures the velocity state, including a bias affected by random noise.

Customize the sensor model by inheriting from the `positioning.INSSensorModel` interface class and implementing its methods. Note that only the `measurement` method is required for implementation in the `positioning.INSSensorModel` interface class. These sections provide an overview of how the `BiasSensor` class implements the `positioning.INSSensorModel` methods, but for details on their implementation, see the details of the implementation are in the attached `BiasSensor.m` file.

#### Implement `sensorStates` method

To model bias, the `sensorStates` method needs to return a state, `Bias`, as a structure. When you add a `BiasSensor` object to an `insEKF` filter object, the filter adds the bias component to the state vector of the filter.

#### Implement `measurement` method

The measurement is the velocity component of the filter state, including the bias. Therefore, return the summation of the velocity component from the filter and the bias.

#### Implement `measurementJacobian` method

The `measurementJacobian` method returns the partial derivative of the `measurement` method with respect to the state vector of the filter as a structure. All the partial derivatives are `0`, except the partial derivatives of the measurement with respect to the velocity and bias state components.

#### Implement `stateTransition` method

The `stateTransiton` method returns the derivative of the sensor state defined in the `sensorStates` method. Assume the derivative of the bias is affected by a white noise with a standard deviation of `0.01`. Return the derivative as a structure. Note that this only showcases how to set up the method, and does not correspond to any practical application.

#### Implement `stateTransitionJacobian` method

Since the `stateTransiton` function does not depend on the state of the filter, the Jacobian matrix is 0.

#### Create and add inherited object

Create a `BiasSensor` object.

```
biSensor = BiasSensor
```

```
biSensor = 
  BiasSensor with no properties.
```

Create an `insEKF` object with the `biSensor` object.

```
filter = insEKF(biSensor,insMotionPose)
```

```
filter = 
  insEKF with properties:

                   State: [17x1 double]
         StateCovariance: [17x17 double]
    AdditiveProcessNoise: [17x17 double]
             MotionModel: [1x1 insMotionPose]
                 Sensors: {[1x1 BiasSensor]}
             SensorNames: {'BiasSensor'}
          ReferenceFrame: 'NED'
```

The filter state contains the bias component.

```
stateinfo(filter)
```

```
ans = struct with fields:
        Orientation: [1 2 3 4]
    AngularVelocity: [5 6 7]
           Position: [8 9 10]
           Velocity: [11 12 13]
       Acceleration: [14 15 16]
    BiasSensor_Bias: 17
```

#### Show customized `BiasSensor` class

```
type BiasSensor.m
```

```
classdef BiasSensor < positioning.INSSensorModel
%BIASSENSOR Sensor measuring velocity with bias

%   Copyright 2021 The MathWorks, Inc.
```

```
    methods
        function s = sensorstates(~,~)
            % Assume the sensor has a bias. Define a Bias state to enable
            % the filter to estimate the bias.
            s = struct('Bias',0);
        end
        function z = measurement(sensor,filter)
            % Measurement is the summation of the velocity measurement and
            % the bias.
            velocity = stateparts(filter,'Velocity');
            bias = stateparts(filter,sensor,'Bias');
            z = velocity + bias;
        end
        function dzdx = measurementJacobian(sensor,filter)
            % Compute the Jacobian, which is the partial derivative of the
            % measurement (velocity plus bias) with respect to the filter
            % state vector.
            % Obtain the dimension of the filter state.
            N = numel(filter.State);

            % The partial derviative of the Bias with respect to all the
            % states is zero, except the Bias state itself.
            dzdx = zeros(1,N);

            % Obtain the index for the Bias state component in the filter.
            bidx = stateinfo(filter,sensor,'Bias');
            dzdx(:,bidx) = 1;

            % The partial derivative of the Velocity with respect to all the
            % states is zero, except the Velocity state itself.
            vidx = stateinfo(filter,'Velocity');
            dzdx(:,vidx) = 1;
        end
        function dBias = stateTransition(~,~,dt,~)
            % Assume the derivative of the bias is affected by a zero-mean
            % white noise with a standard deviation of 0.01.
            noise = 0.01*randn*dt;
            dBias = struct('Bias',noise);
        end
        function dBiasdx = stateTransitonJacobian(~,filter,~,~)
            % Since the stateTransiton function does not depend on the
            % state of the filter, the Jacobian is all zero.
            N = numel(filter.State);
            dBiasdx = zeros(1,N);
        end
    end
end
```

## Input Arguments

**`filter` — INS filter**
`insEKF` object

INS filter, specified as an `insEKF` object.

**`options` — Options for INS filter**
`insOptions` object

Options for the INS filter, specified as an `insOptions` object.

### Output Arguments

**`s` — State structure**
structure

State structure, returned as a structure. The field names of the structure are the names of the states that you want estimate. The filter uses the value of each field as the default value of the corresponding state component, and uses the size of the value as the size of the corresponding state component.

**Tip** You can use the `stateparts` object function of the `insEKF` filter object to access the states saved in the filter.

## Version History

**Introduced in R2022a**

### See Also

`measurement` | `measurementJacobian` | `stateTransition` | `stateTransitionJacobian`

# stateTransition

**Package:** `positioning`

State transition of sensor states

## Syntax

```
statedot = stateTransition(sensor,filter,dt,varargin)
```

## Description

`statedot = stateTransition(sensor,filter,dt,varargin)` returns the derivatives of the states of the sensor used in the INS filter.

---

**Tip** You only need to implement this method for the sensor object inherited from the `positioning.INSSensorModel` abstract class if you both of these two conditions are true:

- You have implemented the `sensorStates` method of the `sensor`.
- The states of the sensor are time-varying.

---

## Examples

### Customize Sensor Model Used with `insEKF`

Customize a sensor model used with the `insEKF` object. The sensor measures the velocity state, including a bias affected by random noise.

Customize the sensor model by inheriting from the `positioning.INSSensorModel` interface class and implementing its methods. Note that only the `measurement` method is required for implementation in the `positioning.INSSensorModel` interface class. These sections provide an overview of how the `BiasSensor` class implements the `positioning.INSSensorModel` methods, but for details on their implementation, see the details of the implementation are in the attached `BiasSensor.m` file.

#### Implement `sensorStates` method

To model bias, the `sensorStates` method needs to return a state, `Bias`, as a structure. When you add a `BiasSensor` object to an `insEKF` filter object, the filter adds the bias component to the state vector of the filter.

#### Implement `measurement` method

The measurement is the velocity component of the filter state, including the bias. Therefore, return the summation of the velocity component from the filter and the bias.

#### Implement `measurementJacobian` method

The `measurementJacobian` method returns the partial derivative of the `measurement` method with respect to the state vector of the filter as a structure. All the partial derivatives are `0`, except the partial derivatives of the measurement with respect to the velocity and bias state components.

#### Implement `stateTransition` method

The `stateTransiton` method returns the derivative of the sensor state defined in the `sensorStates` method. Assume the derivative of the bias is affected by a white noise with a standard deviation of `0.01`. Return the derivative as a structure. Note that this only showcases how to set up the method, and does not correspond to any practical application.

#### Implement `stateTransitionJacobian` method

Since the `stateTransiton` function does not depend on the state of the filter, the Jacobian matrix is 0.

#### Create and add inherited object

Create a `BiasSensor` object.

```
biSensor = BiasSensor
```

```
biSensor = 
  BiasSensor with no properties.
```

Create an `insEKF` object with the `biSensor` object.

```
filter = insEKF(biSensor,insMotionPose)
```

```
filter = 
  insEKF with properties:

                   State: [17x1 double]
         StateCovariance: [17x17 double]
    AdditiveProcessNoise: [17x17 double]
             MotionModel: [1x1 insMotionPose]
                 Sensors: {[1x1 BiasSensor]}
             SensorNames: {'BiasSensor'}
          ReferenceFrame: 'NED'
```

The filter state contains the bias component.

```
stateinfo(filter)
```

```
ans = struct with fields:
        Orientation: [1 2 3 4]
    AngularVelocity: [5 6 7]
           Position: [8 9 10]
           Velocity: [11 12 13]
       Acceleration: [14 15 16]
    BiasSensor_Bias: 17
```

**Show customized BiasSensor class**

```
type BiasSensor.m
```

```
classdef BiasSensor < positioning.INSSensorModel
%BIASSENSOR Sensor measuring velocity with bias

%   Copyright 2021 The MathWorks, Inc.

    methods
        function s = sensorstates(~,~)
            % Assume the sensor has a bias. Define a Bias state to enable
            % the filter to estimate the bias.
            s = struct('Bias',0);
        end
        function z = measurement(sensor,filter)
            % Measurement is the summation of the velocity measurement and
            % the bias.
            velocity = stateparts(filter,'Velocity');
            bias = stateparts(filter,sensor,'Bias');
            z = velocity + bias;
        end
        function dzdx = measurementJacobian(sensor,filter)
            % Compute the Jacobian, which is the partial derivative of the
            % measurement (velocity plus bias) with respect to the filter
            % state vector.
            % Obtain the dimension of the filter state.
            N = numel(filter.State);

            % The partial derviative of the Bias with respect to all the
            % states is zero, except the Bias state itself.
            dzdx = zeros(1,N);

            % Obtain the index for the Bias state component in the filter.
            bidx = stateinfo(filter,sensor,'Bias');
            dzdx(:,bidx) = 1;

            % The partial derivative of the Velocity with respect to all the
            % states is zero, except the Velocity state itself.
            vidx = stateinfo(filter,'Velocity');
            dzdx(:,vidx) = 1;
        end
        function dBias = stateTransition(~,~,dt,~)
            % Assume the derivative of the bias is affected by a zero-mean
            % white noise with a standard deviation of 0.01.
            noise = 0.01*randn*dt;
            dBias = struct('Bias',noise);
        end
        function dBiasdx = stateTransitonJacobian(~,filter,~,~)
            % Since the stateTransiton function does not depend on the
            % state of the filter, the Jacobian is all zero.
            N = numel(filter.State);
            dBiasdx = zeros(1,N);
        end
```

```
    end
end
```

## Input Arguments

**`sensor` — Sensor model used with INS filter**
object inherited from `positioning.INSSensorModel` class

Sensor model used with an INS filter, specified as an object inherited from the `positioning.INSSensorModel` abstract class.

**`filter` — INS filter**
`insEKF` object

INS filter, specified as an `insEKF` object.

**`dt` — Filter time step**
positive scalar

Filter time step, specified as a positive scalar.

Data Types: `single` | `double`

**`varargin` — Additional inputs**
any data type

Additional inputs that are passed as the `varargin` inputs of the `predict` object function of the `insEKF` object.

## Output Arguments

**`statedot` — Derivatives of sensor states**
structure

Derivatives of the sensor states, returned as a structure. The field names must be exactly the same as those of the `sensorStates` method of `sensor`. The field values are the corresponding time derivatives of the sensor states.

# Version History

**Introduced in R2022a**

## See Also

`measurement` | `measurementJacobian` | `sensorStates` | `stateTransitionJacobian`

# stateTransitionJacobian

**Package:** `positioning`

Jacobian of sensor state transition function

## Syntax

```
jac = stateTransitionJacobian(sensor,filter,dt,varargin)
```

## Description

`jac = stateTransitionJacobian(sensor,filter,dt,varargin)` returns the Jacobian matrix for the state transition function of the `sensor` object inherited from the `positioning.INSSensorModel` abstract class.

**Note** Implementing this method is optional for a subclass of the `positioning.INSSensorModel` abstract class. If you do not implement this method, the subclass uses a Jacobian matrix calculated by numerical differentiation.

## Examples

### Customize Sensor Model Used with `insEKF`

Customize a sensor model used with the `insEKF` object. The sensor measures the velocity state, including a bias affected by random noise.

Customize the sensor model by inheriting from the `positioning.INSSensorModel` interface class and implementing its methods. Note that only the `measurement` method is required for implementation in the `positioning.INSSensorModel` interface class. These sections provide an overview of how the `BiasSensor` class implements the `positioning.INSSensorModel` methods, but for details on their implementation, see the details of the implementation are in the attached `BiasSensor.m` file.

#### Implement `sensorStates` method

To model bias, the `sensorStates` method needs to return a state, `Bias`, as a structure. When you add a `BiasSensor` object to an `insEKF` filter object, the filter adds the bias component to the state vector of the filter.

#### Implement `measurement` method

The measurement is the velocity component of the filter state, including the bias. Therefore, return the summation of the velocity component from the filter and the bias.

#### Implement `measurementJacobian` method

The `measurementJacobian` method returns the partial derivative of the `measurement` method with respect to the state vector of the filter as a structure. All the partial derivatives are `0`, except the partial derivatives of the measurement with respect to the velocity and bias state components.

#### Implement `stateTransition` method

The `stateTransiton` method returns the derivative of the sensor state defined in the `sensorStates` method. Assume the derivative of the bias is affected by a white noise with a standard deviation of `0.01`. Return the derivative as a structure. Note that this only showcases how to set up the method, and does not correspond to any practical application.

#### Implement `stateTransitionJacobian` method

Since the `stateTransiton` function does not depend on the state of the filter, the Jacobian matrix is 0.

#### Create and add inherited object

Create a `BiasSensor` object.

```
biSensor = BiasSensor
```

```
biSensor = 
  BiasSensor with no properties.
```

Create an `insEKF` object with the `biSensor` object.

```
filter = insEKF(biSensor,insMotionPose)
```

```
filter = 
  insEKF with properties:

                   State: [17x1 double]
         StateCovariance: [17x17 double]
    AdditiveProcessNoise: [17x17 double]
             MotionModel: [1x1 insMotionPose]
                 Sensors: {[1x1 BiasSensor]}
             SensorNames: {'BiasSensor'}
          ReferenceFrame: 'NED'
```

The filter state contains the bias component.

```
stateinfo(filter)
```

```
ans = struct with fields:
        Orientation: [1 2 3 4]
    AngularVelocity: [5 6 7]
           Position: [8 9 10]
           Velocity: [11 12 13]
       Acceleration: [14 15 16]
    BiasSensor_Bias: 17
```

**Show customized BiasSensor class**

```
type BiasSensor.m
```

```
classdef BiasSensor < positioning.INSSensorModel
%BIASSENSOR Sensor measuring velocity with bias

%   Copyright 2021 The MathWorks, Inc.

    methods
        function s = sensorstates(~,~)
            % Assume the sensor has a bias. Define a Bias state to enable
            % the filter to estimate the bias.
            s = struct('Bias',0);
        end
        function z = measurement(sensor,filter)
            % Measurement is the summation of the velocity measurement and
            % the bias.
            velocity = stateparts(filter,'Velocity');
            bias = stateparts(filter,sensor,'Bias');
            z = velocity + bias;
        end
        function dzdx = measurementJacobian(sensor,filter)
            % Compute the Jacobian, which is the partial derivative of the
            % measurement (velocity plus bias) with respect to the filter
            % state vector.
            % Obtain the dimension of the filter state.
            N = numel(filter.State);

            % The partial derviative of the Bias with respect to all the
            % states is zero, except the Bias state itself.
            dzdx = zeros(1,N);

            % Obtain the index for the Bias state component in the filter.
            bidx = stateinfo(filter,sensor,'Bias');
            dzdx(:,bidx) = 1;

            % The partial derivative of the Velocity with respect to all the
            % states is zero, except the Velocity state itself.
            vidx = stateinfo(filter,'Velocity');
            dzdx(:,vidx) = 1;
        end
        function dBias = stateTransition(~,~,dt,~)
            % Assume the derivative of the bias is affected by a zero-mean
            % white noise with a standard deviation of 0.01.
            noise = 0.01*randn*dt;
            dBias = struct('Bias',noise);
        end
        function dBiasdx = stateTransitonJacobian(~,filter,~,~)
            % Since the stateTransiton function does not depend on the
            % state of the filter, the Jacobian is all zero.
            N = numel(filter.State);
            dBiasdx = zeros(1,N);
        end
```

```
    end
end
```

## Input Arguments

**`sensor` — Sensor model used with INS filter**
object inherited from `positioning.INSSensorModel` class

Sensor model used with an INS filter, specified as an object inherited from the `positioning.INSSensorModel` abstract class.

**`filter` — INS filter**
`insEKF` object

INS filter, specified as an `insEKF` object.

**`dt` — Filter time step**
positive scalar

Filter time step, specified as a positive scalar.

Data Types: `single` | `double`

**`varargin` — Additional inputs**
any data type

Additional inputs that are passed as the `varargin` inputs of the `predict` object function of the `insEKF` object.

## Output Arguments

**`jac` — Jacobian matrix for state transition equation**
*S*-by-*N* real-valued matrix

Jacobian matrix for the state transition equation, returned as an *NS*-by-*N* real-valued matrix. *S* is the number of fields in the returned structure of the `sensorState` method of sensor, and *N* is the dimension of the state maintained in the `State` property of the `filter`.

# Version History

**Introduced in R2022a**

## See Also

`measurement` | `measurementJacobian` | `sensorStates` | `stateTransition`

# copy

**Package:** `positioning`

Create copy of sensor model

## Syntax

`newSensor = copy(sensor)`

## Description

`newSensor = copy(sensor)` creates a copy of the sensor model.

---

**Note** Implementing this method is optional for a subclass of the `positioning.INSSensorModel` abstract class. You need to implement this method only when both of these conditions are true.

- You need to use the `copy` object function of the `insEKF` object.
- You want to copy at least one non-public property of the implemented sensor model.

---

## Examples

### Implement copy Method of positioning.INSSensorModel

Use the `copy` method to copy a private property, `PrivateProp`.

```
classdef mySensor < positioning.INSSensorModel
    properties (Access = private)
        PrivateProp  % A private property
    end
    % Implement the class as desired.
    methods
        function m = measurement(sensor, filt)
        % ....
        end
    end
    % Add a public copy method to additonally copy the private property.
        function newSensor = copy(obj)
            newSensor = obj;
            newSensor.PrivateProp = obj.PrivateProp;
        end
    end
end
```

## Input Arguments

**`sensor` — Sensor model used with INS filter**
object inherited from `positioning.INSSensorModel` class

Sensor model used with an INS filter, specified as an object inherited from the `positioning.INSSensorModel` abstract class.

### Output Arguments

**`newSensor` — Copy of sensor model**
object inherited from `positioning.INSSensorModel` class

Copy of the sensor model, returned as an object inherited from the `positioning.INSSensorModel` abstract class.

## Version History

**Introduced in R2022b**

3

# Methods

# clone

Create deep clone of `controllerTEB` object

## Syntax

```
controller2 = clone(controller1)
```

## Description

`controller2 = clone(controller1)` creates a deep clone of the `controllerTEB` object `controller1`.

## Examples

### Compute Velocity Commands and Optimal Trajectory for Differential-Drive Robot Using Timed Elastic Band Algorithm

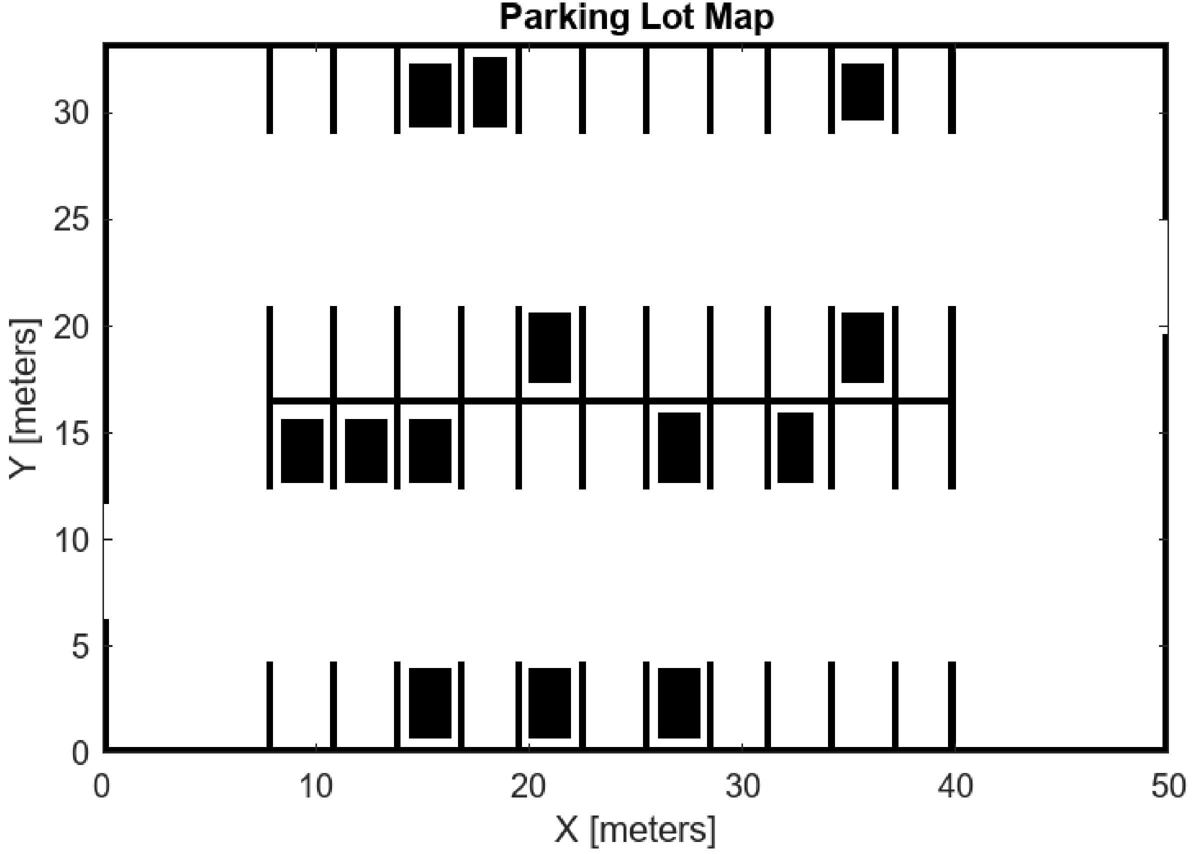
#### Set Up Parking Lot Environment

Create an `occupancyMap` object from a parking lot map and set the map resolution to 3 cells per meter.

```
load parkingMap.mat;
resolution = 3;
map = occupancyMap(map,resolution);
```

Visualize the map. The map contains the floor plan of a parking lot with some parking slots already occupied.

```
show(map)
title("Parking Lot Map")
hold on
```




#### Set Up and Run Global Planner

Create a `validatorOccupancyMap` state validator using the `stateSpaceSE2` definition. Specify the map and the distance for interpolating and validating path segments.

```
validator = validatorOccupancyMap(stateSpaceSE2,Map=map);
validator.ValidationDistance = 0.1;
```

Create an RRT* path planner. Increase the maximum connection distance.

```
rrtstar = plannerRRTStar(validator.StateSpace,validator);
rrtstar.MaxConnectionDistance = 0.2;
```

Set the start and goal states.

```
start = [2 9 0];
goal = [27 18 -pi/2];
```

Plan a path with default settings.

```
rng(42,"twister") % Set random number generator seed for repeatable result.
route = plan(rrtstar,start,goal);
refpath = route.States;
```

RRT* uses a random orientation, which can cause unnecessary turns.

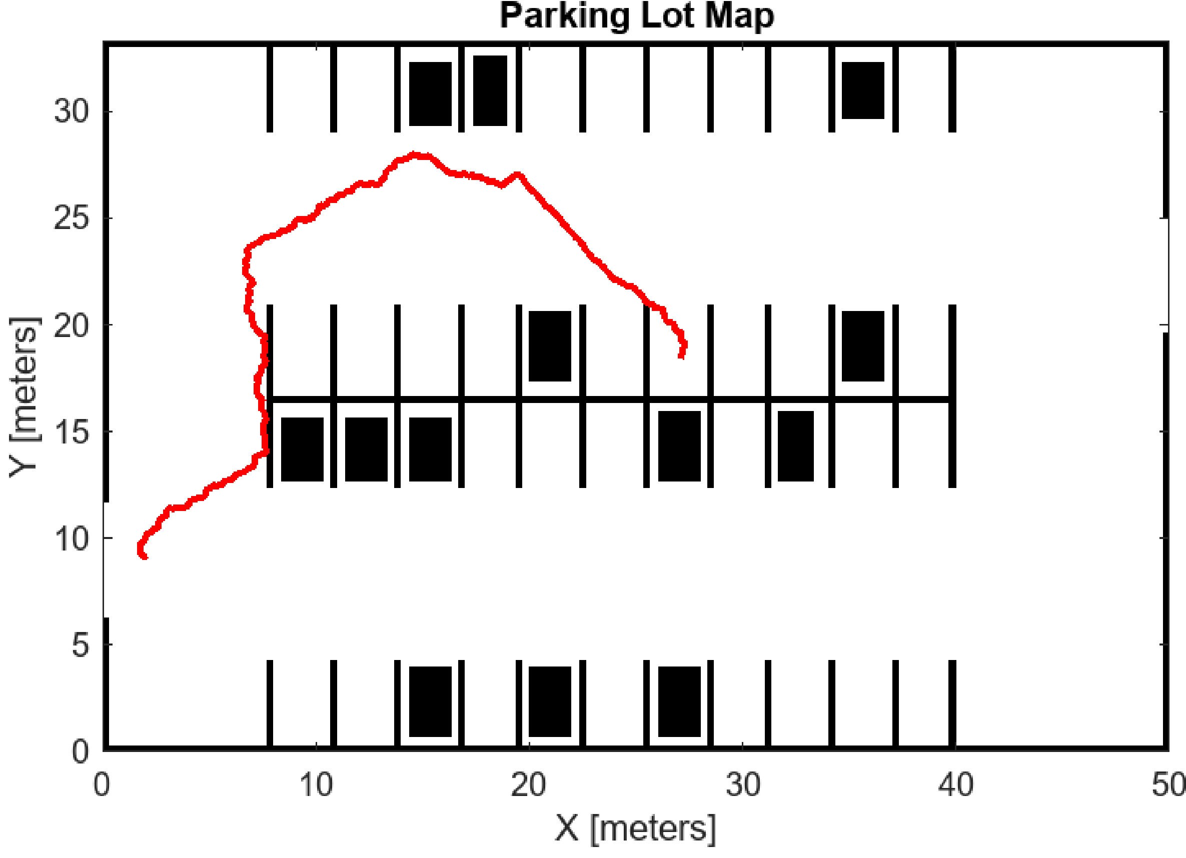
```
headingToNextPose = headingFromXY(refpath(:,1:2));
```

Align the orientation to the path, except for at the start and goal states.

```
refpath(2:end-1,3) = headingToNextPose(2:end-1);
```

Visualize the path.

```
plot(refpath(:,1),refpath(:,2),"r-",LineWidth=2)
hold off
```




#### Set Up and Run Local Planner

Create a local `occupancyMap` object with a width and height of 15 meters and the same resolution as the global map.

```
localmap = occupancyMap(15,15,map.Resolution);
```

Create a `controllerTEB` object by using the reference path generated by the global planner and the local map.

```
teb = controllerTEB(refpath,localmap);
```

Specify the properties of the `controllerTEB` object.

```
teb.LookAheadTime = 10;         % sec
teb.ObstacleSafetyMargin = 0.4; % meters

% To generate time-optimal trajectories, specify a larger weight value,
% like 100, for the cost function, Time. To follow the reference path
% closely, keep the weight to a smaller value like 1e-3.
teb.CostWeights.Time = 100;
```

Create a deep clone of the `controllerTEB` object.

```
teb2 = clone(teb);
```

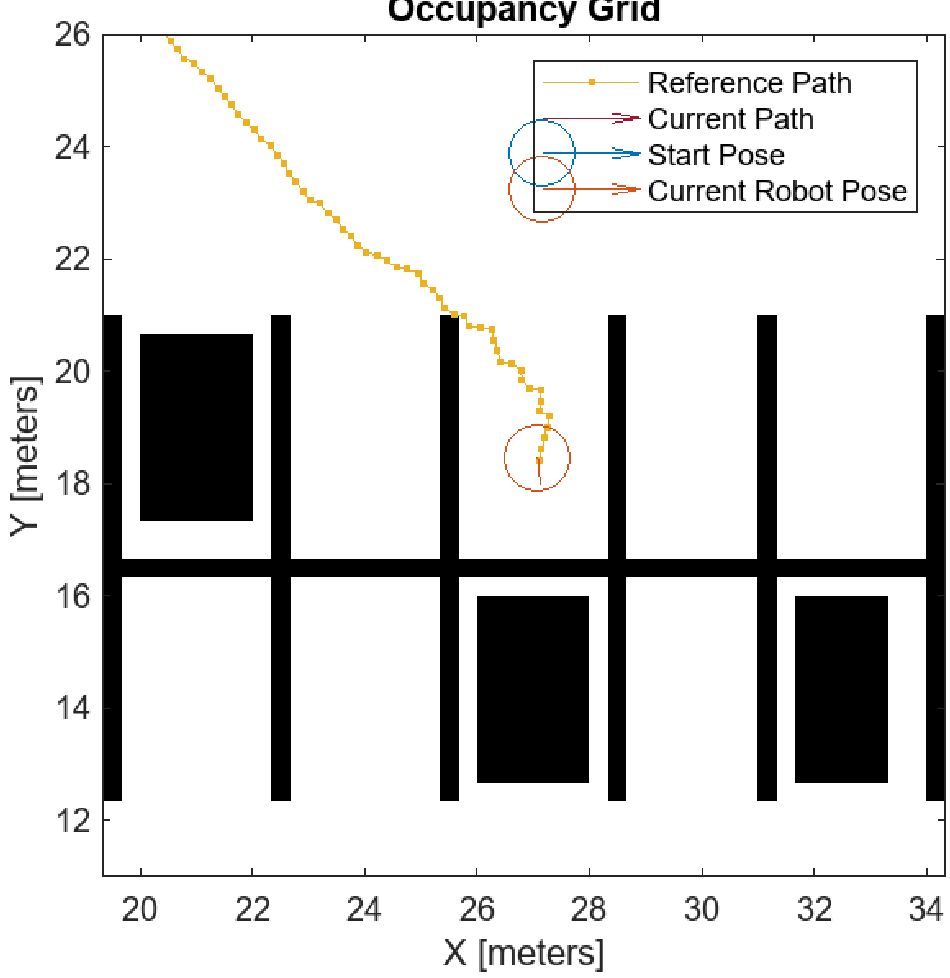
Initialize parameters.

```
curpose = refpath(1,:);
curvel = [0 0];
simtime = 0;
% Reducing timestep can lead to more accurate path tracking.
timestep = 0.1;
itr = 0;
goalReached = false;
```

Compute velocity commands and optimal trajectory.

```
while ~goalReached && simtime < 200
    % Update map to keep robot in the center of the map. Also update the
    % map with new information from the global map or sensor measurements.
    moveMapBy = curpose(1:2) - localmap.XLocalLimits(end)/2;
    localmap.move(moveMapBy,FillValue=0.5)
    syncWith(localmap,map)

    if mod(itr,10) == 0 % every 1 sec
        % Generate new vel commands with teb
        [velcmds,tstamps,curpath,info] = step(teb,curpose,curvel);
        goalReached = info.HasReachedGoal;
        feasibleDriveDuration = tstamps(info.LastFeasibleIdx);
        % If robot is far from goal and only less than third of trajectory
        % is feasible, then an option is to re-plan the path to follow to
        % reach the goal.
        if info.LastFeasibleIdx ~= height(tstamps) && ...
                feasibleDriveDuration < (teb.LookAheadTime/3)
            route = plan(rrtstar,curpose,[27 18 -pi/2]);
            refpath = route.States;
            headingToNextPose = headingFromXY(refpath(:,1:2));
            refpath(2:end-1,3) = headingToNextPose(2:end-1);
            teb.ReferencePath = refpath;
        end
        timestamps = tstamps + simtime;

        % Show the updated information input to or output
```

```
        % from controllerTEB
        clf
        show(localmap)
        hold on
        plot(refpath(:,1),refpath(:,2),".-",Color="#EDB120", ...
             DisplayName="Reference Path")
        quiver(curpath(:,1),curpath(:,2), ...
               cos(curpath(:,3)),sin(curpath(:,3)), ...
               0.2,Color="#A2142F",DisplayName="Current Path")
        quiver(curpose(:,1),curpose(:,2), ...
               cos(curpose(:,3)),sin(curpose(:,3)), ...
               0.5,"o",MarkerSize=20,ShowArrowHead="off", ...
               Color="#0072BD",DisplayName="Start Pose")
    end

    simtime = simtime+timestep;
    % Compute the instantaneous velocity to be sent to the robot from the
    % series of timestamped commands generated by controllerTEB
    velcmd = velocityCommand(velcmds,timestamps,simtime);
    % Very basic robot model, should be replaced by simulator.
    statedot = [velcmd(1)*cos(curpose(3)) ...
                velcmd(1)*sin(curpose(3)) ...
                velcmd(2)];
    curpose = curpose + statedot*timestep;

    if exist("hndl","var")
        delete(hndl)
    end
    hndl = quiver(curpose(:,1),curpose(:,2), ...
                  cos(curpose(:,3)),sin(curpose(:,3)), ...
                  0.5,"o",MarkerSize=20,ShowArrowHead="off", ...
                  Color="#D95319",DisplayName="Current Robot Pose");
    itr = itr + 1;
    drawnow
end
legend
```




## Input Arguments

**controller1 — TEB controller**
controllerTEB object

TEB controller, specified as a `controllerTEB` object.

## Output Arguments

**controller2 — Clone of TEB controller**
controllerTEB object

Clone of TEB controller, returned as a `controllerTEB` object.

# Version History

**Introduced in R2023a**

## See Also

**Objects**
`controllerTEB`

**Functions**
`step`

# step

Compute velocity commands and optimal trajectory for subsequent time steps

## Syntax

```
[velcmds,timestamps,optPath] = step(controller,curState,curVel)
[ ___ ,extraInfo] = step( ___ )
```

## Description

`[velcmds,timestamps,optPath] = step(controller,curState,curVel)` computes the linear and angular velocity commands `velcmds`, with their corresponding `timestamps` and corresponding optimized path `optPath`, for the specified current pose `curState` and current velocity `curVel` of a robot.

`[ ___ ,extraInfo] = step( ___ )` returns extra information, `extraInfo`, to evaluate the solution, in addition to all arguments from the previous syntax.

## Examples

### Compute Velocity Commands and Optimal Trajectory for Differential-Drive Robot Using Timed Elastic Band Algorithm

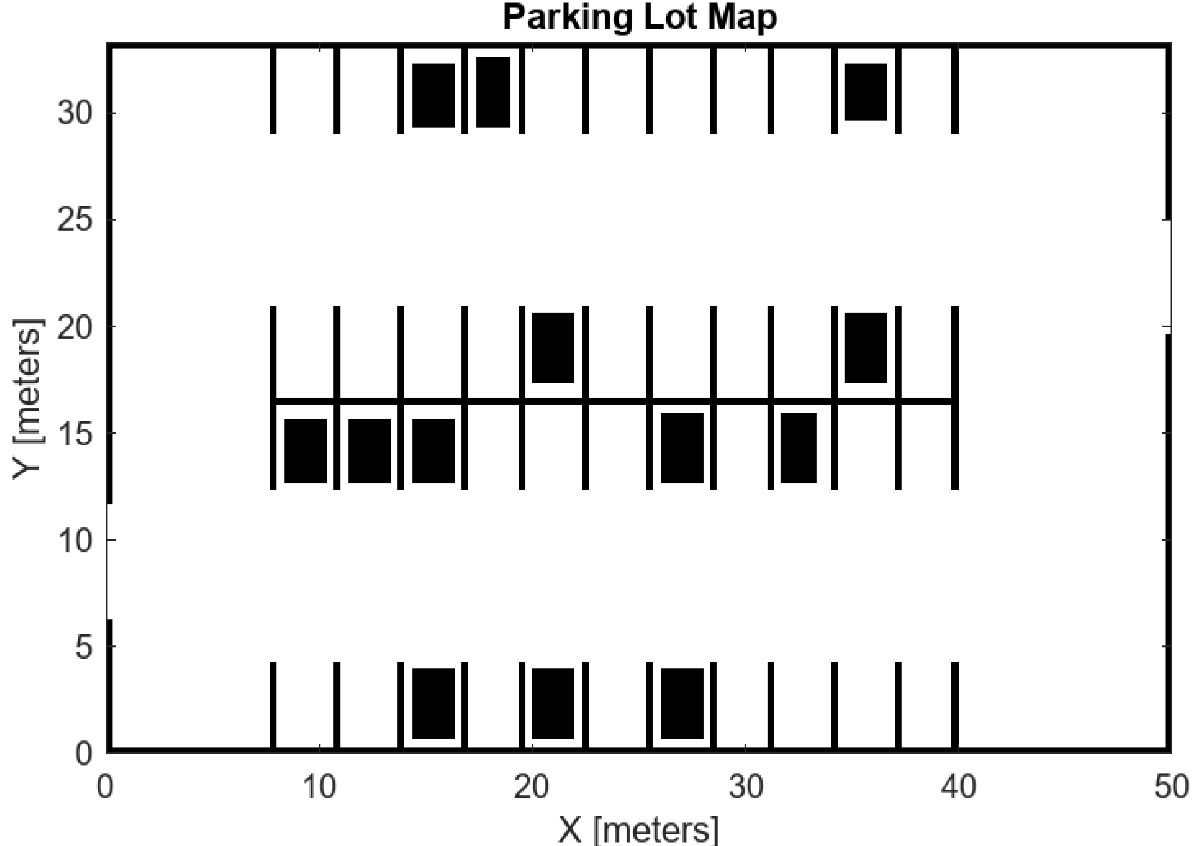
#### Set Up Parking Lot Environment

Create an `occupancyMap` object from a parking lot map and set the map resolution to 3 cells per meter.

```
load parkingMap.mat;
resolution = 3;
map = occupancyMap(map,resolution);
```

Visualize the map. The map contains the floor plan of a parking lot with some parking slots already occupied.

```
show(map)
title("Parking Lot Map")
hold on
```




### Set Up and Run Global Planner

Create a `validatorOccupancyMap` state validator using the `stateSpaceSE2` definition. Specify the map and the distance for interpolating and validating path segments.

```
validator = validatorOccupancyMap(stateSpaceSE2,Map=map);
validator.ValidationDistance = 0.1;
```

Create an RRT* path planner. Increase the maximum connection distance.

```
rrtstar = plannerRRTStar(validator.StateSpace,validator);
rrtstar.MaxConnectionDistance = 0.2;
```

Set the start and goal states.

```
start = [2 9 0];
goal = [27 18 -pi/2];
```

Plan a path with default settings.

```
rng(42,"twister") % Set random number generator seed for repeatable result.
route = plan(rrtstar,start,goal);
refpath = route.States;
```

RRT* uses a random orientation, which can cause unnecessary turns.

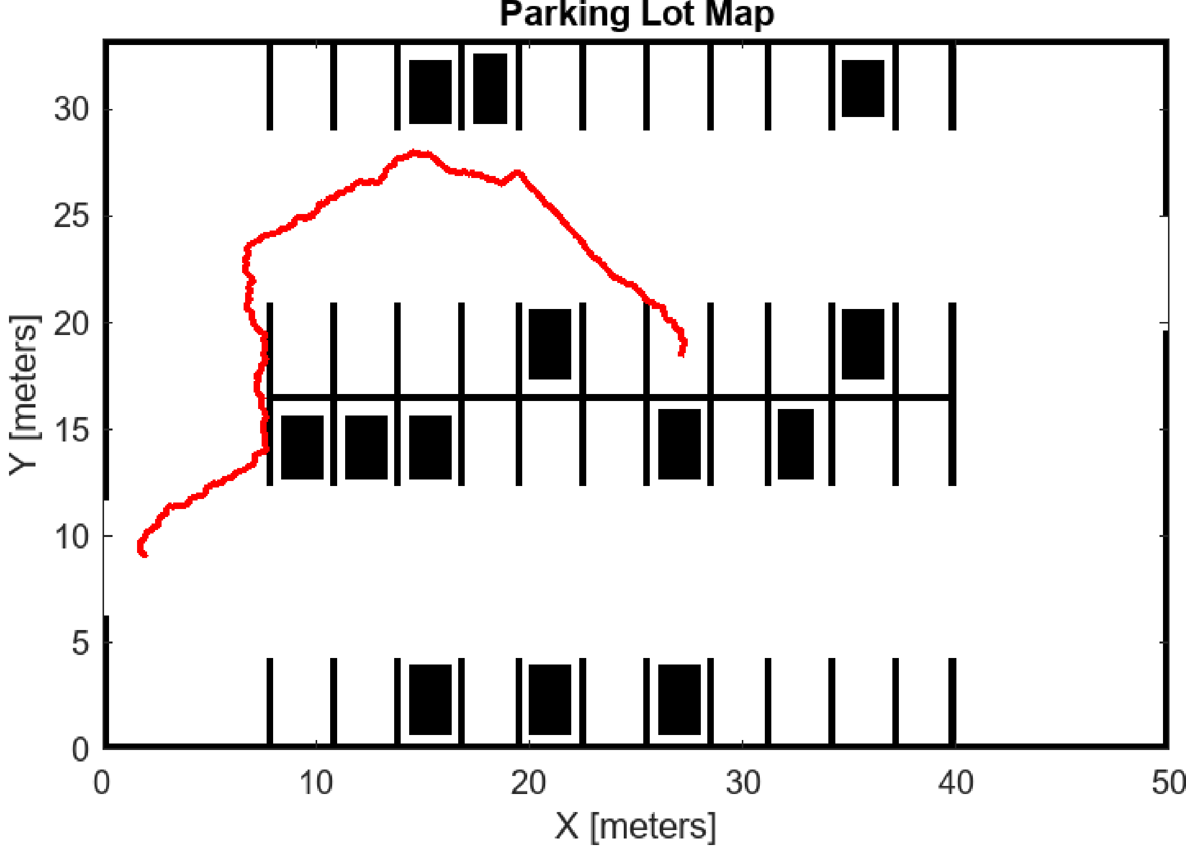
```
headingToNextPose = headingFromXY(refpath(:,1:2));
```

Align the orientation to the path, except for at the start and goal states.

```
refpath(2:end-1,3) = headingToNextPose(2:end-1);
```

Visualize the path.

```
plot(refpath(:,1),refpath(:,2),"r-",LineWidth=2)
hold off
```




**Set Up and Run Local Planner**

Create a local `occupancyMap` object with a width and height of 15 meters and the same resolution as the global map.

```
localmap = occupancyMap(15,15,map.Resolution);
```

Create a `controllerTEB` object by using the reference path generated by the global planner and the local map.

```
teb = controllerTEB(refpath,localmap);
```

Specify the properties of the `controllerTEB` object.

```
teb.LookAheadTime = 10;         % sec
teb.ObstacleSafetyMargin = 0.4; % meters

% To generate time-optimal trajectories, specify a larger weight value,
% like 100, for the cost function, Time. To follow the reference path
% closely, keep the weight to a smaller value like 1e-3.
teb.CostWeights.Time = 100;
```

Create a deep clone of the `controllerTEB` object.

```
teb2 = clone(teb);
```

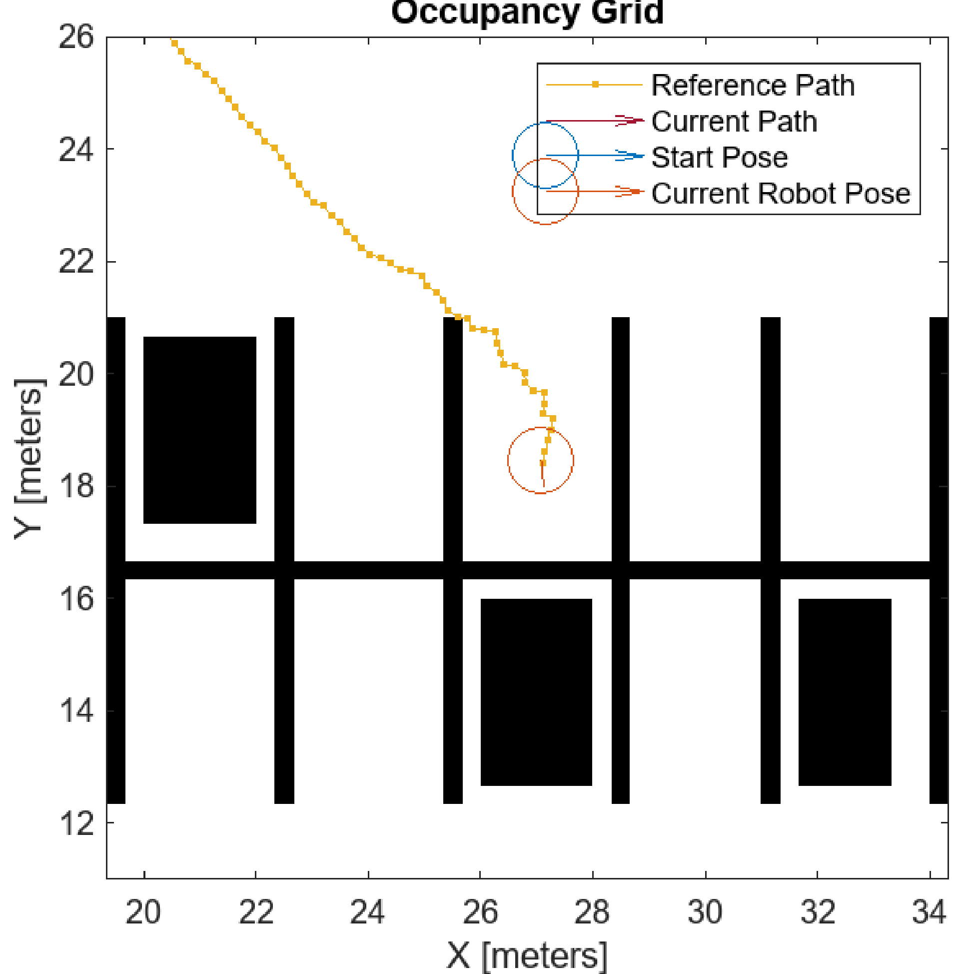
Initialize parameters.

```
curpose = refpath(1,:);
curvel = [0 0];
simtime = 0;
% Reducing timestep can lead to more accurate path tracking.
timestep = 0.1;
itr = 0;
goalReached = false;
```

Compute velocity commands and optimal trajectory.

```
while ~goalReached && simtime < 200
    % Update map to keep robot in the center of the map. Also update the
    % map with new information from the global map or sensor measurements.
    moveMapBy = curpose(1:2) - localmap.XLocalLimits(end)/2;
    localmap.move(moveMapBy,FillValue=0.5)
    syncWith(localmap,map)

    if mod(itr,10) == 0 % every 1 sec
        % Generate new vel commands with teb
        [velcmds,tstamps,curpath,info] = step(teb,curpose,curvel);
        goalReached = info.HasReachedGoal;
        feasibleDriveDuration = tstamps(info.LastFeasibleIdx);
        % If robot is far from goal and only less than third of trajectory
        % is feasible, then an option is to re-plan the path to follow to
        % reach the goal.
        if info.LastFeasibleIdx ~= height(tstamps) && ...
                feasibleDriveDuration < (teb.LookAheadTime/3)
            route = plan(rrtstar,curpose,[27 18 -pi/2]);
            refpath = route.States;
            headingToNextPose = headingFromXY(refpath(:,1:2));
            refpath(2:end-1,3) = headingToNextPose(2:end-1);
            teb.ReferencePath = refpath;
        end
        timestamps = tstamps + simtime;

        % Show the updated information input to or output
```

```
        % from controllerTEB
        clf
        show(localmap)
        hold on
        plot(refpath(:,1),refpath(:,2),".-",Color="#EDB120", ...
             DisplayName="Reference Path")
        quiver(curpath(:,1),curpath(:,2), ...
               cos(curpath(:,3)),sin(curpath(:,3)), ...
               0.2,Color="#A2142F",DisplayName="Current Path")
        quiver(curpose(:,1),curpose(:,2), ...
               cos(curpose(:,3)),sin(curpose(:,3)), ...
               0.5,"o",MarkerSize=20,ShowArrowHead="off", ...
               Color="#0072BD",DisplayName="Start Pose")
    end

    simtime = simtime+timestep;
    % Compute the instantaneous velocity to be sent to the robot from the
    % series of timestamped commands generated by controllerTEB
    velcmd = velocityCommand(velcmds,timestamps,simtime);
    % Very basic robot model, should be replaced by simulator.
    statedot = [velcmd(1)*cos(curpose(3)) ...
                velcmd(1)*sin(curpose(3)) ...
                velcmd(2)];
    curpose = curpose + statedot*timestep;

    if exist("hndl","var")
        delete(hndl)
    end
    hndl = quiver(curpose(:,1),curpose(:,2), ...
                  cos(curpose(:,3)),sin(curpose(:,3)), ...
                  0.5,"o",MarkerSize=20,ShowArrowHead="off", ...
                  Color="#D95319",DisplayName="Current Robot Pose");
    itr = itr + 1;
    drawnow
end
legend
```




## Input Arguments

**`controller` — TEB controller**
`controllerTEB` object

TEB controller, specified as a `controllerTEB` object.

**`curState` — Current pose of robot**
three-element vector of form [*x* *y* *theta*]

Current pose of the robot, specified as a three-element vector of the form [*x* *y* *theta*]. *x* and *y* specify the robot position in meters. *theta* specifies the robot orientation in radians.

Data Types: `single` | `double`

**`curVel` — Current velocity of robot**
two-element vector of form [*v* *w*]

Current velocity of the robot, specified as a two-element vector of the form [*v w*]. *v* specifies the linear velocity of the robot in meters per second. *w* specifies the angular velocity of the robot in radians per second.

Data Types: `single` | `double`

## Output Arguments

**`velcmds` — Velocity commands**
*N*-by-2 matrix

Velocity commands, returned as an *N*-by-2 matrix. The first column is the linear velocity in meters per second, and the second column is the angular velocity in radians per second.

Data Types: `double`

**`timestamps` — Timestamps corresponding to velocity commands**
*N*-element column vector

Timestamps corresponding to velocity commands, returned as an *N*-element column vector.

Data Types: `double`

**`optPath` — Optimized path**
*N*-by-3 matrix

Optimized path, returned as an *N*-by-3 matrix. Each row is of the form [*x y theta*], which defines the *xy*-position and orientation angle *theta* at a point in the path.

*N* is affected by the ReferenceDeltaTime and LookAheadTime properties of `controller`. The algorithm tries to keep the difference between any two consecutive `timestamps` close to `ReferenceDeltaTime`. If the gap between a pair of consecutive timestamps is greater than `ReferenceDeltaTime`, the function adds poses and timestamps to the path. If the gap is less than `ReferenceDeltaTime`, the function removes poses and timestamps from the path. In addition, the algorithm tries to keep the final value of `timestamps` close to `LookAheadTime`, so increasing `LookAheadTime` increases *N* as well.

Data Types: `double`

**`extraInfo` — Extra information**
structure

Extra information, returned as a structure. The fields of the structure are:

| Field | Description |
| --- | --- |
| `LastFeasibleIdx` | The index of the last collision-free pose in the `optPath`. |
| `DistanceFromStartPose` | Distance of each pose in `optPath` from the first pose in `optPath`. The value of `curState` is always the first pose in `optPath`. |

| Field | Description |
|---|---|
| `HasReachedGoal` | Indicates whether the robot has successfully reached the last pose in the ReferencePath within a tolerance, and returns as `true` if successful. Otherwise, this value returns `false`. |
| `TrajectoryCost` | Cost of optimized trajectory for cost functions in the Timed Elastic Band algorithm. |

**Note** If the value of the `LastFeasibleIdx` field is `1`, and the `HasReachedGoal` field is `false`, then no successful set of velocity commands or trajectory has been generated. Generate a new reference path to the goal to continue the robot motion.

Data Types: `struct`

## Version History

**Introduced in R2023a**

### See Also

**Objects**
`controllerTEB`

**Functions**
`clone`

# copy

Create deep copy of navGraph object

## Syntax

```
graph2 = copy(graph1)
```

## Description

`graph2 = copy(graph1)` creates a deep copy of a `navGraph` object.

## Examples

### Create navGraph Object with State and Link Tables

Load data for states and links.

```
load navGraphData.mat
```

Create state and link tables.

```
stateTable = table(data.states,data.names,data.numLanes, ...
    VariableNames=["StateVector","Name","Lanes"]);
linkTable = table(data.links,data.linkWt,data.curvature, ...
    VariableNames=["EndStates","Weight","Curvature"]);
```

Create a `navGraph` object from the state and link tables.

```
graphObj = navGraph(stateTable,linkTable);
```

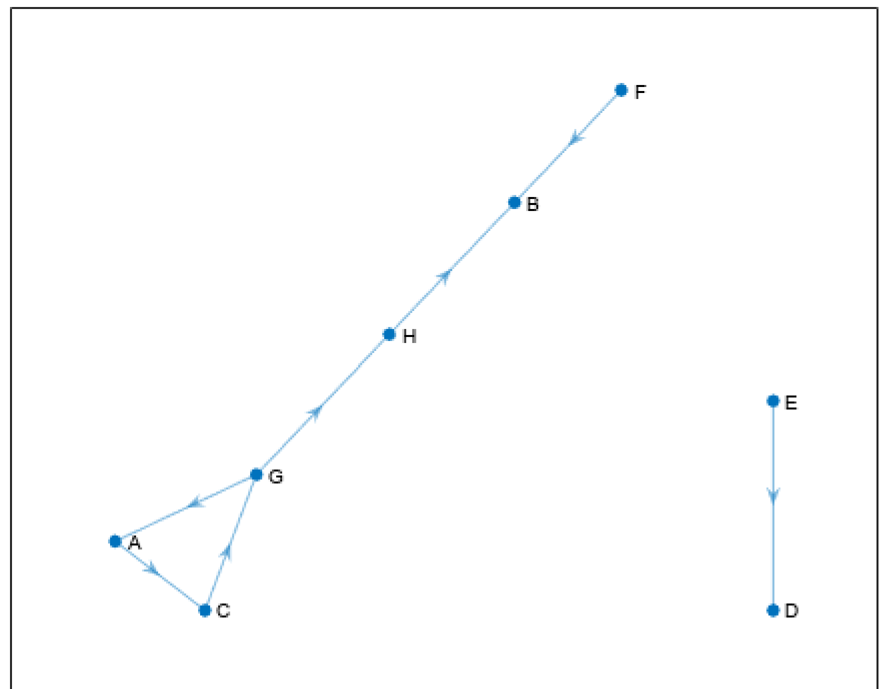
Create a deep copy of the `navGraph` object.

```
graph2 = copy(graphObj)
```

```
graph2 = 
  navGraph with properties:

           States: [8x3 table]
            Links: [7x3 table]
    LinkWeightFcn: @nav.algs.distanceEuclidean
```

Visualize the `navGraph` object.

```
show(graphObj)
```




Find the link IDs of two state pairs. The function returns the link ID for the state pair `["G","A"]`. However, it returns `0` as the link ID for the state pair `["C","D"]` as the link does not exist in the `navGraph` object.

```
linkIDS = findlink(navGraphObj,["G","A"; "C","D"])
```

```
linkIDS = 2×1

     5
     0
```

## Input Arguments

**graph1 — Graph object**
`navGraph` object

Graph object, specified as a `navGraph` object.

Example: `graphcopy = copy(graph)`

## Output Arguments

**graph2 — Copy of graph object**
`navGraph` object

Copy of a graph object, returned as a `navGraph` object.

# Version History

**Introduced in R2023a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
`navGraph`

**Functions**
`findlink` | `findstate` | `index2state` | `state2index` | `successors` | `show`

# findlink

Find IDs of links

## Syntax

```
linkIDS = findlink(graph,statePairs)
```

## Description

`linkIDS = findlink(graph,statePairs)` finds the link IDs `linkIDS` of the state pairs `statePairs`, if they exist in the `navGraph` object `graph`.

## Examples

### Create navGraph Object with State and Link Tables

Load data for states and links.

```
load navGraphData.mat
```

Create state and link tables.

```
stateTable = table(data.states,data.names,data.numLanes, ...
    VariableNames=["StateVector","Name","Lanes"]);
linkTable = table(data.links,data.linkWt,data.curvature, ...
    VariableNames=["EndStates","Weight","Curvature"]);
```

Create a `navGraph` object from the state and link tables.

```
graphObj = navGraph(stateTable,linkTable);
```

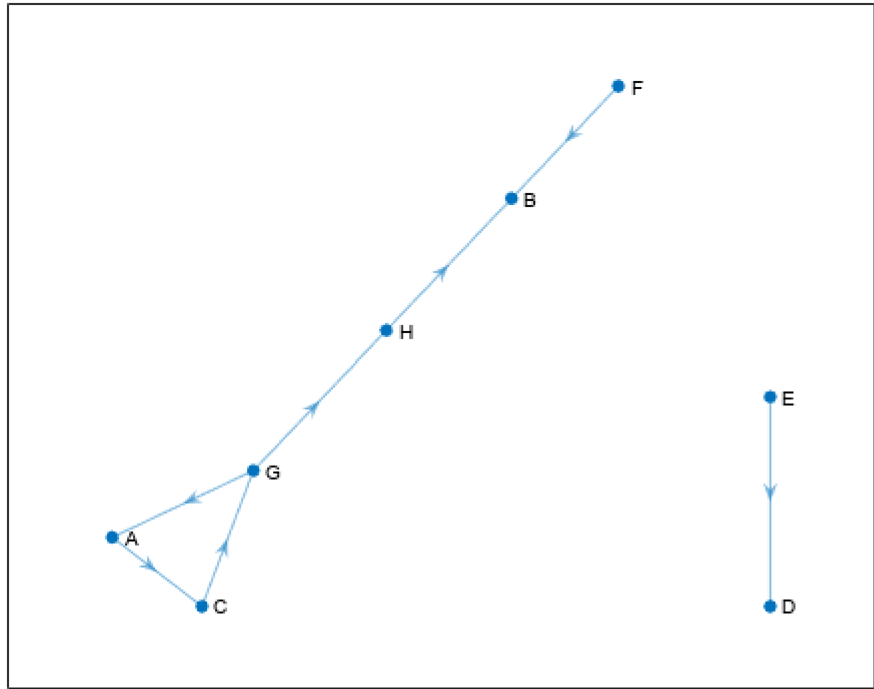
Create a deep copy of the `navGraph` object.

```
graph2 = copy(graphObj)
```

```
graph2 = 
  navGraph with properties:

           States: [8x3 table]
            Links: [7x3 table]
    LinkWeightFcn: @nav.algs.distanceEuclidean
```

Visualize the `navGraph` object.

```
show(graphObj)
```




Find the link IDs of two state pairs. The function returns the link ID for the state pair `["G","A"]`. However, it returns `0` as the link ID for the state pair `["C","D"]` as the link does not exist in the `navGraph` object.

```
linkIDS = findlink(navGraphObj,["G","A"; "C","D"])
```

```
linkIDS = 2×1

     5
     0
```

## Input Arguments

**graph — Graph object**
`navGraph` object

Graph object, specified as a `navGraph` object.

**statePairs — State pairs**
*N*-by-2 string array | *N*-by-2 cell array of character vectors | *N*-by-2 matrix of positive integers

State pairs, specified as pairs of state names or pairs of state IDs.

Specify the pairs of state names as an *N*-by-2 string array or *N*-by-2 cell array of character vectors. Specify the pairs of state IDs as an *N*-by-2 matrix of positive integers. *N* is the number of state pairs specified.

Data Types: `single` | `double` | `cell` | `char` | `string`

## Output Arguments

**`linkIDS` — Link IDs**
column vector of positive integers

Link IDs, returned as a column vector of positive integers. When the function does not find a specified state pair, the value for the corresponding element in `linkIDS` is `0`.

Data Types: `double`

# Version History

**Introduced in R2023a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
`navGraph`

**Functions**
`findstate` | `index2state` | `state2index` | `successors` | `show` | `copy`

# findstate

Find IDs of states

## Syntax

```
stateIDS = findstate(graph,stateData)
```

## Description

`stateIDS = findstate(graph,stateData)` finds the state IDs `stateIDS` of the states specified by `stateData`, if they exist in the `navGraph` object `graph`.

The function returns `stateIDS` when all elements of a row of `stateData` are identical to elements of a row in the States table.

## Examples

### Find Indices of States in navGraph Object

Load `navGraph` data for states and links.

```
load navGraphData.mat
```

Create a table to use to search for the state ID.

```
stateData = table([3 6 0.142170047601527; 1 1 1],["F"; "A"],[2; 2], ...
                  VariableNames={'StateVector','Name','Lanes'});
```

Find the indices of the states.

```
id = findstate(navGraphObj,stateData)
```

```
id = 2×1

     6
     0
```

The `navGraph` states table contains a state corresponding to the first state data, so the function returns its index. However, the states table does not contain a state that corresponds to the second state, so the function returns `0`.

```
navGraphObj.States
```

```
ans=8×3 table
          StateVector             Name      Lanes
    _______________________      _____      _____

    8          2    0.72176      {'A'}        2
    1          1    0.29188      {'B'}        2
    7          7    0.91777      {'C'}        2
```

```
    8         10    0.71458    {'D'}      2
    5          1    0.54254    {'E'}      2
    3          6    0.14217    {'F'}      2
    2          9    0.37334    {'G'}      3
    8          7    0.67413    {'H'}      2
```

```
stateIDS = state2index(navGraphObj,stateData.StateVector)
```

```
stateIDS = 2×1

     6
     0
```

## Input Arguments

**graph — Graph object**
navGraph object

Graph object, specified as a `navGraph` object.

**stateData — State data**
column vector of character vectors | column vector of string scalars | cell array of character vectors | matrix | table

State data, specified as the names of the states, the state vectors, or a states table.

Specify the names of the states as a column vector of character vectors, column vector of string scalars, or cell array of character vectors.

Specify the state vectors as a matrix in which each row represents a state vector. The state vectors must be of the same size as those in the `StateVector` column of the States table.

Specify the states table as a table that the same columns as the States table.

Data Types: `single` | `double` | `cell` | `char` | `string` | `table`

## Output Arguments

**stateIDS — State IDs**
column vector of positive integers

State IDs, returned as a column vector of positive integers. When the function does not find a specified state pair, the value for the corresponding element in `stateIDS` is `0`

Data Types: `double`

# Version History

**Introduced in R2023a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
`navGraph`

**Functions**
`findlink` | `index2state` | `state2index` | `successors` | `show` | `copy`

# index2state

Find state vectors of state indices

## Syntax

```
states = index2state(graph,stateIDS)
```

## Description

`states = index2state(graph,stateIDS)` finds the state vectors `states` for the queried state indices `stateIDS`, if they exist in the `navGraph` object `graph`.

## Examples

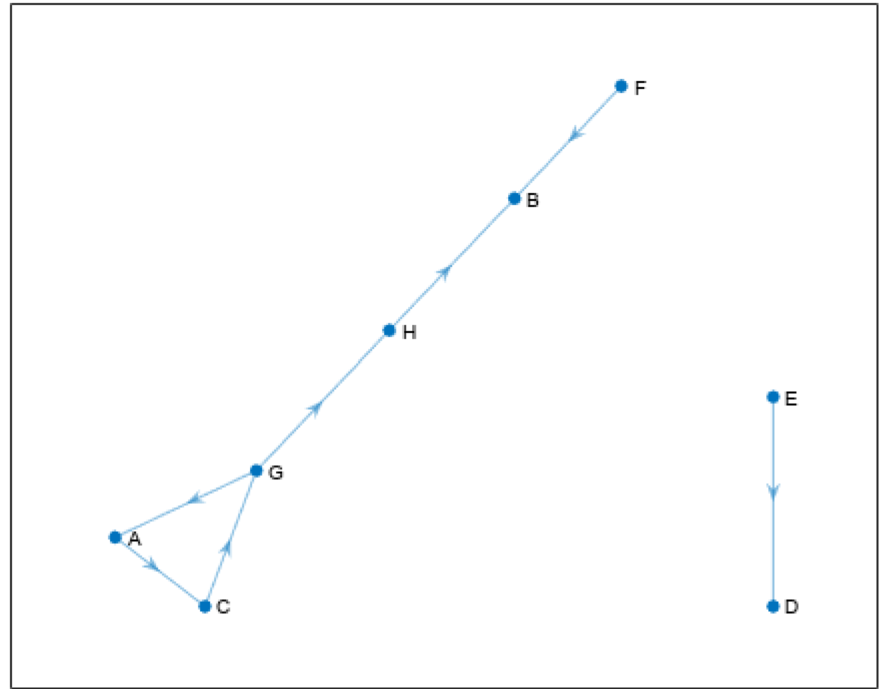
### Find Successive State Indices and Costs in navGraph Object

Load `navGraph` data for states and links.

```
load navGraphData.mat
```

Visualize the `navGraph` object.

```
show(navGraphObj);
```




Find successive state indices and costs based on a state name.

```
[succIDS,costs] = successors(navGraphObj,"G")
```

```
succIDS = 2×1

     1
     8


costs = 2×1

   38.7759
   13.9383
```

Find the state vectors of the successive states.

```
states = index2state(navGraphObj,succIDS)
```

```
states = 2×3

    8.0000    2.0000    0.7218
    8.0000    7.0000    0.6741
```

## Input Arguments

**graph — Graph object**
navGraph object

Graph object, specified as a navGraph object.

**stateIDS — State indices**
column vector of positive integers

State indices, specified as a column vector of positive integers.

Data Types: single | double

## Output Arguments

**states — State vectors**
matrix

State vectors, returned as a matrix in which each row represents a state vector. The state vectors must be of the same size as those in the StateVector column of the States table in the navGraph object graph.

Data Types: double

# Version History

**Introduced in R2023a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
navGraph

**Functions**
findlink | findstate | state2index | successors | show | copy

# show

Plot graph representation

## Syntax

```
show(graph)
show(graph,Parent=ax)
axHandle = show( ___ )
```

## Description

`show(graph)` plots the graph representation.

`show(graph,Parent=ax)` specifies the axes on which to plot the graph representation.

`axHandle = show( ___ )` returns the axes handle of the graph representation plot, in addition to any combination of input arguments from previous syntaxes.

## Examples

### Create navGraph Object with State and Link Tables

Load data for states and links.

```
load navGraphData.mat
```

Create state and link tables.

```
stateTable = table(data.states,data.names,data.numLanes, ...
    VariableNames=["StateVector","Name","Lanes"]);
linkTable = table(data.links,data.linkWt,data.curvature, ...
    VariableNames=["EndStates","Weight","Curvature"]);
```

Create a `navGraph` object from the state and link tables.

```
graphObj = navGraph(stateTable,linkTable);
```

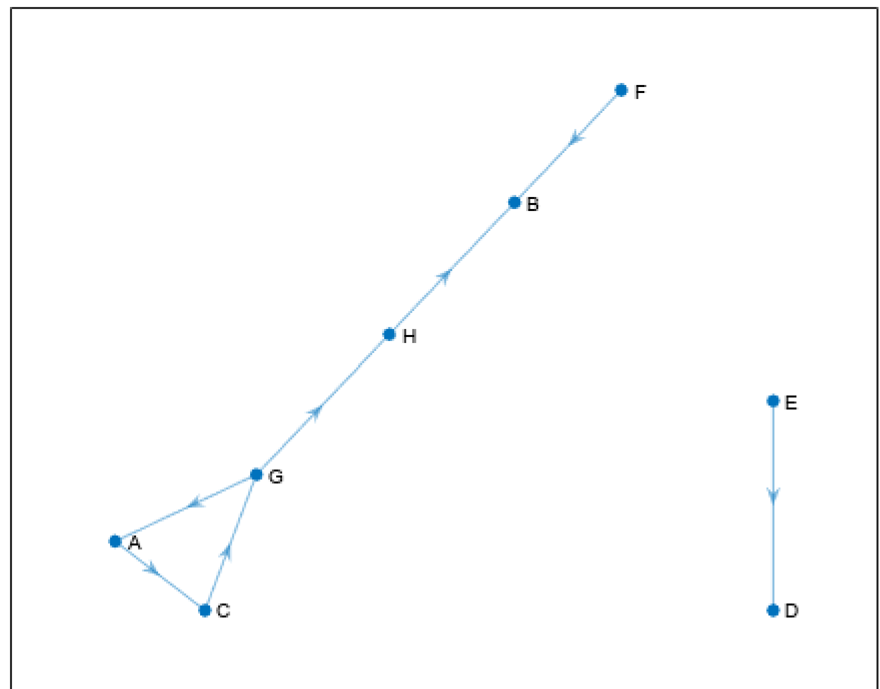
Create a deep copy of the `navGraph` object.

```
graph2 = copy(graphObj)
```

```
graph2 = 
  navGraph with properties:

           States: [8x3 table]
            Links: [7x3 table]
    LinkWeightFcn: @nav.algs.distanceEuclidean
```

Visualize the `navGraph` object.

```
show(graphObj)
```




Find the link IDs of two state pairs. The function returns the link ID for the state pair `["G","A"]`. However, it returns `0` as the link ID for the state pair `["C","D"]` as the link does not exist in the `navGraph` object.

```
linkIDS = findlink(navGraphObj,["G","A"; "C","D"])
```

```
linkIDS = 2×1

     5
     0
```

## Input Arguments

**graph — Graph object**
`navGraph` object

Graph object, specified as a `navGraph` object.

Example: `show(graph)`

Example: `axHandle = show(graph);`

**ax — Axes on which to plot graph representation**
`Axes` object

Axes on which to plot the graph representation, specified as an `Axes` object.

Example: `show(graph,Parent=ax)`

Example: `axHandle = show(graph,Parent=ax);`

## Output Arguments

**`axHandle` — Axes handle of graph representation plot**
`Axes` object

Axes handle of the graph representation plot, returned as an `Axes` object.

# Version History

**Introduced in R2023a**

## See Also

**Objects**
`navGraph`

**Functions**
`findlink` | `findstate` | `index2state` | `state2index` | `successors` | `copy`

# state2index

Find indices for queried state vectors

## Syntax

```
stateIDS = state2index(graph,states)
```

## Description

`stateIDS = state2index(graph,states)` finds the state indices `stateIDS` for the queried state vectors `states`, if they exist in the `navGraph` object `graph`.

## Examples

### Find Indices of States in navGraph Object

Load `navGraph` data for states and links.

```
load navGraphData.mat
```

Create a table to use to search for the state ID.

```
stateData = table([3 6 0.142170047601527; 1 1 1],["F"; "A"],[2; 2], ...
                  VariableNames={'StateVector','Name','Lanes'});
```

Find the indices of the states.

```
id = findstate(navGraphObj,stateData)
```

```
id = 2×1

     6
     0
```

The `navGraph` states table contains a state corresponding to the first state data, so the function returns its index. However, the states table does not contain a state that corresponds to the second state, so the function returns `0`.

```
navGraphObj.States
```

```
ans=8×3 table
          StateVector            Name     Lanes
    _______________________     _____     _____

    8           2    0.72176    {'A'}       2
    1           1    0.29188    {'B'}       2
    7           7    0.91777    {'C'}       2
    8          10    0.71458    {'D'}       2
    5           1    0.54254    {'E'}       2
    3           6    0.14217    {'F'}       2
```

```
    2          9    0.37334    {'G'}      3
    8          7    0.67413    {'H'}      2
```

```
stateIDS = state2index(navGraphObj,stateData.StateVector)
```

```
stateIDS = 2×1

     6
     0
```

## Input Arguments

**graph — Graph object**
navGraph object

Graph object, specified as a navGraph object.

**states — State vectors**
matrix

State vectors, specified as a matrix in which each row represents a state vector. The state vectors must be of the same size as those in the StateVector column of the States table in the navGraph object graph.

Data Types: single | double

## Output Arguments

**stateIDS — State indices**
column vector of positive integers

State indices, returned as a column vector of positive integers. When the function does not find a specified state vector, the value for the corresponding element in stateIDS is 0.

Data Types: double

# Version History

**Introduced in R2023a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
navGraph

**Functions**

findlink | findstate | index2state | successors | show | copy

# successors

Find successive state indices and costs

## Syntax

```
[succIDS,costs] = successors(graph,currID)
```

## Description

`[succIDS,costs] = successors(graph,currID)` finds the state indices `succIDS` and the cost of all states `costs` that are connected to the specified state `currID` using the directed link.

## Examples

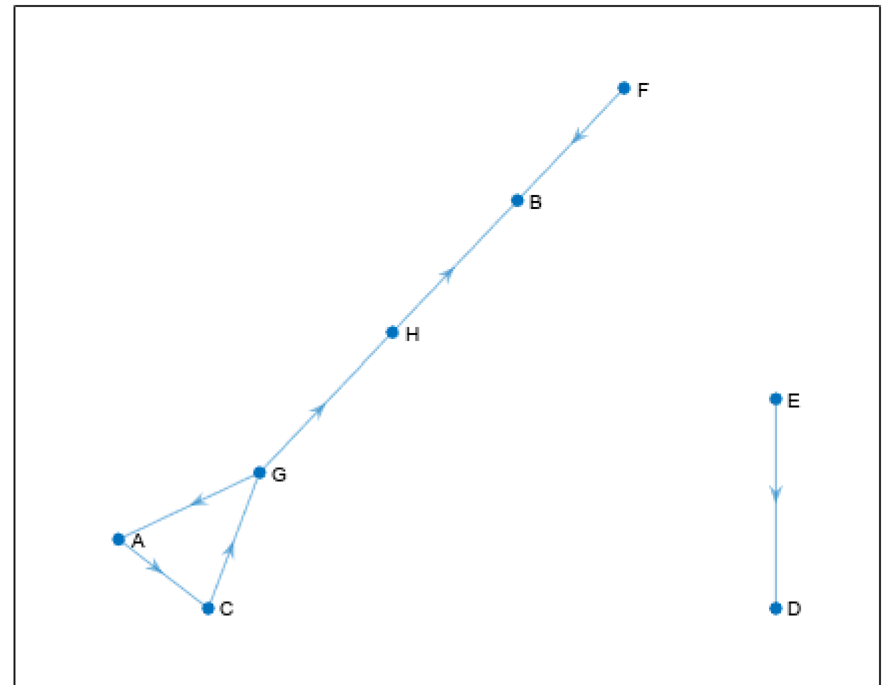
### Find Successive State Indices and Costs in `navGraph` Object

Load `navGraph` data for states and links.

```
load navGraphData.mat
```

Visualize the `navGraph` object.

```
show(navGraphObj);
```




Find successive state indices and costs based on a state name.

```
[succIDS,costs] = successors(navGraphObj,"G")
```

```
succIDS = 2×1

     1
     8


costs = 2×1

   38.7759
   13.9383
```

Find the state vectors of the successive states.

```
states = index2state(navGraphObj,succIDS)
```

```
states = 2×3

    8.0000    2.0000    0.7218
    8.0000    7.0000    0.6741
```

## Input Arguments

**graph — Graph object**
navGraph object

Graph object, specified as a navGraph object.

**currID — Current state**
positive integer | string scalar | character vector

Current state, specified as a positive integer, representing a state index, or as a string scalar or character vector representing a state name.

Data Types: double | char | string

## Output Arguments

**succIDS — Successive state indices**
column vector of positive integers

Successive state indices, returned as a column vector of positive integers.

Data Types: double

**costs — Cost of all successive states**
numeric column vector

Cost of all successive states, returned as a numeric column vector of the same size as succIDS. The function computes costs using the Weight or LinkWeightFcn property of the navGraph object graph.

Data Types: double

# Version History

**Introduced in R2023a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
navGraph

**Functions**
findlink | findstate | index2state | state2index | show | copy

# copy

Create deep copy of A* path planner object

## Syntax

```
planner2 = copy(planner1)
```

## Description

`planner2 = copy(planner1)` creates a deep copy of the `plannerAStar` object `planner1`.

## Examples

### Plan Shortest Path Between Two States in Graph Using A-Star Path Planner

Load the Queensland road network.

```
load("queenslandRoutes","places","routes")
```

Specify states, links, and weights for a `navGraph` object.

```
states = places.utm;              % UTM coordinates of cities
names = places.name;              % Names of cities
links = [routes.start routes.end]; % Adjacent cities
weights = routes.time;            % Travel time between adjacent cities
```

Create a `navGraph` object.

```
graphObj = navGraph(states,links,Weight=weights, ...
                    Name=names);
```

Create a graph-based A* path planner.

```
planner = plannerAStar(graphObj);
```

Create a deep copy of the `plannerAStar` object.

```
planner2 = copy(planner)
```

```
planner2 = 
  plannerAStar with properties:

    HeuristicCostFcn: @nav.algs.distanceManhattan
          TieBreaker: 0
               Graph: [1x1 navGraph]
```

Specify a heuristic function returns an estimated time to reach the goal.

```
planner.HeuristicCostFcn = @(state1,state2) ...
    sum(abs(state1-state2),2)/100;
```

Define the start and goal cities.

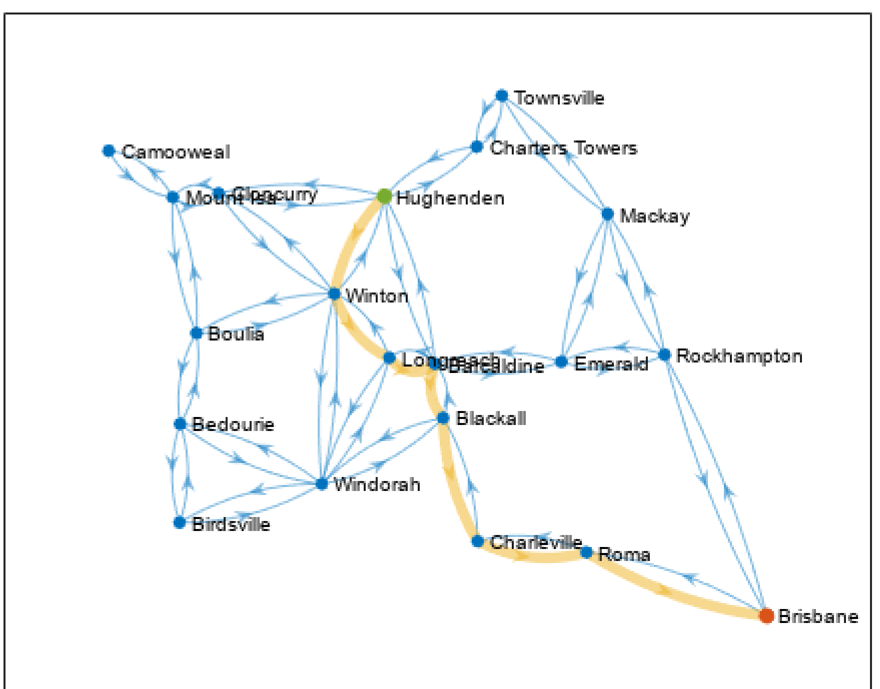
```
start = "Hughenden";
goal = "Brisbane";
```

Find the shortest path using the graph-based A* algorithm.

```
[pathOutput,solutionInfo] = plan(planner,start,goal);
```

Visualize the results.

```
h = show(graphObj);
set(h,XData=graphObj.States.StateVector(:,1), ...
      YData=graphObj.States.StateVector(:,2))
pathStateIDs = solutionInfo.PathStateIDs;
highlight(h,pathStateIDs,EdgeColor="#EDB120",LineWidth=4)
highlight(h,pathStateIDs(1),NodeColor="#77AC30",MarkerSize=5)
highlight(h,pathStateIDs(end),NodeColor="#D95319",MarkerSize=5)
```




## Input Arguments

**planner1 — A* path planner**
`plannerAStar` object

A* path planner, specified as a `plannerAStar` object.

## Output Arguments

**`planner2` — Copy of A* path planner**
`plannerAStar` object

Copy of A* path planner, returned as a `plannerAStar` object.

# Version History

**Introduced in R2023a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

`plannerAStar` | `plan`

# plan

Find shortest path between two states in graph

## Syntax

```
path = plan(planner,start,goal)
[path,solutionInfo] = plan( ___ )
```

## Description

`path = plan(planner,start,goal)` finds the shortest path `path` between a specified `start` and `goal` in the graph using the specified A* path planner `planner`.

`[path,solutionInfo] = plan( ___ )` returns the solution information of the path planning `solutionInfo`.

## Examples

### Plan Shortest Path Between Two States in Graph Using A-Star Path Planner

Load the Queensland road network.

```
load("queenslandRoutes","places","routes")
```

Specify states, links, and weights for a `navGraph` object.

```
states = places.utm;              % UTM coordinates of cities
names = places.name;              % Names of cities
links = [routes.start routes.end]; % Adjacent cities
weights = routes.time;            % Travel time between adjacent cities
```

Create a `navGraph` object.

```
graphObj = navGraph(states,links,Weight=weights, ...
                    Name=names);
```

Create a graph-based A* path planner.

```
planner = plannerAStar(graphObj);
```

Create a deep copy of the `plannerAStar` object.

```
planner2 = copy(planner)
```

```
planner2 = 
  plannerAStar with properties:

    HeuristicCostFcn: @nav.algs.distanceManhattan
          TieBreaker: 0
               Graph: [1x1 navGraph]
```

Specify a heuristic function returns an estimated time to reach the goal.

```
planner.HeuristicCostFcn = @(state1,state2) ...
    sum(abs(state1-state2),2)/100;
```

Define the start and goal cities.

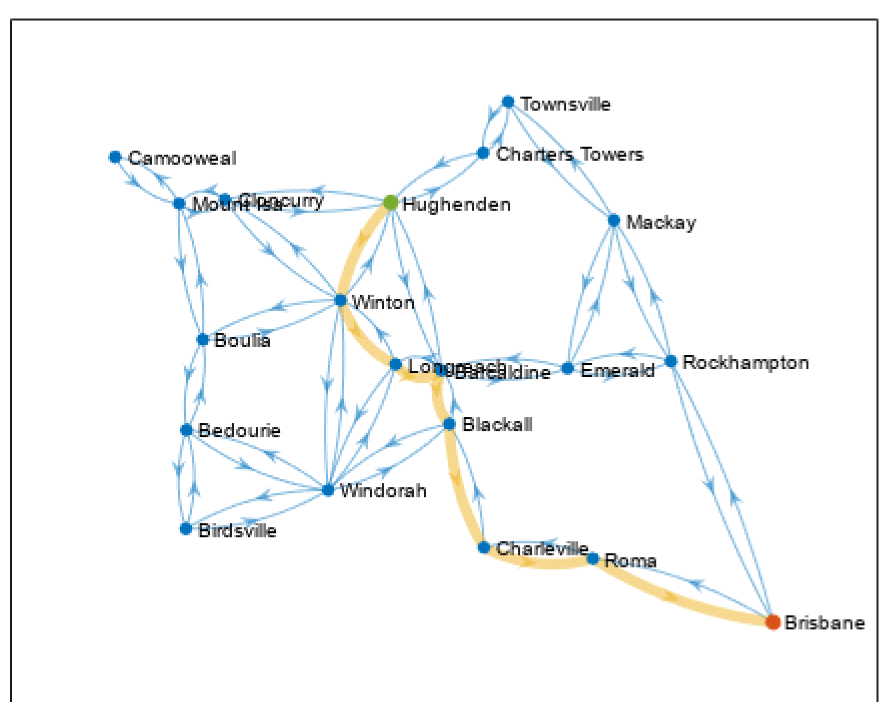
```
start = "Hughenden";
goal = "Brisbane";
```

Find the shortest path using the graph-based A* algorithm.

```
[pathOutput,solutionInfo] = plan(planner,start,goal);
```

Visualize the results.

```
h = show(graphObj);
set(h,XData=graphObj.States.StateVector(:,1), ...
      YData=graphObj.States.StateVector(:,2))
pathStateIDs = solutionInfo.PathStateIDs;
highlight(h,pathStateIDs,EdgeColor="#EDB120",LineWidth=4)
highlight(h,pathStateIDs(1),NodeColor="#77AC30",MarkerSize=5)
highlight(h,pathStateIDs(end),NodeColor="#D95319",MarkerSize=5)
```



## Input Arguments

**`planner` — A* path planner**
`plannerAStar` object

A* path planner, specified as a `plannerAStar` object.

**`start` — Start state of path**
positive integer | string scalar | character vector | numeric vector

Start state of the path, specified as a positive integer, string scalar, character vector, or numeric vector.

- Positive integer — Specify the state ID of the start state. The state ID is the index of the state in the `navGraph` object in the Graph property of `planner`.
- String scalar or character vector — Specify the name of the state.
- Numeric vector — Specify the coordinates of the state.

Example: `1`

Example: `"Brisbane"`

Example: `[1095.91458671447 6947.04365801860]`

Data Types: `single` | `double` | `char` | `string`

**`goal` — Goal state of path**
positive integer | string scalar | character vector | numeric vector

Goal state of the path, specified as a positive integer, string scalar, character vector, or numeric vector.

- Positive integer — Specify the state ID of the start state. The state ID is the index of the state in the `navGraph` object in the Graph property of `planner`.
- String scalar or character vector — Specify the name of the state.
- Numeric vector — Specify the coordinates of the state.

Example: `5`

Example: `"Hughenden"`

Example: `[208.622393818849 7691.91766093269]`

Data Types: `single` | `double` | `char` | `string`

## Output Arguments

**`path` — Shortest path between states**
numeric matrix

Shortest path between states, returned as a numeric matrix.

Data Types: `double`

**`solutionInfo` — Solution information**
structure

Solution information, returned as a structure. The fields of the structure are:

| Field | Description |
|---|---|
| `IsPathFound` | Indicates whether a path has been found. Returns `true` if a path has been found. Otherwise, returns `false`. |
| `PathStateIDs` | List of IDs of the states along the path found by A*. By default, the IDs are the numeric indices of the states in the graph object. If you specify names for the states while constructing the graph object, this field contains the names instead. |
| `PathCost` | Total cost of the path. If no path is found, then the cost is `NaN`. |
| `ExploredStateIDs` | List of IDs of the states explored by A* during the search. By default, the IDs are the numeric indices of the states in the graph object. If you specify names for the states while constructing the graph object, this field contains the names instead. |
| `NumExploredStates` | Number of states explored during the search. Equal to the length of the `ExploredStateIDs` list. |

Data Types: `struct`

# Version History

**Introduced in R2023a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

`plannerAStar` | `copy`

# axang

Convert transformation or rotation into axis-angle rotations

## Syntax

```
angles = axang(transformation)
angles = axang(rotation)
```

## Description

`angles = axang(transformation)` converts the rotation of the transformation `transformation` to the axis-angle rotations `angles`.

`angles = axang(rotation)` converts the rotation `rotation` to the axis-angle rotations `angles`.

## Examples

### Convert SE(3) Transformation to Axis-Angle Rotation

Create SE(3) transformation with no translation but with a rotation defined by an axis-angle rotation. Define the axis-rotation with vector of `[0.5 0.25 0.5]` to be the axis and a `pi/2` rotation about that axis.

```
axa1 = [0.5 0.25 0.5 pi/2];
T = se3(axa1,"axang");
```

Plot the axis-angle and the transformation on the same axes.

```
plot3([0 axa1(1)],[0 axa1(2)],[0 axa1(3)],LineWidth=1)
hold on
plotTransforms(T,FrameAxisLabels="on")
```

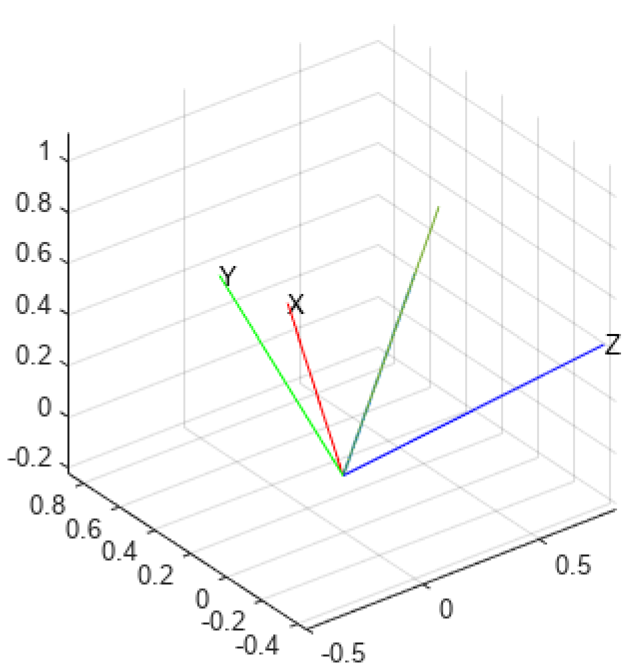
Get the axis-angle rotation from the transformation. Note that the vector of the axis-angle rotation has a different magnitude from the axis-angle rotation specified to the transformation but the defined axis and rotation are the same.

```
axa2 = axang(T)
```

```
axa2 = 1×4

    0.6667    0.3333    0.6667    1.5708
```

Plot the new axis-angle rotation on the same axis.

```
plot3([0 axa2(1)],[0 axa2(2)],[0 axa2(3)])
legend(["Original Rotation Axis","New Rotation Axis"])
hold off
```




#### Convert SO(3) Rotation to Axis-Angle Rotation

Create SO(3) transformation with a rotation defined by an axis-angle rotation. Define the axis-rotation with vector of `[0.5 0.25 0.5]` to be the axis and a `pi/2` rotation about that axis.

```
axa1 = [0.5 0.25 0.5 pi/2];
R = so3(axa1,"axang");
```

Plot the axis-angle and the transformation on the same axes.

```
plot3([0 axa1(1)],[0 axa1(2)],[0 axa1(3)],LineWidth=1)
hold on
plotTransforms([0 0 0],R,FrameAxisLabels="on")
```

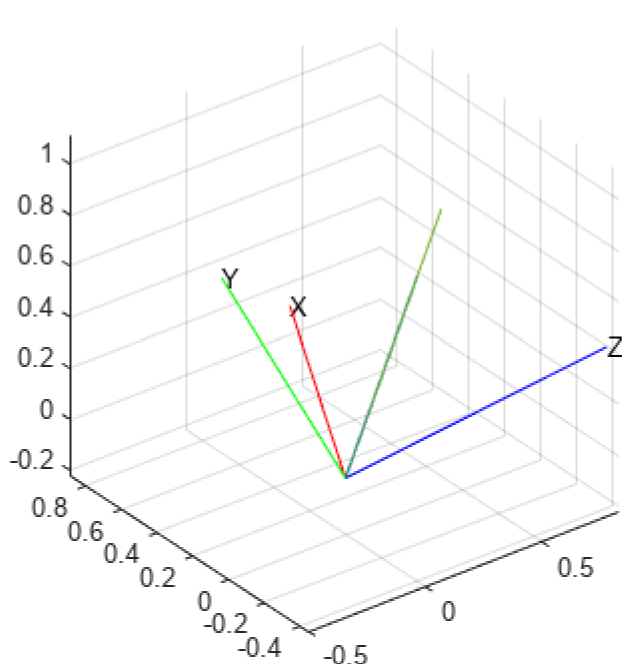
Get the axis-angle rotation from the transformation. Note that the vector of the axis-angle rotation has a different magnitude from the axis-angle rotation specified to the transformation but the defined axis and rotation are the same.

```
axa2 = axang(R)
```

```
axa2 = 1×4

    0.6667    0.3333    0.6667    1.5708
```

Plot the new axis-angle rotation on the same axis.

```
plot3([0 axa2(1)],[0 axa2(2)],[0 axa2(3)])
legend(["Original Rotation Axis","New Rotation Axis"])
hold off
```




## Input Arguments

**`transformation` — Transformation**

`se3` object | *N*-element array of `se3` objects

Transformation, specified as an `se3` object or as an *N*-element array of `se3` objects. *N* is the total number of transformations.

**`rotation` — Rotation**

`so3` object | *N*-element array of `so3` objects

Rotation, specified as an `so3` object or as an *N*-element array of `so3` objects. *N* is the total number of rotations.

## Output Arguments

**`angles` — Axis-angle rotation angles**

*N*-by-4 matrix

Axis-angle rotation angles, specified as an *N*-by-4 matrix of *N* axis-angle rotations. The first three elements of every row specify the rotation axes, and the last element defines the rotation angle, in radians.

## Version History

**Introduced in R2023a**

### See Also

`se3` | `so3`

# eul

Convert transformation or rotation into Euler angles

## Syntax

```
angles = eul(transformation)
angles = eul(rotation)
angles = eul( ___ ,sequence)
```

## Description

`angles = eul(transformation)` converts the rotation of the transformation `transformation` to the Euler angles `angles`.

`angles = eul(rotation)` converts the rotation `rotation` to the Euler angles `angles`.

`angles = eul( ___ ,sequence)` specifies the sequence of the Euler-angle rotations `sequence` using any of the input arguments in previous syntaxes. For example, a sequence of `"ZYX"` first rotates the *z*-axis, followed by the *y*-axis and *x*-axis.

## Examples

### Convert SE(3) Transformation to Euler Angles

Create SE(3) transformation with no translation but with a rotation defined by a Euler angles.

```
eul1 = [pi/4 pi/3 pi/8]
```

```
eul1 = 1×3

    0.7854    1.0472    0.3927
```

```
T = se3(eul1,"eul")
```

```
T = se3
    0.3536   -0.4189    0.8364         0
    0.3536    0.8876    0.2952         0
   -0.8660    0.1913    0.4619         0
         0         0         0    1.0000
```

Get the Euler angles from the transformation.

```
eul2 = eul(T)
```

```
eul2 = 1×3

    0.7854    1.0472    0.3927
```

#### Convert SO(3) Rotation to Euler Angles

Create SO(3) rotation defined by a Euler angles.

```
eul1 = [pi/4 pi/3 pi/8]
```

```
eul1 = 1×3

    0.7854    1.0472    0.3927
```

```
R = so3(eul1,"eul")
```

```
R = so3
    0.3536   -0.4189    0.8364
    0.3536    0.8876    0.2952
   -0.8660    0.1913    0.4619
```

Get the Euler angles from the transformation.

```
eul2 = eul(R)
```

```
eul2 = 1×3

    0.7854    1.0472    0.3927
```

## Input Arguments

**`transformation` — Transformation**
`se3` object | *N*-element array of `se3` objects

Transformation, specified as an `se3` object or as an *N*-element array of `se3` objects. *N* is the total number of transformations.

**`rotation` — Rotation**
`so3` object | *N*-element array of `so3` objects

Rotation, specified as an `so3` object or as an *N*-element array of `so3` objects. *N* is the total number of rotations.

**`sequence` — Axis-rotation sequence**
`"ZYX"` (default) | `"ZYZ"` | `"ZXY"` | `"ZXZ"` | `"YXY"` | `"YZX"` | `"YXZ"` | `"YZY"` | `"XYX"` | `"XYZ"` | `"XZX"` | `"XZY"`

Axis-rotation sequence for the Euler angles, specified as one of these string scalars:

- `"ZYX"` (default)
- `"ZYZ"`
- `"ZXY"`
- `"ZXZ"`

- `"YXY"`
- `"YZX"`
- `"YXZ"`
- `"YZY"`
- `"XYX"`
- `"XYZ"`
- `"XZX"`
- `"XZY"`

Each character indicates the corresponding axis. For example, if the sequence is `"ZYX"`, then the three specified Euler angles are interpreted in order as a rotation around the *z*-axis, a rotation around the *y*-axis, and a rotation around the *x*-axis. When applying this rotation to a point, it will apply the axis rotations in the order *x*, then *y*, then *z*.

Data Types: `string` | `char`

## Output Arguments

**`angles` — Euler angles**
*M*-by-3 matrix

Euler angles, returned as an *M*-by-3 matrix of Euler rotation angles. Each row represents one Euler angle set.

# Version History

**Introduced in R2023a**

## See Also

`se3` | `so3`

# dist

Calculate distance between transformations

## Syntax

```
distance = dist(transformation1,transformation2)
distance = dist(transformation1,transformation2,weights)
distance = dist(rotation1,rotation2)
```

## Description

`distance = dist(transformation1,transformation2)` returns the distance `distance` between the poses represented by transformation `transformation1` and transformation `transformation2`.

For the homogeneous transformation objects `se2`, and `se3`, the `dist` function calculates translational and rotational distance independently and combines them in a weighted sum. Translational distance is the Euclidean distance, and rotational distance is the angular difference between the rotation quaternions of `transformation1` and `transformation2`.

`distance = dist(transformation1,transformation2,weights)` specifies the weights `weights` for the translational and rotational distances for calculating the weighted sum of two homogeneous transformations.

`distance = dist(rotation1,rotation2)` returns the distance `distance` between the poses represented by transformation `rotation1` and transformation `rotation2`.

For the homogeneous transformation objects `se2`, and `se3`, the `dist` function calculates translational and rotational distance independently and combines them in a weighted sum. Translational distance is the Euclidean distance, and rotational distance is the angular difference between the rotation quaternions of `rotation1` and `rotation2`.

For rotation objects `so2`, and `so3`, the `dist` function calculates the rotational distance as the angular difference between the rotation quaternions of `rotation1` and `rotation2`.

## Input Arguments

**`transformation1` — First transformation**
`se2` object | `se3` object | *N*-element array of transformation objects

First transformation, specified as a scalar `se2` object, a scalar `se3` object, or as an *N*-element array of transformation objects, where *N* is the total number of transformations. If you specify `transformation1` as an array, each element must be of the same type.

Either `transformation1` or `transformation2` must be a scalar transformation object of the same type. For example, if `transformation1` is an array of `se2` objects, `transformation2` must be a scalar `se2` object.

**`transformation2` — Last transformation**
`se2` object | `se3` object | *N*-element array of transformation objects

Last transformation, specified as a scalar `se2` object, a scalar `se3` object, or as an *N*-element array of transformation objects, where *N* is the total number of transformations. If you specify `transformation2` as an array, each element must be of the same type.

Either `transformation1` or `transformation2` must be a scalar transformation object of the same type. For example, if `transformation1` is an array of `se2` objects, `transformation2` must be a scalar `se2` object.

**`rotation1` — First rotation**
`so2` object | `so3` object | *N*-element array of rotation objects

First rotation, specified as a scalar `so2` object, a scalar `so3` object, or as an *N*-element array of rotation objects, where *N* is the total number of rotations. If you specify `rotation1` as an array, each element must be of the same type.

Either `rotation1` or `rotation2` must be a scalar rotation object of the same type. For example, if `rotation1` is an array of `so2` objects, `rotation2` must be a scalar `so2` object.

**`rotation2` — Last rotation**
`so2` object | `so3` object | *N*-element array of rotation objects

Last rotation, specified as a scalar `so2` object, a scalar `so3` object, or as an *N*-element array of rotation objects, where *N* is the total number of rotations. If you specify `rotation2` as an array, each element must be of the same type.

Either `rotation1` or `rotation2` must be a scalar rotation object of the same type. For example, if `rotation1` is an array of `se2` objects, `rotation2` must be a scalar `se2` object.

**`weights` — Weights of translation and rotation in distance sum**
`[1.0 0.1]` (default) | two-element row vector

Weights of the translation and rotation in the distance sum, specified as a two-element row vector in the form [*WeightXYZ* *WeightQ*]. *WeightXYZ* is the translational weight and *WeightQ* is the rotational weight. Both weights must be nonnegative numeric values.

Data Types: `single` | `double`

## Output Arguments

**`distance` — Distance between transformations or rotations**
nonnegative numeric scalar

Distance between transformations, returned as a nonnegative numeric scalar. The distance calculate changes depending on the transformation object type of `transformation1` and `transformation2` or `rotation1` and `rotation2`:

- `se2` and `se3` — The `dist` function calculates translational and rotational distance independently and combines them in a weighted sum specified by the `weights` argument. The translational distance is the Euclidean distance between `transformation1` and `transformation2`. The rotational distance is the angular difference between the rotations of `transformation1` and `transformation2`.
- `so2` and `so3` — The `dist` function calculates the rotational distance as the angular difference between the rotations of `rotation1` and `rotation2`.

To calculate the rotational distance, the `dist` function converts the rotation matrix of `transformation1` and `transformation2` or `rotation1` and `rotation2` into `quaternion` objects and uses the `quaternion` `dist` function to calculate the angular distance.

## Version History

**Introduced in R2022b**

### See Also

**Functions**
`normalize` | `interp` | `transform` | `plotTransforms`

**Objects**
`se2` | `se3` | `so2` | `so3`

# interp

Interpolate between transformations

## Syntax

```
transformation0 = interp(transformation1,transformation2,points)
rotation0 = interp(rotation1,rotation2,points)
___ = interp( ___ ,transformation2,N)
```

## Description

`transformation0 = interp(transformation1,transformation2,points)` interpolates at normalized positions `points` between transformations `transformation1` and `transformation2`.

The function interpolates rotations using a quaternion spherical linear interpolation, and linearly interpolates translations.

`rotation0 = interp(rotation1,rotation2,points)` interpolates at normalized rotations `points` between rotations `rotation1` and `rotation2`.

The function interpolates rotations using a quaternion spherical linear interpolation

`___ = interp( ___ ,transformation2,N)` interpolates `N` steps between the specified transformations or rotations.

## Input Arguments

**`transformation1` — First transformation**
`se2` object | `se3` object | *N*-element array of transformation objects

First transformation, specified as a scalar `se2` object, a scalar `se3` object, or as an *N*-element array of transformation objects, where *N* is the total number of transformations. If you specify `transformation1` as an array, each element must be of the same type.

Either `transformation1` or `transformation2` must be a scalar transformation object of the same type. For example, if `transformation1` is an array of `se2` objects, `transformation2` must be a scalar `se2` object.

**`transformation2` — Last transformation**
`se2` object | `se3` object | *N*-element array of transformation objects

Last transformation, specified as a scalar `se2` object, a scalar `se3` object, or as an *N*-element array of transformation objects, where *N* is the total number of transformations. If you specify `transformation2` as an array, each element must be of the same type.

Either `transformation1` or `transformation2` must be a scalar transformation object of the same type. For example, if `transformation1` is an array of `se2` objects, `transformation2` must be a scalar `se2` object.

**`rotation1` — First rotation**
`so2` object | `so3` object | *N*-element array of rotation objects

First rotation, specified as a scalar `so2` object, a scalar `so3` object, or as an *N*-element array of rotation objects, where *N* is the total number of rotations. If you specify `rotation1` as an array, each element must be of the same type.

Either `rotation1` or `rotation2` must be a scalar rotation object of the same type. For example, if `rotation1` is an array of `so2` objects, `rotation2` must be a scalar `so2` object.

**`rotation2` — Last rotation**
`so2` object | `so3` object | *N*-element array of rotation objects

Last rotation, specified as a scalar `so2` object, a scalar `so3` object, or as an *N*-element array of rotation objects, where *N* is the total number of rotations. If you specify `rotation2` as an array, each element must be of the same type.

Either `rotation1` or `rotation2` must be a scalar rotation object of the same type. For example, if `rotation1` is an array of `se2` objects, `rotation2` must be a scalar `se2` object.

**`points` — Normalized positions**
*N*-element row vector of values in range [`0`, `1`]

Normalized positions, specified as an *N*-element row vector of values in the range [`0`, `1`], where *N* is the total number of interpolated positions. Normalized positions `0` and `1` correspond to the first and last transformations or rotations, respectively.

Example: `interp(tf1,tf2,0.5)` interpolates a transformation halfway between `tf1` and `tf2`.

Example: `interp(r1,r2,0.5)` interpolates a rotation halfway between `r1` and `r2`.

**`N` — Number of interpolated positions**
positive integer

Number of interpolated positions, specified as a positive integer.

Example: `interp(tf1,tf2,5)` interpolates five transformations between transformations `tf1` and `tf2`.

Example: `interp(r1,r2,7)` interpolates seven rotations between rotations `r1` and `r2`.

## Output Arguments

**`transformation0` — Interpolated transformations**
*N*-by-*M* matrix

Interpolated transformations, returned as an *N*-by-*M* matrix of the same transformation type as `transformation1` and `transformation2`, where *N* is the length of the longer argument between `transformation1` and `transformation2`, and *M* is the number of interpolated positions. Each row represents an interpolated transformation between `transformation1` and `transformation2`.

**`rotation0` — Interpolated rotations**
*N*-by-*M* matrix

Interpolated rotations, returned as an *N*-by-*M* matrix of the same rotation type as `rotation1` and `rotation2`, where *N* is the length of the longer argument between `rotation1` and `rotation2`, and

*M* is the number of interpolated positions. Each row represents an interpolated transformation between `rotation1` and `rotation2`.

# Version History

**Introduced in R2022b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Functions

`dist` | `normalize` | `transform` | `plotTransforms`

### Objects

`se2` | `se3` | `so2` | `so3`

# mrdivide, /

Transformation or rotation right division

## Syntax

```
transformationC = transformationA/transformationB
rotationC = rotationA/rotationB
```

## Description

`transformationC = transformationA/transformationB` right divides transformation `transformationA` by transformation `transformationB` and returns the quotient, transformation `transformationC`. `transformationC` is the same value as `transformationA*inv(transformationB)`.

You can use division to compose a sequence of transformations, so that `transformationC` represents a transformation where the inverse of `transformationB` is applied first, followed by `transformationA`.

`rotationC = rotationA/rotationB` right divides transformation `rotationA` by transformation `rotationB` and returns the quotient, transformation `rotationC`. `rotationC` is the same value as `rotationA*inv(rotationB)`.

## Input Arguments

**`transformationA` — First transformation**
`se2` object | `se3` object | *N*-element array of transformation objects

First transformation, specified as a scalar `se2` object, a scalar `se3` object, or as an *N*-element array of transformation objects, where *N* is the total number of transformations. If you specify `transformationA` as an array, each element must be of the same type.

Either `transformationA` or `transformationB` must be a scalar transformation object of the same type. For example, if `transformationA` is an array of `se2` objects, `transformationB` must be a scalar `se2` object.

**`transformationB` — Last transformation**
`se2` object | `se3` object | *N*-element array of transformation objects

Last transformation, specified as a scalar `se2` object, a scalar `se3` object, or as an *N*-element array of transformation objects, where *N* is the total number of transformations. If you specify `transformationB` as an array, each element must be of the same type.

Either `transformationA` or `transformationB` must be a scalar transformation object of the same type. For example, if `transformationA` is an array of `se2` objects, `transformationB` must be a scalar `se2` object.

**`rotationA` — First rotation**
`so2` object | `so3` object | *N*-element array of rotation objects

First rotation, specified as a scalar `so2` object, a scalar `so3` object, or as an *N*-element array of rotation objects, where *N* is the total number of rotations. If you specify `rotationA` as an array, each element must be of the same type.

Either `rotationA` or `rotationB` must be a scalar rotation object of the same type. For example, if `rotationA` is an array of `so2` objects, `rotationB` must be a scalar `so2` object.

**`rotationB` — Last rotation**
`so2` object | `so3` object | *N*-element array of rotation objects

Last rotation, specified as a scalar `so2` object, a scalar `so3` object, or as an *N*-element array of rotation objects, where *N* is the total number of rotations. If you specify `rotationB` as an array, each element must be of the same type.

Either `rotationA` or `rotationB` must be a scalar rotation object of the same type. For example, if `rotationA` is an array of `se2` objects, `rotationB` must be a scalar `se2` object.

## Output Arguments

**`transformationC` — Transformation quotient**
`se2` object | `se3` object | *N*-element array of transformation objects

Transformation quotient, returned as a scalar `se2` object, a scalar `se3` object, or as an *N*-element array of the same transformation type as `transformationA` and `transformationB`. *N* is the length of the longer argument between `transformationA` and `transformationB` and each row represents the quotient between `transformationA` and `transformationB`.

**`rotationC` — Rotation quotient**
`so2` object | `so3` object | *N*-element array of rotation objects

Rotation quotient, returned as a scalar `so2` object, a scalar `so3` object, or as an *N*-element array of the same rotation type as `rotationA` and `rotationB`. *N* is the length of the longer argument between `rotationA` and `rotationB` and each row represents the quotient between `rotationA` and `rotationB`.

# Version History

**Introduced in R2022b**

## See Also

**Functions**
`rdivide, ./` | `mtimes, *` | `times, .*`

**Objects**
`se2` | `se3` | `so2` | `so3`

# mtimes, *

Transformation or rotation multiplication

## Syntax

```
transformationC = transformationA*transformationB
rotationC = rotationA*rotationB
```

## Description

`transformationC = transformationA*transformationB` performs transformation multiplication between transformation `transformationA` and transformation `transformationB` and returns the product, transformation `transformationC`.

You can use transformation multiplication to compose a sequence of transformations, so that `transformationC` represents a transformation where `transformationB` is applied first, followed by `transformationA`.

`rotationC = rotationA*rotationB` performs rotation multiplication between rotation `rotationA` and rotation `rotationB` and returns the product, rotation `rotationC`.

You can use rotation multiplication to compose a sequence of rotations, so that `rotationC` represents a rotation where `rotationB` is applied first, followed by `rotationA`.

## Input Arguments

### `transformationA` — First transformation

`se2` object | `se3` object | *N*-element array of transformation objects

First transformation, specified as a scalar `se2` object, a scalar `se3` object, or as an *N*-element array of transformation objects, where *N* is the total number of transformations. If you specify `transformationA` as an array, each element must be of the same type.

Either `transformationA` or `transformationB` must be a scalar transformation object of the same type. For example, if `transformationA` is an array of `se2` objects, `transformationB` must be a scalar `se2` object.

### `transformationB` — Last transformation

`se2` object | `se3` object | *N*-element array of transformation objects

Last transformation, specified as a scalar `se2` object, a scalar `se3` object, or as an *N*-element array of transformation objects, where *N* is the total number of transformations. If you specify `transformationB` as an array, each element must be of the same type.

Either `transformationA` or `transformationB` must be a scalar transformation object of the same type. For example, if `transformationA` is an array of `se2` objects, `transformationB` must be a scalar `se2` object.

### `rotationA` — First rotation

`so2` object | `so3` object | *N*-element array of rotation objects

First rotation, specified as a scalar `so2` object, a scalar `so3` object, or as an *N*-element array of rotation objects, where *N* is the total number of rotations. If you specify `rotationA` as an array, each element must be of the same type.

Either `rotationA` or `rotationB` must be a scalar rotation object of the same type. For example, if `rotationA` is an array of `so2` objects, `rotationB` must be a scalar `so2` object.

**`rotationB` — Last rotation**
`so2` object | `so3` object | *N*-element array of rotation objects

Last rotation, specified as a scalar `so2` object, a scalar `so3` object, or as an *N*-element array of rotation objects, where *N* is the total number of rotations. If you specify `rotationB` as an array, each element must be of the same type.

Either `rotationA` or `rotationB` must be a scalar rotation object of the same type. For example, if `rotationA` is an array of `se2` objects, `rotationB` must be a scalar `se2` object.

## Output Arguments

**`transformationC` — Transformation product**
`se2` object | `se3` object | *N*-element array of transformation objects

Transformation product, returned as a scalar `se2` object, a scalar `se3` object, or as an *N*-element array of the same transformation type as `transformationA` and `transformationB`. *N* is the length of the longer argument between `transformationA` and `transformationB` and each row represents the product between `transformationA` and `transformationB`.

**`rotationC` — Rotation product**
`so2` object | `so3` object | *N*-element array of rotation objects

Rotation product, returned as a scalar `so2` object, a scalar `so3` object, or as an *N*-element array of the same rotation type as `rotationA` and `rotationB`. *N* is the length of the longer argument between `rotationA` and `rotationB` and each row represents the product between `rotationA` and `rotationB`.

# Version History

**Introduced in R2022b**

## See Also

**Functions**
`mrdivide, /` | `rdivide, ./` | `times, .*`

**Objects**
`se2` | `se3` | `so2` | `so3`

# normalize

Normalize transformation or rotation matrix

## Syntax

```
transformationN = normalize(transformation)
rotationN = normalize(rotation)
___ = normalize(___,Method=normMethod)
```

## Description

`transformationN = normalize(transformation)` normalizes the rotation of the transformation `transformation` and returns a transformation, `transformationN`, that is equivalent to `transformation`, but with normalized rotation.

`rotationN = normalize(rotation)` normalizes the rotation of the rotation `rotation` and returns a rotation, `rotationN`, that is equivalent to `rotation`, but with normalized rotation.

---

**Note** The transformation and rotation objects do not automatically normalize their rotations. You must use `normalize` each time you need to normalize a transformation or rotation. You may need to do this if:

- You specified an unnormalized input transformation or rotation at the creation of the transformation or rotation object.
- You performed many operations on the transformation or rotation objects such as `mtimes, *`, which may cause the transformation or rotation to become unnormalized due to data type precision.

---

`___ = normalize(___,Method=normMethod)` specifies the normalization method `normMethod` that the `normalize` function uses to normalize the specified transformation or rotation.

## Input Arguments

**`transformation` — Transformation**
`se2` object | `se3` object | *N*-element array of transformation objects

Transformation, specified as a scalar `se2` object, a scalar `se3` object, or an *N*-element array of transformation objects. *N* is the total number of transformations.

If you specify `transformation` as an array, each element must be of the same type.

**`rotation` — Rotation**
`so2` object | `so3` object | *N*-element array of rotation objects

Rotation, specified as a scalar `so2` object, a scalar `so3` object, or as an *N*-element array of rotation objects. *N* is the total number of rotations.

If you specify `rotation` as an array, each element must be of the same type.

**`normMethod` — Normalization method**
`"quat"` (default) | `"cross"` | `"svd"`

Normalization method, specified as one of these options:

- `"quat"` — Convert the rotation submatrix into a normalized quaternion and then convert the normalized quaternion back to a transformation or rotation object. For more information, see the `normalize` of the `quaternion` object.
- `"cross"` — Normalize the third column of the rotation submatrix and then determine the other two columns through cross products.
- `"svd"` — Use singular value decomposition to find the closest orthonormal matrix by setting singular values to `1`. This solves the orthogonal Procrustes problem.

Data Types: `char` | `string`

## Output Arguments

**`transformationN` — Normalized transformation**
`se2` object | `se3` object

Normalized transformation, returned as an `se2` or `se3` object.

**`rotationN` — Normalized rotation**
`so2` object | `so3` object

Normalized rotation, returned as an `so2` or `so3` object.

# Version History

**Introduced in R2022b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Functions**
`dist` | `interp` | `transform` | `plotTransforms`

**Objects**
`se2` | `se3` | `so2` | `so3` | `quaternion`

# plot

Draw transformation coordinate frame

## Syntax

```
plot(T)
plot(___,Name=Value)
AX = plot(___,Name=Value)
```

## Description

`plot(T)` draws a 3-D coordinate frame of transformation `T` with labeled axes. The *x*-axis is colored in red, the *y*-axis in green, and the *z*-axis in blue.

`plot(___,Name=Value)` specifies optional arguments using one or more name-value arguments. For example, `plot(T,AxisLabels="off")` hides the *xyz* labels.

`AX = plot(___,Name=Value)` returns the axis object, `AX`, containing the transformation plots.

## Input Arguments

### T — Transformation

SE3 object | SO3 object | *M*-element array of SE3 or SO3 objects

Transformation, specified as either an individual `SE3` or `SO3` object, or as an *M*-element array of transformation objects. *M* is the total number of transformations. Ever transformation in `T` is plotted if `T` is an *M*-element array.

Data Types: `single` | `double`

### Name-Value Pair Arguments

Specify optional pairs of arguments as `Name1=Value1,...,NameN=ValueN`, where `Name` is the argument name and `Value` is the corresponding value. Name-value arguments must appear after other arguments, but the order of the pairs does not matter.

*Before R2021a, use commas to separate each name and value, and enclose* `Name` *in quotes.*

Example: `plot(T,AxisLabels="off")`

### `AxisLabels` — Show axis labels

`"on"` (default) | `"off"`

Show axis labels, specified as `"off"` or `"on"`.

Example: `plot(T,AxisLabels="off")`

Data Types: `char` | `string`

### `FrameLabel` — Name of coordinate frame

`""` (default) | string scalar | character vector

Name of the coordinate frame, specified as a string scalar or character vector.

Example: `plot(T,FrameLabel="TF1")`

Data Types: `char` | `string`

**`Color` — Use uniform color for coordinate frame**
`"off"` (default) | `"on"`

Use uniform color for coordinate frame, specified as `"off"` or `"on"`.

Example: `plot(T,Color="on")`

Data Types: `char` | `string`

## Output Arguments

**`AX` — Axes handle**
`Axes` object

Axes handle, specified as an `Axes` object.

# Version History

**Introduced in R2022b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Functions**
`interpolate` | `normalize` | `rotm` | `showdetails` | `tform` | `transformPoints` | `trvec`

**Objects**
SE3 | SO3

# quat

Convert transformation or rotation to numeric quaternion

## Syntax

```
q = quat(transformation)
q = quat(rotation)
```

## Description

`q = quat(transformation)` creates a quaternion `q` from the rotation of the transformation `transformation`.

`q = quat(rotation)` creates a quaternion `q` from the rotation `rotation`.

## Examples

### Convert SE(3) Transformation to Numeric Quaternion

Create SE(3) transformation with zero translation and a rotation defined by a numeric quaternion. Use the `eul2quat` function to create the numeric quaternion.

```
quat1 = eul2quat([0 0 deg2rad(30)])
```

```
quat1 = 1×4

    0.9659    0.2588         0         0
```

```
T = se3(quat1,"quat")
```

```
T = se3
    1.0000         0         0         0
         0    0.8660   -0.5000         0
         0    0.5000    0.8660         0
         0         0         0    1.0000
```

Convert the transformation back into a numeric quaternion.

```
quat2 = quat(T)
```

```
quat2 = 1×4

    0.9659    0.2588         0         0
```

#### Convert SO(3) Rotation to Numeric Quaternion

Create SO(3) rotation defined by a numeric quaternion. Use the `eul2quat` function to create the numeric quaternion.

```
quat1 = eul2quat([0 0 deg2rad(30)])
```

```
quat1 = 1×4

    0.9659    0.2588         0         0
```

```
R = so3(quat1,"quat")
```

```
R = so3
    1.0000         0         0
         0    0.8660   -0.5000
         0    0.5000    0.8660
```

Convert the rotation into a numeric quaternion.

```
quat2 = quat(R)
```

```
quat2 = 1×4

    0.9659    0.2588         0         0
```

## Input Arguments

**`transformation` — Transformation**
`se3` object | *N*-element array of `se3` objects

Transformation, specified as an `se3` object or as an *N*-element array of `se3` objects. *N* is the total number of transformations.

**`rotation` — Rotation**
`so3` object | *N*-element array of `so3` objects

Rotation, specified as an `so3` object or as an *N*-element array of `so3` objects. *N* is the total number of rotations.

## Output Arguments

**q — Quaternion rotation angles**
*M*-by-4 matrix

Quaternion rotation angles, returned as an *M*-by-4 matrix, where each row is of the form [*qw qx qy qz*]. *M* is the total number of transformations or rotations specified.

# Version History

**Introduced in R2023a**

## See Also

`se3` | `so3`

# rdivide, ./

Element-wise transformation or rotation right division

## Syntax

```
transformationC = transformationA./transformationB
rotationC = rotationA./rotationB
```

## Description

`transformationC = transformationA./transformationB` divides transformations element-by-element by dividing each element of transformation `transformationA` with the corresponding element of transformation `transformationB` and returns the quotient, transformation `transformationC`.

`rotationC = rotationA./rotationB` divides rotations element-by-element by dividing each element of rotation `rotationA` with the corresponding element of rotation `rotationB` and returns the quotient, rotation `rotationC`.

## Input Arguments

**`transformationA` — First transformation**
`se2` object | `se3` object | *N*-element array of transformation objects

First transformation, specified as a scalar `se2` object, a scalar `se3` object, or as an *N*-element array of transformation objects, where *N* is the total number of transformations. If you specify `transformationA` as an array, each element must be of the same type.

Either `transformationA` or `transformationB` must be a scalar transformation object of the same type. For example, if `transformationA` is an array of `se2` objects, `transformationB` must be a scalar `se2` object.

**`transformationB` — Last transformation**
`se2` object | `se3` object | *N*-element array of transformation objects

Last transformation, specified as a scalar `se2` object, a scalar `se3` object, or as an *N*-element array of transformation objects, where *N* is the total number of transformations. If you specify `transformationB` as an array, each element must be of the same type.

Either `transformationA` or `transformationB` must be a scalar transformation object of the same type. For example, if `transformationA` is an array of `se2` objects, `transformationB` must be a scalar `se2` object.

**`rotationA` — First rotation**
`so2` object | `so3` object | *N*-element array of rotation objects

First rotation, specified as a scalar `so2` object, a scalar `so3` object, or as an *N*-element array of rotation objects, where *N* is the total number of rotations. If you specify `rotationA` as an array, each element must be of the same type.

Either `rotationA` or `rotationB` must be a scalar rotation object of the same type. For example, if `rotationA` is an array of `so2` objects, `rotationB` must be a scalar `so2` object.

**`rotationB` — Last rotation**
`so2` object | `so3` object | *N*-element array of rotation objects

Last rotation, specified as a scalar `so2` object, a scalar `so3` object, or as an *N*-element array of rotation objects, where *N* is the total number of rotations. If you specify `rotationB` as an array, each element must be of the same type.

Either `rotationA` or `rotationB` must be a scalar rotation object of the same type. For example, if `rotationA` is an array of `se2` objects, `rotationB` must be a scalar `se2` object.

## Output Arguments

**`transformationC` — Transformation quotient**
`se2` object | `se3` object | *N*-element array of transformation objects

Transformation quotient, returned as a scalar `se2` object, a scalar `se3` object, or as an *N*-element array of the same transformation type as `transformationA` and `transformationB`. *N* is the length of the longer argument between `transformationA` and `transformationB` and each row represents the quotient between `transformationA` and `transformationB`.

**`rotationC` — Rotation quotient**
`so2` object | `so3` object | *N*-element array of rotation objects

Rotation quotient, returned as a scalar `so2` object, a scalar `so3` object, or as an *N*-element array of the same rotation type as `rotationA` and `rotationB`. *N* is the length of the longer argument between `rotationA` and `rotationB` and each row represents the quotient between `rotationA` and `rotationB`.

# Version History

**Introduced in R2022b**

## See Also

**Functions**
`mrdivide, /` | `mtimes, *` | `times, .*`

**Objects**
`se2` | `se3` | `so2` | `so3`

# rotm

Extract rotation matrix

## Syntax

```
rotationMatrix = rotm(transformation)
rotationMatrix = rotm(rotation)
```

## Description

`rotationMatrix = rotm(transformation)` returns the rotation matrix `rotationMatrix` from the SE(2) or SE(3) transformation `transformation`.

`rotationMatrix = rotm(rotation)` returns the rotation matrix `rotationMatrix` from the SO(2) or SO(3) rotation `rotation`.

## Input Arguments

**`transformation` — Transformation**
`se2` object | `se3` object | *N*-element array of transformation objects

Transformation, specified as a scalar `se2` object, a scalar `se3` object, or an *N*-element array of transformation objects. *N* is the total number of transformations.

If you specify `transformation` as an array, each element must be of the same type.

**`rotation` — Rotation**
`so2` object | `so3` object | *N*-element array of rotation objects

Rotation, specified as a scalar `so2` object, a scalar `so3` object, or an *N*-element array of rotation objects. *N* is the total number of rotations.

If you specify `rotation` as an array, each element must be of the same type.

## Output Arguments

**`rotationMatrix` — Rotation matrix**
2-by-2-by-*N* array | 3-by-3-by-*N* array

Rotation matrix, returned as a 2-by-2-by-*N* array for 2-D transformations or a 3-by-3-by-*N* array for 3-D transformations. *N* is the total number of transformations.

# Version History

**Introduced in R2022b**

## Extended Capabilities

### C/C++ Code Generation
Generate C and C++ code using MATLAB® Coder™.

## See Also

### Functions
`dist` | `interp` | `normalize` | `tform` | `transform` | `trvec` | `plotTransforms`

### Objects
`se2` | `se3` | `so2` | `so3`

# showdetails

Display transformation in compact form

## Syntax

```
showdetails(transformation)
showdetails(rotation)
showdetails( ___ Name=Value)
```

## Description

`showdetails(transformation)` displays the translational and rotational components of the transformation `transformation` on a single line. The rotation units are in degrees.

`showdetails(rotation)` displays the rotational components of the rotation `rotation` on a single line.

`showdetails( ___ Name=Value)` specifies additional options using one or more name-value arguments.

## Input Arguments

**`transformation` — Transformation**
`se2` object | `se3` object | *N*-element array of transformation objects

Transformation, specified as a scalar `se2` object, a scalar `se3`, or an *N*-element array of transformation objects. *N* is the total number of transforms.

If you specify `transformation` as an array, each element must be of the same type. Additionally, `showdetails` prints the details on a new line for each of the *N* transformations.

**`rotation` — Rotation**
`so2` object | `so3` object | *N*-element array of rotation objects

Rotation, specified as a scalar `so2` object, a scalar `so3` object, or as an *N*-element array of rotation objects. *N* is the total number of rotations.

If you specify `rotation` as an array, each element must be of the same type. Additionally, `showdetails` prints the details on a new line for each of the *N* rotations.

### Name-Value Pair Arguments

Specify optional pairs of arguments as `Name1=Value1,...,NameN=ValueN`, where `Name` is the argument name and `Value` is the corresponding value. Name-value arguments must appear after other arguments, but the order of the pairs does not matter.

*Before R2021a, use commas to separate each name and value, and enclose* `Name` *in quotes.*

Example: `showdetails(T,Sequence="ZYX")`

**Sequence — Euler angle sequence order**
"ZYX" (default) | "ZYZ" | "ZXY" | "ZXZ" | "YXY" | "YZX" | "YXZ" | "YZY" | "XYX" | "XYZ" | "XZX" | "XZY"

Euler angle sequence order, specified as one of these string scalars:

- "ZYX" (default)
- "ZYZ"
- "ZXY"
- "ZXZ"
- "YXY"
- "YZX"
- "YXZ"
- "YZY"
- "XYX"
- "XYZ"
- "XZX"
- "XZY"

Each character indicates the corresponding axis. For example if the sequence is "ZYX", then the printed order of rotation angles is *z*-axis, *y*-axis, and then the *x*-axis.

This parameter does not affect the output when `transformation` contains an `se2` object or if `rotation` contains an `so2` object.

Example: `showdetails(T,Sequence="ZYX")`

Data Types: `char` | `string`

**AngleUnit — Angle unit**
"deg" (default) | "rad"

Angle unit, specified as "deg" for degrees, or "rad" for radians.

Example: `showdetails(T,AngleUnit="rad")`

Data Types: `char` | `string`

# Version History

**Introduced in R2022b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Functions

`dist` | `interp` | `normalize` | `transform`

**Objects**
se2 | se3 | so2 | so3

# theta

Convert transformation or rotation to 2-D rotation angle

## Syntax

```
angle = theta(transformation)
angle = theta(rotation)
```

## Description

`angle = theta(transformation)` extracts the 2-D rotation angle `angle` from the transformation `transformation`.

`angle = theta(rotation)` extracts the 2-D rotation angle `angle` from the rotation `rotation`.

## Examples

### Convert SE(2) Transformation to Angle

Create SE(2) transformation with a rotation defined by an angle `pi/2`.

```
angle1 = pi/2
```

```
angle1 = 1.5708
```

```
T = se2(angle1,"theta")
```

```
T = se2
    0.0000   -1.0000         0
    1.0000    0.0000         0
         0         0    1.0000
```

Get the rotation angle from the transformation.

```
angle2 = theta(T)
```

```
angle2 = 1.5708
```

### Convert SO(2) Transformation to Angle

Create SO(2) rotation defined by an angle `pi/2`.

```
angle1 = pi/2
```

```
angle1 = 1.5708
```

```
R = so2(angle1,"theta")
```

```
R = so2
    0.0000   -1.0000
    1.0000    0.0000
```

Get the rotation angle from the rotation.

```
angle2 = theta(R)
```

```
angle2 = 1.5708
```

## Input Arguments

### `transformation` — Transformation

`se2` object | *N*-by-*M* array of `se2` objects

Transformation, specified as an `se2` object or as an *N*-by-*M* array of `se2` objects. *N* is the total number of transformations.

If `transformation` is a *N*-by-*M* array, the `angle` argument is the same size and contains an angle for each of the `se2` objects specified in the array.

Data Types: `single` | `double`

### `rotation` — Rotation

`so2` object | *N*-by-*M* array of `so2` objects

Rotation, specified as an `so2` object or as an *N*-by-*M* array of `so2` objects. *N* is the total number of rotations.

If `rotation` is a *N*-by-*M* array, the `angle` argument is the same size and contains an angle for each of the `so2` objects specified in the array.

## Output Arguments

### `angle` — Rotation angle

numeric scalar | *N*-by-*M* matrix

Rotation angle, returned as a numeric scalar for a scalar input and as an *N*-by-*M* matrix for an array input. *N* and *M* are the dimensions of the input `rotation` or `transformation` argument. Each element of the matrix is an angle, in radians, and each angle corresponds to a rotation or transformation in the input at the same index location.

The rotation angle is counterclockwise positive when you look along the specified axis toward the origin.

Data Types: `single` | `double`

# Version History

**Introduced in R2023a**

## See Also
se2 | so2

# tform

Extract homogeneous transformation

## Syntax

```
transformationMatrix = tform(transformation)
transformationMatrix = tform(rotation)
```

## Description

`transformationMatrix = tform(transformation)` extracts the homogeneous transformation matrix `transformationMatrix` that corresponds to the SE(2) or SE(3) transformation `transformation`.

`transformationMatrix = tform(rotation)` creates a homogeneous transformation matrix `transformationMatrix`, with zero translation, that corresponds to the SO(2) or SO(3) rotation `rotation`.

## Input Arguments

**`transformation` — Transformation**

`se2` object | `se3` object | *N*-element array of transformation objects

Transformation, specified as a scalar `se2` object, a scalar `se3` object, or an *N*-element array of transformation objects. *N* is the total number of transformations.

If you specify `transformation` as an array, each element must be of the same type.

**`rotation` — Rotation**

`so2` object | `so3` object | *N*-element array of rotation objects

Rotation, specified as a scalar `so2` object, a scalar `so3` object, or an *N*-element array of rotation objects. *N* is the total number of rotations.

If you specify `rotation` as an array, each element must be of the same type.

## Output Arguments

**`transformationMatrix` — Homogeneous transformation matrix**

3-by-3-by-*N* array | 4-by-4-by-*N* array

Homogeneous transformation matrix, returned as a 3-by-3-by-*N* array for `se2` and `so2` objects, or a 4-by-4-by-*N* array for `se3` and `so3` objects. *N* is the total number of transformations.

# Version History

**Introduced in R2022b**

## Extended Capabilities

### C/C++ Code Generation
Generate C and C++ code using MATLAB® Coder™.

## See Also

### Functions
`rotm` | `trvec`

### Objects
`se2` | `se3` | `so2` | `so3`

# times, .*

Element-wise transformation or rotation multiplication

## Syntax

```
transformationC = transformationA.*transformationB
rotationC = rotationA.*rotationB
```

## Description

`transformationC = transformationA.*transformationB` multiplies transformations element-by-element by multiplying each element of transformation `transformationA` with the corresponding element of transformation `transformationB` and returns the product, transformation `transformationC`.

`rotationC = rotationA.*rotationB` multiplies rotations element-by-element by multiplying each element of rotation `rotationA` with the corresponding element of rotation `rotationB` and returns the product, rotation `rotationC`.

## Input Arguments

**`transformationA` — First transformation**
`se2` object | `se3` object | *N*-element array of transformation objects

First transformation, specified as a scalar `se2` object, a scalar `se3` object, or as an *N*-element array of transformation objects, where *N* is the total number of transformations. If you specify `transformationA` as an array, each element must be of the same type.

Either `transformationA` or `transformationB` must be a scalar transformation object of the same type. For example, if `transformationA` is an array of `se2` objects, `transformationB` must be a scalar `se2` object.

**`transformationB` — Last transformation**
`se2` object | `se3` object | *N*-element array of transformation objects

Last transformation, specified as a scalar `se2` object, a scalar `se3` object, or as an *N*-element array of transformation objects, where *N* is the total number of transformations. If you specify `transformationB` as an array, each element must be of the same type.

Either `transformationA` or `transformationB` must be a scalar transformation object of the same type. For example, if `transformationA` is an array of `se2` objects, `transformationB` must be a scalar `se2` object.

**`rotationA` — First rotation**
`so2` object | `so3` object | *N*-element array of rotation objects

First rotation, specified as a scalar `so2` object, a scalar `so3` object, or as an *N*-element array of rotation objects, where *N* is the total number of rotations. If you specify `rotationA` as an array, each element must be of the same type.

Either `rotationA` or `rotationB` must be a scalar rotation object of the same type. For example, if `rotationA` is an array of `so2` objects, `rotationB` must be a scalar `so2` object.

**`rotationB` — Last rotation**
`so2` object | `so3` object | *N*-element array of rotation objects

Last rotation, specified as a scalar `so2` object, a scalar `so3` object, or as an *N*-element array of rotation objects, where *N* is the total number of rotations. If you specify `rotationB` as an array, each element must be of the same type.

Either `rotationA` or `rotationB` must be a scalar rotation object of the same type. For example, if `rotationA` is an array of `se2` objects, `rotationB` must be a scalar `se2` object.

## Output Arguments

**`transformationC` — Transformation product**
`se2` object | `se3` object | *N*-element array of transformation objects

Transformation product, returned as a scalar `se2` object, a scalar `se3` object, or as an *N*-element array of the same transformation type as `transformationA` and `transformationB`. *N* is the length of the longer argument between `transformationA` and `transformationB` and each row represents the product between `transformationA` and `transformationB`.

**`rotationC` — Rotation product**
`so2` object | `so3` object | *N*-element array of rotation objects

Rotation product, returned as a scalar `so2` object, a scalar `so3` object, or as an *N*-element array of the same rotation type as `rotationA` and `rotationB`. *N* is the length of the longer argument between `rotationA` and `rotationB` and each row represents the product between `rotationA` and `rotationB`.

# Version History

**Introduced in R2022b**

## See Also

**Functions**
`mrdivide, /` | `rdivide, ./` | `mtimes, *`

**Objects**
`se2` | `se3` | `so2` | `so3`

# transform

Apply rigid body transformation to points

## Syntax

```
tpoints = transform(transformation,points)
tpoints = transform(rotation,points)
tpoints = transform( ___ ,isCol=format)
```

## Description

`tpoints = transform(transformation,points)` applies the rigid body transformation `transformation` to the input points `points`, and returns the transformed points `tpoints`.

`tpoints = transform(rotation,points)` applies the rotation `rotation` to the input points `points`, and returns the transformed points `tpoints`.

`tpoints = transform( ___ ,isCol=format)` sets the expected format of the input points `points` to be either column-wise or row-wise by using the logical flag `format` in addition to the input arguments from the previous syntax.

## Input Arguments

**`transformation` — Transformation**
`se2` object | `se3` object | *N*-element array of transformation objects

Transformation, specified as a scalar `se2` object, a scalar `se3` object, or an *N*-element array of transformation objects. *N* is the total number of transformations.

If you specify `transformation` as an array, each element must be of the same type.

**`rotation` — Rotation**
`so2` object | `so3` object | *N*-element array of rotation objects

Rotation, specified as a scalar `so2` object, a scalar `so3` object, or as an *N*-element array of rotation objects. *N* is the total number of rotations.

If you specify `rotation` as an array, each element must be of the same type.

**`points` — Points to transform**
*N*-by-*D*-by-*M* array | *D*-by-*N*-by-*M* array

Points to transform, specified as an *N*-by-*D*-by-*M* array, where:

- *D* is the dimension of the transformation, defined as 2 for 2-D transformations and 3 for 3-D transformations.
- *N* is the total number of input points to transform.
- *M* is the total number of transforms to perform on each point.

For 2-D transformations and rotations, each row specifies a point in the form [*X Y*]. For 3-D transformations and rotations, each row specifies a point in the form [*X Y Z*].

If you specify `format` as `true`, then you must specify `points` as a *D*-by-*N*-by-*M* array, where each column specifies a point.

Data Types: `single` | `double`

**`format` — Point format**
`false` or `0` (default) | `true` or `1`

Point format, specified as a logical `0` (`false`) or `1` (`true`). If you specify this argument as true, you must specify the points in points as columns. Otherwise, specify points as rows.

Example: `isCol=true`

Data Types: `logical`

## Output Arguments

**`tpoints` — Transformed points**
*N*-by-*D*-by-*M* array | *D*-by-*N*-by-*M* array

Transformed points, returned as an *N*-by-*D*-by-*M* array, where:

- *D* is the dimension of the transformation, defined as 2 for 2-D transformations and rotations and 3 for 3-D transformations or rotations.
- *N* is the total number of input points to transform.
- *M* is the total number of transforms to perform on each point.

For 2-D transformations and rotations, each row specifies a point in the form [*X Y*]. For 3-D transformations and rotations, each row specifies a point in the form [*X Y Z*].

If you specify `format` as `true`, `tpoints` is returned as a *D*-by-*N*-by-*M* array, where each column specifies a point.

# Version History

**Introduced in R2022b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Functions**
`dist` | `interp` | `normalize` | `rotm` | `tform` | `trvec` | `plotTransforms`

**Objects**
`se2` | `se3` | `so2` | `so3`

# trvec

Extract translation vector

## Syntax

```
translationVector = trvec(transformation)
```

## Description

`translationVector = trvec(transformation)` extracts the translation vector `translationVector` of the SE(2) or SE(3) transformation `transformation`.

## Input Arguments

**`transformation` — Transformation**
`se2` object | `se3` object | *N*-element array of transformation objects

Transformation, specified as a scalar `se2` object, a scalar `se3` object, or an *N*-element array of transformation objects. *N* is the total number of transformations.

If you specify `transformation` as an array, each element must be of the same type.

## Output Arguments

**`translationVector` — Translation vector**
*N*-by-2 matrix | *N*-by-3 matrix

Translation vector, returned as an *N*-by-2 matrix for `se2` objects or an *N*-by-3 matrix for `se3` objects. *N* is the total number of transformations or rotations, and each row is a translation vector in the form [*X Y*] for 2-D transformations or [*X Y Z*] for 3-D transformations.

# Version History

**Introduced in R2022b**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Functions**
`dist` | `interp` | `normalize` | `rotm` | `tform` | `transform` | `plotTransforms`

**Objects**
`se2` | `se3`

# xytheta

Convert transformation or rotation to compact 2-D pose representation

## Syntax

```
pose = xytheta(transformation)
pose = xytheta(rotation)
```

## Description

`pose = xytheta(transformation)` converts a transformation `transformation` to a compact 2-D pose representation `pose`.

`pose = xytheta(rotation)` converts a rotation `rotation` to a compact 2-D pose representation `pose` with no translation.

## Examples

### Convert SE(2) Transformation to 2-D Compact Pose

Create SE(2) transformation with an *xy*-position of `[2 3]` and a rotation defined by an angle `pi/2`.

```
pose1 = [2 3 pi/2];
T = se2(pose1,"xytheta")
```

```
T = se2
    0.0000   -1.0000    2.0000
    1.0000    0.0000    3.0000
         0         0    1.0000
```

Convert the transformation back into a compact pose.

```
pose2 = xytheta(T)
```

```
pose2 = 1×3

    2.0000    3.0000    1.5708
```

### Convert SO(2) Rotation to 2-D Compact Pose

Create SO(2) rotation defined by an angle `pi/2`.

```
angle = pi/2
```

```
angle = 1.5708
```

```
R = so2(angle,"theta")
```

```
R = so2
    0.0000   -1.0000
    1.0000    0.0000
```

Convert the transformation back into a compact pose.

```
pose = xytheta(R)
```

```
pose = 1×3

         0         0    1.5708
```

## Input Arguments

### `transformation` — Transformation

`se2` object | *N*-element array of `se2` objects

Transformation, specified as an `se2` object or as an *N*-element array of `se2` objects. *N* is the total number of transformations.

Data Types: `single` | `double`

### `rotation` — Rotation

`so2` object | *N*-element array of `so2` objects

Rotation, specified as an `so2` object or as an *N*-element array of `so2` objects. *N* is the total number of rotations.

## Output Arguments

### `pose` — 2-D compact pose

*N*-by-3 matrix

2-D compact pose, returned as an *N*-by-3 matrix, where each row is of the form [*x* *y* *theta*]. *N* is the total number of transformations specified. *x* and *y* are the *xy*-position and *theta* is the rotation about the *z*-axis.

# Version History

**Introduced in R2023a**

## See Also

`se2` | `so2`

# xyzquat

Convert transformation or rotation to compact 3-D pose representation

## Syntax

```
pose = xyzquat(transformation)
pose = xyzquat(rotation)
```

## Description

`pose = xyzquat(transformation)` converts a transformation `transformation` to a compact 3-D pose representation `pose`.

`pose = xyzquat(rotation)` converts a rotation `rotation` to a compact 3-D pose representation `pose` with no translation.

## Examples

### Convert SE(3) Transformation to 3-D Compact Pose

Create SE(3) transformation with an *xyz*-position of `[2 3 1]` and a rotation defined by a numeric quaternion. Use the `eul2quat` function to create the numeric quaternion.

```
trvec = [2 3 1];
quat1 = eul2quat([0 0 deg2rad(30)]);
pose1 = [trvec quat1]
```

```
pose1 = 1×7

    2.0000    3.0000    1.0000    0.9659    0.2588         0         0
```

```
T = se3(pose1,"xyzquat")
```

```
T = se3
    1.0000         0         0    2.0000
         0    0.8660   -0.5000    3.0000
         0    0.5000    0.8660    1.0000
         0         0         0    1.0000
```

Convert the transformation back into a compact pose.

```
pose2 = xyzquat(T)
```

```
pose2 = 1×7

    2.0000    3.0000    1.0000    0.9659    0.2588         0         0
```

#### Convert SO(3) Rotation to 3-D Compact Pose

Create SO(3) rotation defined by a numeric quaternion. Use the `eul2quat` function to create the numeric quaternion.

```
quat1 = eul2quat([0 0 deg2rad(30)])
```

```
quat1 = 1×4

    0.9659    0.2588         0         0
```

```
R = so3(quat1,"quat")
```

```
R = so3
    1.0000         0         0
         0    0.8660   -0.5000
         0    0.5000    0.8660
```

Convert the rotation into a 3-D compact pose.

```
pose1 = xyzquat(R)
```

```
pose1 = 1×7

         0         0         0    0.9659    0.2588         0         0
```

## Input Arguments

**`transformation` — Transformation**
`se3` object | *N*-element array of `se3` objects

Transformation, specified as an `se3` object or as an *N*-element array of `se3` objects. *N* is the total number of transformations.

**`rotation` — Rotation**
`so3` object | *N*-element array of `so3` objects

Rotation, specified as an `so3` object or as an *N*-element array of `so3` objects. *N* is the total number of rotations.

## Output Arguments

**`pose` — 3-D compact pose**
*M*-by-3 matrix

3-D compact pose, returned as an *M*-by-3 matrix, where each row is of the form [*x y z qx qy qz qw*]. *M* is the total number of transformations specified. *x*, *y*, *z* comprise the xyz-position and *qw*, *qx*, *qy*, and *qz* are the quaternion rotations in *w*, *x*, *y*, and *z*, respectively.

# Version History

**Introduced in R2023a**

## See Also

se3 | so3

# addPlanner

Add path planner for benchmarking

## Syntax

```
addPlanner(plannerBM,planFcn)
addPlanner(plannerBM,planFcn,initializationFcn)
addPlanner( ___ ,Name=Value)
```

## Description

`addPlanner(plannerBM,planFcn)` adds the plan function of a planner as a function handle `planFcn` to the `plannerBenchmark` object.

`addPlanner(plannerBM,planFcn,initializationFcn)` also adds the initialization function of a planner as a function handle `initializationFcn` to the `plannerBenchmark` object.

`addPlanner( ___ ,Name=Value)` specifies options using one or more name-value arguments in addition to any combination of input arguments from previous syntaxes.

## Examples

### Benchmark 2-D Path Planners

Create an occupancy map from an example map.

```
load("exampleMaps.mat","simpleMap");
map = occupancyMap(simpleMap);
```

Create a state validator with `stateSpaceSE2` using the map.

```
sv = validatorOccupancyMap(stateSpaceSE2,Map=map);
```

Specify the start and goal states.

```
start = [5 8 pi/2];
goal = [7 18 pi/2];
```

Create a `plannerBenchmark` object.

```
pbo = plannerBenchmark(sv,start,goal);
```

Define the function handles for the initialization functions of the planners.

```
plannerHAFcn = @(sv)plannerHybridAStar(sv);
plannerRRTSFcn = @(sv)plannerRRTStar(sv.StateSpace,sv);
```

Define the function handle for the plan function, which is common for both planners.

```
plnFcn = @(initOut,s,g)plan(initOut,s,g);
```

Add the path planners for benchmarking.

```
addPlanner(pbo,plnFcn,plannerHAFcn);
addPlanner(pbo,plnFcn,plannerRRTSFcn,PlannerName="ppRRTStar");
```

Set the `rng` for repetitive results.

```
rng('default')
```

Run the path planners for the number of times specified in `runCount` to collect metrics.

```
runCount = 5;
runPlanner(pbo,runCount)
```

```
Initializing plannerHAFcn_plnFcn ...
Done.
Planning a path from the start pose (5 8 1.5708) to the goal pose (7 18 1.5708) using plannerHAFc
Executing run 1.
Executing run 2.
Executing run 3.
Executing run 4.
Executing run 5.
Initializing ppRRTStar ...
Done.
Planning a path from the start pose (5 8 1.5708) to the goal pose (7 18 1.5708) using ppRRTStar.
Executing run 1.
Executing run 2.
Executing run 3.
Executing run 4.
Executing run 5.
```

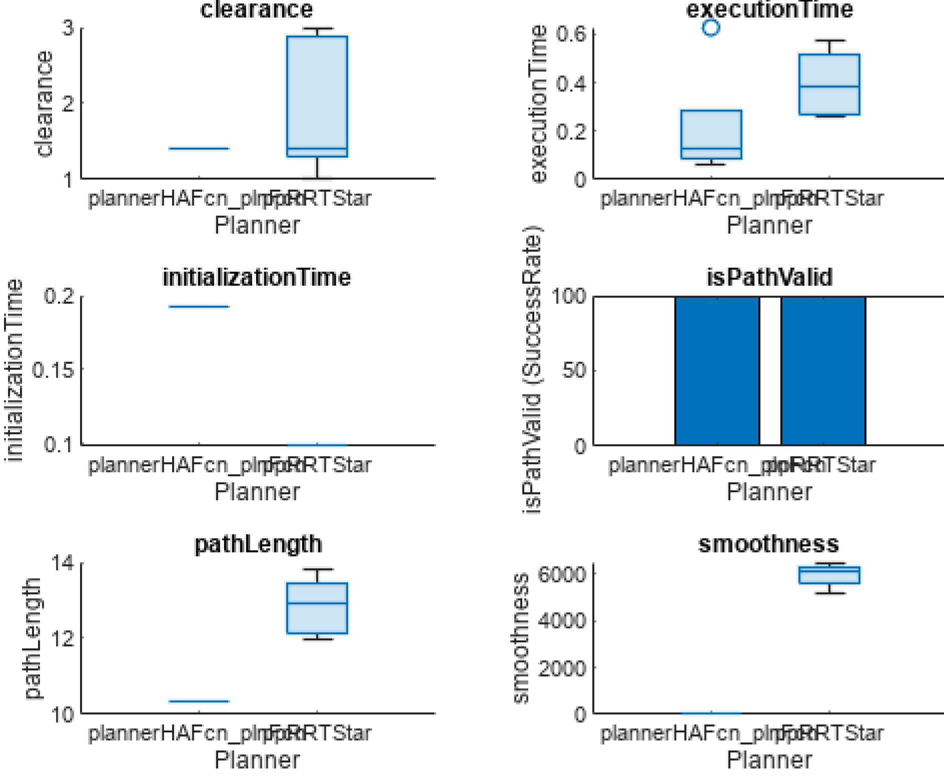
Access path length metric for all the runs on the environment.

```
[pLenSummary,pLenData] = metric(pbo,"pathLength")
```

```
pLenSummary=2×4 table
                            Mean      Median     StdDev      sampleSize
                           ______     ______     _______     __________

    plannerHAFcn_plnFcn    10.349     10.349           0         5     
    ppRRTStar               12.84       12.9     0.67112         5     


pLenData=2×5 table
                            Run1       Run2       Run3       Run4       Run5 
                           ______     ______     ______     ______     ______

    plannerHAFcn_plnFcn    10.349     10.349     10.349     10.349     10.349
    ppRRTStar                13.8       12.9       12.2         12       13.3
```

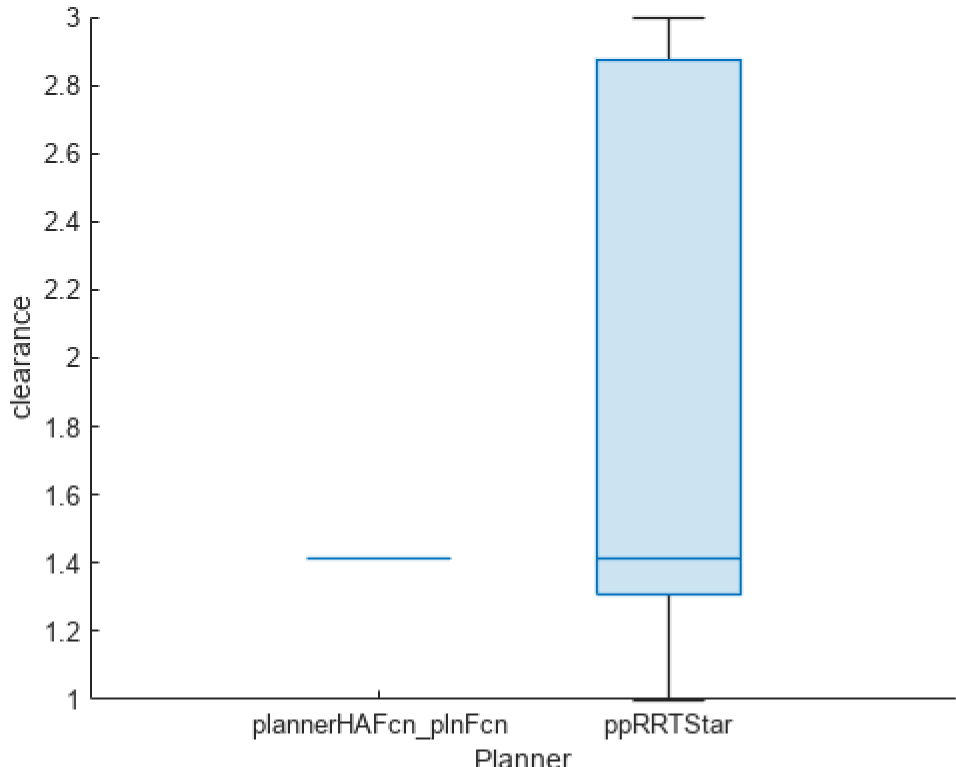
Visualize all the metrics.

```
show(pbo)
```




Closely inspect the clearance metric.

```
figure
show(pbo,"clearance")
```




## Input Arguments

**plannerBM — Path planner benchmark**
plannerBenchmark object

Path planner benchmark, specified as a `plannerBenchmark` object.

**planFcn — Plan function of path planner**
function handle

Plan function of path planner, specified as a function handle.

The function handle should be of the form, `@(initOut,start,goal)planFcn(...)`, where `initOut` is the output of the initialization function.

If the `initializationFcn` input is not specified, the function handle should be `@(env,start,goal)planFcn(...)`, where `env` is the `Environment` property of `plannerBenchmark` object.

The first output of `planFcn` must be either a `navPath` object, *m*-by-2, or *m*-by-3 matrix.

Data Types: `function_handle`

**initializationFcn — Initialization function of path planner**
function handle

Initialization function of path planner, specified as a function handle.

The function handle should be of the form, `@(env)initializationFcn(...)`, where `env` is the `Environment` property of `plannerBenchmark` object.

The output of `initializationFcn` is the first input to the `planFcn` function handle.

Data Types: `function_handle`

#### Name-Value Pair Arguments

Specify optional pairs of arguments as `Name1=Value1,...,NameN=ValueN`, where `Name` is the argument name and `Value` is the corresponding value. Name-value arguments must appear after other arguments, but the order of the pairs does not matter.

*Before R2021a, use commas to separate each name and value, and enclose* `Name` *in quotes.*

Example: `addPlanner(pbo,plnFcn,plannerRRTSFcn,PlannerName="ppRRTStar")`

**`PlannerName` — Name of planner**
character vector | string scalar

Name of planner, specified as character vector or string scalar.

The default planner name depends on one of the following,

- If workspace variable name of `initializationFcn` and `planFcn` are `initVar` and `planVar`, respectively, the default planner name will be `"initVar_planVar"`.
- If the optional `initializationFcn` input is not specified then the default planner name will be `"planVar"`.
- If the function handles are specified as anonymous functions directly inside the `addPlanner` function, the default planner name will be `"CustomInitFcn_CustomPlanFcn"`.
- If the optional `initializationFcn` input is not specified and the `planFcn` function handle is specified as an anonymous function directly then the default planner name will be `"CustomPlanFcn"`.

Data Types: `char` | `string`

**`NumPlanOutput` — Number of expected output from plan function**
`1` (default) | positive scalar

Number of expected output from plan function, specified as a positive scalar.

Data Types: `single` | `double`

## Version History

**Introduced in R2022a**

### See Also

**Objects**
`plannerBenchmark`

**Functions**
`copy` | `metric` | `report` | `runPlanner` | `show`

# copy

Create deep copy of plannerBenchmark object

## Syntax

```
plannerBM2 = copy(plannerBM1)
```

## Description

`plannerBM2 = copy(plannerBM1)` creates a deep copy of the `plannerBenchmark` object with the same properties.

## Examples

### Create Copy of plannerBenchmark Object

Create an occupancy map from an example map.

```
load("exampleMaps.mat","simpleMap");
map = occupancyMap(simpleMap);
```

Specify the start and goal states.

```
start = [5 8 pi/2];
goal = [7 18 pi/2];
```

Create a `plannerBenchmark` object using the map.

```
pbo = plannerBenchmark(map,start,goal)
```

```
pbo = 
  plannerBenchmark with properties:

      Environment: [1x1 occupancyMap]
            Start: [5 8 1.5708]
             Goal: [7 18 1.5708]
    PlannerOutput: [1x1 struct]
```

Create a copy of `plannerBenchmark` object.

```
pboNew = copy(pbo)
```

```
pboNew = 
  plannerBenchmark with properties:

      Environment: [1x1 occupancyMap]
            Start: [5 8 1.5708]
             Goal: [7 18 1.5708]
    PlannerOutput: [1x1 struct]
```

## Input Arguments

**plannerBM1 — Path planner benchmark**
plannerBenchmark object

Path planner benchmark, specified as a plannerBenchmark object.

## Output Arguments

**plannerBM2 — Copy of path planner benchmark**
plannerBenchmark object

Copy of path planner benchmark, returned as a plannerBenchmark object.

# Version History

**Introduced in R2022a**

## See Also

**Objects**
plannerBenchmark

**Functions**
addPlanner | metric | report | runPlanner | show

# metric

Return path planner metrics

## Syntax

```
metricSummary = metric(plannerBM)
metricSummary = metric(plannerBM,metricName)
[metricSummary,metricData] = metric(plannerBM)
[metricSummary,metricData] = metric(plannerBM,metricName)
```

## Description

`metricSummary = metric(plannerBM)` returns the summary of all the path planner metrics as a table.

`metricSummary = metric(plannerBM,metricName)` returns the summary of a specific metric.

`[metricSummary,metricData] = metric(plannerBM)` returns the `metricData` table with the metric values across each run for all metrics and `metricSummary` table with the summary of all metrics.

`[metricSummary,metricData] = metric(plannerBM,metricName)` returns the summary and the values of a specific metric.

## Examples

### Benchmark 2-D Path Planners

Create an occupancy map from an example map.

```
load("exampleMaps.mat","simpleMap");
map = occupancyMap(simpleMap);
```

Create a state validator with `stateSpaceSE2` using the map.

```
sv = validatorOccupancyMap(stateSpaceSE2,Map=map);
```

Specify the start and goal states.

```
start = [5 8 pi/2];
goal = [7 18 pi/2];
```

Create a `plannerBenchmark` object.

```
pbo = plannerBenchmark(sv,start,goal);
```

Define the function handles for the initialization functions of the planners.

```
plannerHAFcn = @(sv)plannerHybridAStar(sv);
plannerRRTSFcn = @(sv)plannerRRTStar(sv.StateSpace,sv);
```

Define the function handle for the plan function, which is common for both planners.

```
plnFcn = @(initOut,s,g)plan(initOut,s,g);
```

Add the path planners for benchmarking.

```
addPlanner(pbo,plnFcn,plannerHAFcn);
addPlanner(pbo,plnFcn,plannerRRTSFcn,PlannerName="ppRRTStar");
```

Set the `rng` for repetitive results.

```
rng('default')
```

Run the path planners for the number of times specified in `runCount` to collect metrics.

```
runCount = 5;
runPlanner(pbo,runCount)
```

```
Initializing plannerHAFcn_plnFcn ...
Done.
Planning a path from the start pose (5 8 1.5708) to the goal pose (7 18 1.5708) using plannerHAFc
Executing run 1.
Executing run 2.
Executing run 3.
Executing run 4.
Executing run 5.
Initializing ppRRTStar ...
Done.
Planning a path from the start pose (5 8 1.5708) to the goal pose (7 18 1.5708) using ppRRTStar.
Executing run 1.
Executing run 2.
Executing run 3.
Executing run 4.
Executing run 5.
```

Access path length metric for all the runs on the environment.

```
[pLenSummary,pLenData] = metric(pbo,"pathLength")
```

pLenSummary=*2×4 table*

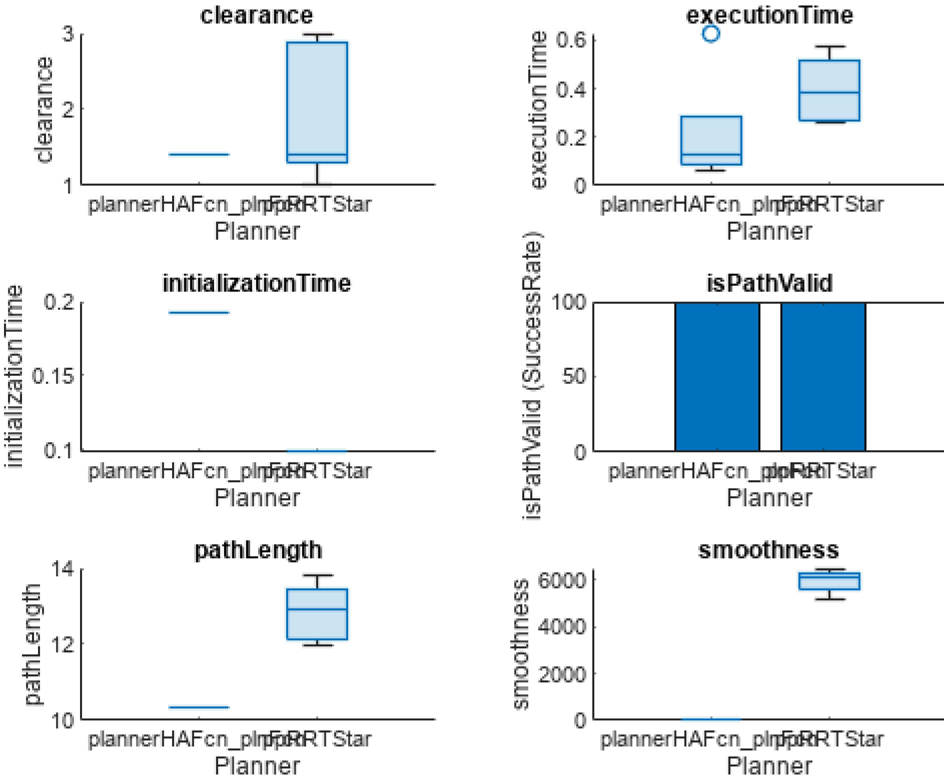
| | Mean | Median | StdDev | sampleSize |
|---|---|---|---|---|
| plannerHAFcn_plnFcn | 10.349 | 10.349 | 0 | 5 |
| ppRRTStar | 12.84 | 12.9 | 0.67112 | 5 |

pLenData=*2×5 table*

| | Run1 | Run2 | Run3 | Run4 | Run5 |
|---|---|---|---|---|---|
| plannerHAFcn_plnFcn | 10.349 | 10.349 | 10.349 | 10.349 | 10.349 |
| ppRRTStar | 13.8 | 12.9 | 12.2 | 12 | 13.3 |

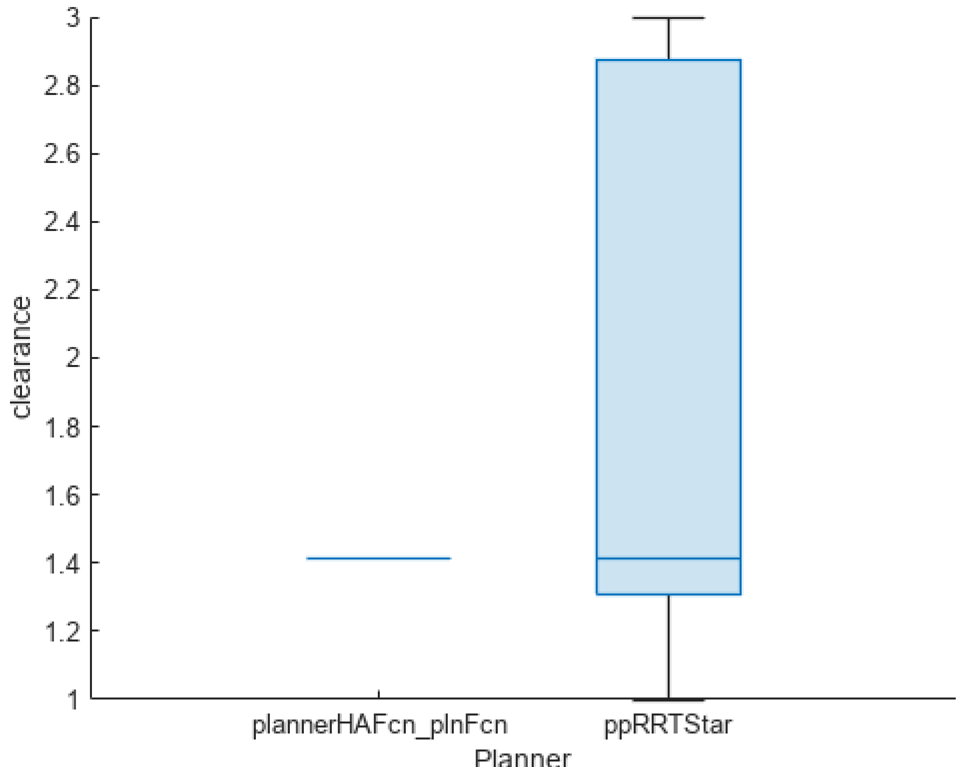
Visualize all the metrics.

```
show(pbo)
```




Closely inspect the clearance metric.

```
figure
show(pbo,"clearance")
```




## Input Arguments

**plannerBM — Path planner benchmark**
plannerBenchmark object

Path planner benchmark, specified as a plannerBenchmark object.

**metricName — Metric name**
"clearance" | "executionTime" | "initializationTime" | "isPathValid" | "pathLength" | "smoothness"

Metric name, specified as "clearance", "executionTime", "initializationTime", "isPathValid", "pathLength", or "smoothness".

Data Types: char | string

## Output Arguments

**metricSummary — Metric summary**
table

Metric summary, returned as table. The summary includes mean, median, standard deviation, and sample size for metrics of numeric type. For the metrics of logical type, the summary includes the TrueCount, FalseCount, and SuccessRate. TrueCount is the number of times the metric value is

true. `FalseCount` is the number of times the metric value is false. `SuccessRate` is the ratio of `TrueCount` to total runs of planner expressed in percentage.

Data Types: `table`

**`metricData` — Metric value**
table

Metric value, returned as table. The table contains the metric values across each run for all metrics.

Data Types: `table`

## Tips

- If the metric value can not be computed due to empty states in path output or error during plan function execution, `NaN` will be displayed for corresponding values in metric data tables. The show function will not display any value for metrics with `NaN` value.
- If the path output is `navPath`, metrics are calculated using the state space in `navPath`.
- If the path output is a *m*-by-2 matrix, state space is assumed as `stateSpaceSE2` with theta as `0` for all poses.
- If the path output is a *m*-by-3 matrix, the third column in the path output is assumed as theta and subsequently `stateSpaceSE2` is assumed as the state space.
- If environment is `validatorOccupancyMap`, the metric `isPathValid` is computed using the specified environment.
- If environment is `occupancyMap` or `binaryOccupancyMap`, default `validatorOccupancyMap` is created using the specified environment as Map and state space is derived as above.
- The value of `ValidationDistance` property is assumed as `0.1*(1/resolution of map)`.

# Version History

**Introduced in R2022a**

## See Also

**Objects**
`plannerBenchmark`

**Functions**
`addPlanner` | `copy` | `report` | `runPlanner` | `show`

# report

Create benchmark report

## Syntax

```
report(plannerBM)
report(plannerBM,filename)
report(plannerBM,filename,Name=Value)
```

## Description

`report(plannerBM)` creates and opens a benchmark report as a live script (`.mlx`) in the MATLAB editor. The function saves the report in the current working directory with the default file name.

---

**Note** The `report` function also exports the input `plannerBenchmark` object to a MAT file and places the file in a folder called `plannerBenchmark`, located in the same directory as the saved report.

---

`report(plannerBM,filename)` specifies the name and location `filename` of the saved report.

`report(plannerBM,filename,Name=Value)` specifies options using one or more name-value arguments. For example, `report(plannerBM,"reportFile",Open=false)` creates a benchmark report file named `reportFile.mlx` and saves it in the current working directory, but does not open the report in the MATLAB editor.

## Examples

### Generate Benchmark Report for 2-D Path Planners

Create an occupancy map from an example map.

```
load("exampleMaps.mat","simpleMap");
map = occupancyMap(simpleMap);
```

Create a state validator in the SE(2) state space using the map.

```
sv = validatorOccupancyMap(stateSpaceSE2,Map=map);
```

Specify the start and goal states.

```
start = [5 8 pi/2];
goal = [7 18 pi/2];
```

Create a `plannerBenchmark` object.

```
pbo = plannerBenchmark(sv,start,goal);
```

Define the function handles for the initialization functions of the planners.

```
plannerHAFcn = @(sv)plannerHybridAStar(sv);
plannerRRTSFcn = @(sv)plannerRRTStar(sv.StateSpace,sv);
```

Define the function handle for the plan function, which is shared by both planners.

```
plnFcn = @(initOut,s,g)plan(initOut,s,g);
```

Add the path planners for benchmarking to the `plannerBenchmark` object.

```
addPlanner(pbo,plnFcn,plannerHAFcn);
addPlanner(pbo,plnFcn,plannerRRTSFcn,PlannerName="ppRRTStar");
```

Configure the random number generator to ensure a repeatable result.

```
rng("default")
```

Run the path planners five times each to collect metrics.

```
runCount = 5;
runPlanner(pbo,runCount)
```

```
Initializing plannerHAFcn_plnFcn ...
Done.
Planning a path from the start pose (5 8 1.5708) to the goal pose (7 18 1.5708) using plannerHAF
Executing run 1.
Executing run 2.
Executing run 3.
Executing run 4.
Executing run 5.
Initializing ppRRTStar ...
Done.
Planning a path from the start pose (5 8 1.5708) to the goal pose (7 18 1.5708) using ppRRTStar.
Executing run 1.
Executing run 2.
Executing run 3.
Executing run 4.
Executing run 5.
```

Generate a benchmark report file named `reportFile.mlx` that contains the clearance and smoothness metrics. The function opens the report in the MATLAB editor.

```
report(pbo,"reportFile",Metric=["clearance","smoothness"])
```

Run the `reportFile.mlx` to visualize the benchmark results of the specified 2-D path planners for each specified metric.

## Input Arguments

**`plannerBM` — Path planner benchmark**
`plannerBenchmark` object

Path planner benchmark, specified as a `plannerBenchmark` object.

**`filename` — Name of report file**
`"report.mlx"` (default) | string scalar | character vector

Name of the report file, specified as string scalar or character vector. The file name can include an absolute path, relative path, or no path. Specifying the `.mlx` extension is optional.

Example: `"reportFile"`

Example: `"reportFile.mlx"`

Example: `"mydir/reportFile"`

Example: `"mydir/reportFile.mlx"`

Example: `"C:/mydir/reportFile"`

Example: `"C:/mydir/reportFile.mlx"`

Data Types: `char` | `string`

### Name-Value Pair Arguments

Specify optional pairs of arguments as `Name1=Value1,...,NameN=ValueN`, where `Name` is the argument name and `Value` is the corresponding value. Name-value arguments must appear after other arguments, but the order of the pairs does not matter.

Example: `report(plannerBM,"reportFile",Open=false)` creates a benchmark report file named `reportFile.mlx` in the current directory, but does not open the report in the MATLAB editor.

#### `Metric` — Metrics to include in report

`["clearance","executionTime","initializationTime","isPathValid","pathLength","smoothness"]` (default) | string scalar | character vector | string array | cell array of character vectors

Metrics to include in the report, specified as a string scalar, character vector, string array, or cell array of character vectors of supported metrics. The supported metrics are:

- `"clearance"`
- `"executionTime"`
- `"initializationTime"`
- `"isPathValid"`
- `"pathLength"`
- `"smoothness"`

Example: `Metric="clearance"`

Example: `Metric='clearance'`

Example: `Metric=["clearance","executionTime"]`

Example: `Metric={'clearance','executionTime'}`

Data Types: `char` | `string` | `cell`

#### `Exclude` — Content sections to exclude from report

`"None"` (default) | string scalar | character vector | string array | cell array of character vectors

Content sections to exclude from the report, specified as a string scalar, character vector, string array, or a cell array of character vectors of supported contents of exclusion. The supported contents of exclusion are:

- "PathVisualization"
- "DetailedTable"

Specifying "PathVisualization" excludes the **Visualize Path on Map** section from the report. Specifying "DetailedTable" excludes the metric tables containing the metric results for the planners from the individual planning executions.

Example: Exclude="PathVisualization"

Example: Exclude='PathVisualization'

Example: Exclude=["PathVisualization","DetailedTable"]

Example: Exclude={'PathVisualization','DetailedTable'}

Data Types: char | string | cell

**Open — Report opens in editor**
true or 1 (default) | false or 0

Report opens in the editor, specified as a logical 1 (true) or 0 (false). When you specify this argument as true, the function opens the report in the MATLAB editor. Otherwise, it does not open the report in the editor.

Example: Open=false

Data Types: logical

# Version History

**Introduced in R2022b**

## See Also

**Objects**
plannerBenchmark

**Functions**
addPlanner | copy | runPlanner | show | metric

# runPlanner

Run path planners

## Syntax

```
runPlanner(plannerBM)
runPlanner(plannerBM,runCount)
runPlanner( ___ ,Verbose=Value)
```

## Description

`runPlanner(plannerBM)` runs all the path planners once.

`runPlanner(plannerBM,runCount)` specifies the number of times to run all the path planners. The function collects outputs of initialization function and plan function. The function also calculates the metric, `executionTime` for the plan function and the metric, `initializationTime` for the initialization function.

`runPlanner( ___ ,Verbose=Value)` specifies verbose which display function progress. Value of verbose is specified as `"on"` or `"off"`. The default value of verbose is `"on"`.

## Examples

### Benchmark 2-D Path Planners

Create an occupancy map from an example map.

```
load("exampleMaps.mat","simpleMap");
map = occupancyMap(simpleMap);
```

Create a state validator with `stateSpaceSE2` using the map.

```
sv = validatorOccupancyMap(stateSpaceSE2,Map=map);
```

Specify the start and goal states.

```
start = [5 8 pi/2];
goal = [7 18 pi/2];
```

Create a `plannerBenchmark` object.

```
pbo = plannerBenchmark(sv,start,goal);
```

Define the function handles for the initialization functions of the planners.

```
plannerHAFcn = @(sv)plannerHybridAStar(sv);
plannerRRTSFcn = @(sv)plannerRRTStar(sv.StateSpace,sv);
```

Define the function handle for the plan function, which is common for both planners.

```
plnFcn = @(initOut,s,g)plan(initOut,s,g);
```

Add the path planners for benchmarking.

```
addPlanner(pbo,plnFcn,plannerHAFcn);
addPlanner(pbo,plnFcn,plannerRRTSFcn,PlannerName="ppRRTStar");
```

Set the `rng` for repetitive results.

```
rng('default')
```

Run the path planners for the number of times specified in `runCount` to collect metrics.

```
runCount = 5;
runPlanner(pbo,runCount)
```

```
Initializing plannerHAFcn_plnFcn ...
Done.
Planning a path from the start pose (5 8 1.5708) to the goal pose (7 18 1.5708) using plannerHAFc
Executing run 1.
Executing run 2.
Executing run 3.
Executing run 4.
Executing run 5.
Initializing ppRRTStar ...
Done.
Planning a path from the start pose (5 8 1.5708) to the goal pose (7 18 1.5708) using ppRRTStar.
Executing run 1.
Executing run 2.
Executing run 3.
Executing run 4.
Executing run 5.
```

Access path length metric for all the runs on the environment.

```
[pLenSummary,pLenData] = metric(pbo,"pathLength")
```

pLenSummary=*2×4 table*

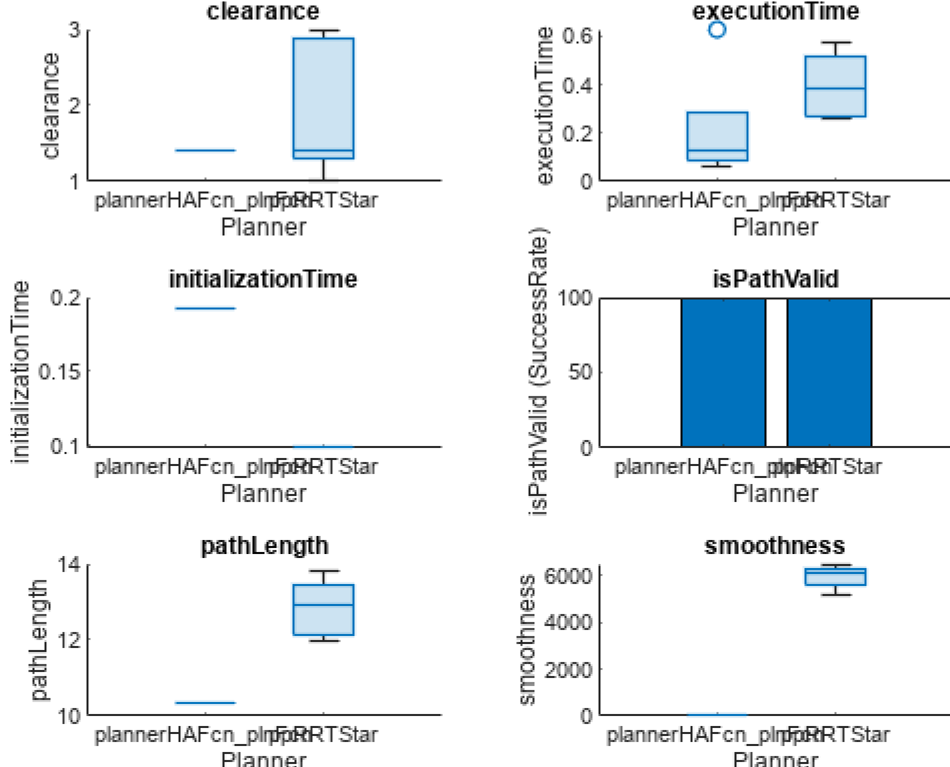
| | Mean | Median | StdDev | sampleSize |
|---|---|---|---|---|
| plannerHAFcn_plnFcn | 10.349 | 10.349 | 0 | 5 |
| ppRRTStar | 12.84 | 12.9 | 0.67112 | 5 |

pLenData=*2×5 table*

| | Run1 | Run2 | Run3 | Run4 | Run5 |
|---|---|---|---|---|---|
| plannerHAFcn_plnFcn | 10.349 | 10.349 | 10.349 | 10.349 | 10.349 |
| ppRRTStar | 13.8 | 12.9 | 12.2 | 12 | 13.3 |

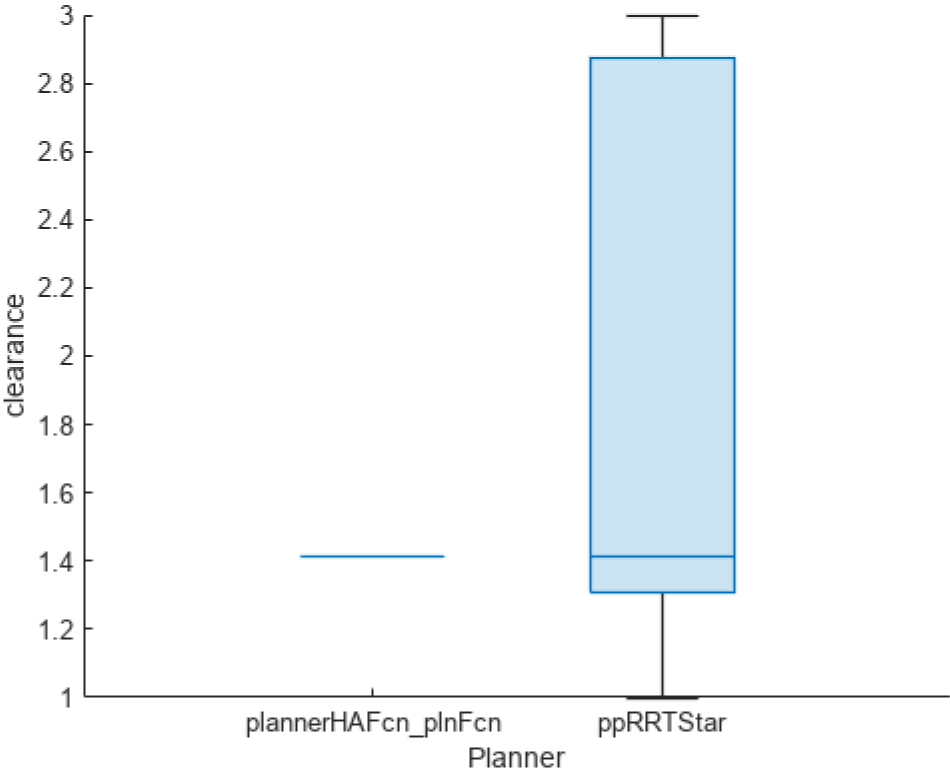
Visualize all the metrics.

```
show(pbo)
```




Closely inspect the clearance metric.

```
figure
show(pbo,"clearance")
```




## Input Arguments

**`plannerBM` — Path planner benchmark**
`plannerBenchmark` object

Path planner benchmark, specified as a `plannerBenchmark` object.

**`runCount` — Number of times of execution of plan functions**
`1` (default) | positive scalar

Number of times of execution of plan functions, specified as a positive scalar.

Data Types: `single` | `double`

# Version History

**Introduced in R2022a**

## See Also

**Objects**
`plannerBenchmark`

**Functions**
`addPlanner` | `copy` | `metric` | `report` | `show`

# show

Visualize path planner metrics

## Syntax

```
show(plannerBM)
axHandle = show(plannerBM)
[ ___ ] = show(plannerBM,metricName)
```

## Description

`show(plannerBM)` visualizes all the path planner metrics in a figure as box plots and bar graphs.

`axHandle = show(plannerBM)` returns the axes handle of the figure used to plot all the metrics.

`[ ___ ] = show(plannerBM,metricName)` visualizes a specific metric.

## Examples

### Benchmark 2-D Path Planners

Create an occupancy map from an example map.

```
load("exampleMaps.mat","simpleMap");
map = occupancyMap(simpleMap);
```

Create a state validator with `stateSpaceSE2` using the map.

```
sv = validatorOccupancyMap(stateSpaceSE2,Map=map);
```

Specify the start and goal states.

```
start = [5 8 pi/2];
goal = [7 18 pi/2];
```

Create a `plannerBenchmark` object.

```
pbo = plannerBenchmark(sv,start,goal);
```

Define the function handles for the initialization functions of the planners.

```
plannerHAFcn = @(sv)plannerHybridAStar(sv);
plannerRRTSFcn = @(sv)plannerRRTStar(sv.StateSpace,sv);
```

Define the function handle for the plan function, which is common for both planners.

```
plnFcn = @(initOut,s,g)plan(initOut,s,g);
```

Add the path planners for benchmarking.

```
addPlanner(pbo,plnFcn,plannerHAFcn);
addPlanner(pbo,plnFcn,plannerRRTSFcn,PlannerName="ppRRTStar");
```

Set the `rng` for repetitive results.

```
rng('default')
```

Run the path planners for the number of times specified in `runCount` to collect metrics.

```
runCount = 5;
runPlanner(pbo,runCount)
```

```
Initializing plannerHAFcn_plnFcn ...
Done.
Planning a path from the start pose (5 8 1.5708) to the goal pose (7 18 1.5708) using plannerHAF
Executing run 1.
Executing run 2.
Executing run 3.
Executing run 4.
Executing run 5.
Initializing ppRRTStar ...
Done.
Planning a path from the start pose (5 8 1.5708) to the goal pose (7 18 1.5708) using ppRRTStar.
Executing run 1.
Executing run 2.
Executing run 3.
Executing run 4.
Executing run 5.
```

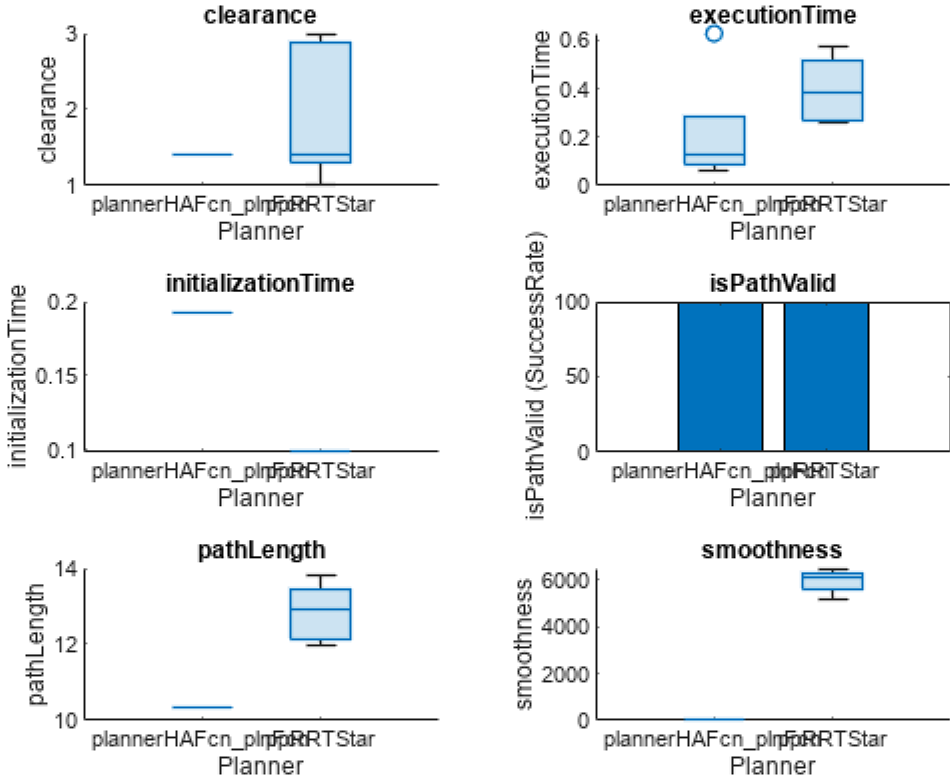
Access path length metric for all the runs on the environment.

```
[pLenSummary,pLenData] = metric(pbo,"pathLength")
```

```
pLenSummary=2×4 table
                            Mean     Median    StdDev     sampleSize
                           ______    ______    _______    __________

    plannerHAFcn_plnFcn    10.349    10.349          0        5     
    ppRRTStar               12.84      12.9    0.67112        5     

pLenData=2×5 table
                            Run1      Run2      Run3      Run4      Run5 
                           ______    ______    ______    ______    ______

    plannerHAFcn_plnFcn    10.349    10.349    10.349    10.349    10.349
    ppRRTStar                13.8      12.9      12.2        12      13.3
```

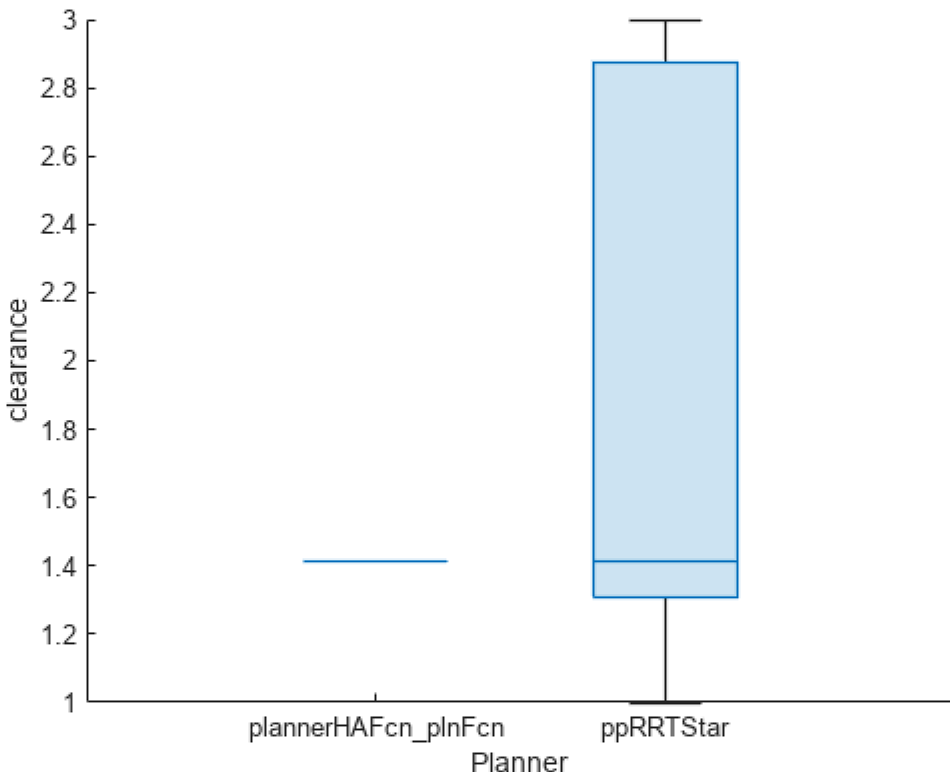
Visualize all the metrics.

```
show(pbo)
```




Closely inspect the clearance metric.

```
figure
show(pbo,"clearance")
```




## Input Arguments

**plannerBM — Path planner benchmark**
plannerBenchmark object

Path planner benchmark, specified as a `plannerBenchmark` object.

**metricName — Metric name**
"clearance" | "executionTime" | "initializationTime" | "isPathValid" | "pathLength" | "smoothness"

Metric name, specified as `"clearance"`, `"executionTime"`, `"initializationTime"`, `"isPathValid"`, `"pathLength"`, or `"smoothness"`.

Data Types: char | string

## Output Arguments

**axHandle — Axes used to plot metrics**
axes object | uiaxes object

Axes used to plot path, returned as either an `axes` or `uiaxes` object.

## Version History

**Introduced in R2022a**

## See Also

**Objects**
`plannerBenchmark`

**Functions**
`addPlanner` | `copy` | `metric` | `report` | `runPlanner`

# copy

Create deep copy of plannerPRM object

## Syntax

```
planner2 = copy(planner1)
```

## Description

`planner2 = copy(planner1)` creates a deep copy of the `plannerPRM` object with the same properties.

## Examples

### Create Copy of plannerPRM Object

Create an occupancy map from an example map and set the map resolution as 10 cells/meter.

```
map = load("exampleMaps.mat").simpleMap;
map = occupancyMap(map,10);
```

Create a state space and update the state space bounds to be the same as the map limits.

```
ss = stateSpaceSE2;
ss.StateBounds = [map.XWorldLimits; map.YWorldLimits; [-pi pi]];
```

Create a state validator with `stateSpaceSE2` using the map and set the validation distance.

```
sv = validatorOccupancyMap(ss,Map=map);
sv.ValidationDistance = 0.01;
```

Create a `plannerPRM` object.

```
planner = plannerPRM(ss,sv)
```

```
planner = 
  plannerPRM with properties:

               StateSpace: [1x1 stateSpaceSE2]
           StateValidator: [1x1 validatorOccupancyMap]
    MaxConnectionDistance: Inf
              MaxNumNodes: 50
```

Create a copy of the `plannerPRM` object.

```
plannerNew = copy(planner)
```

```
plannerNew = 
  plannerPRM with properties:

               StateSpace: [1x1 stateSpaceSE2]
```

```
        StateValidator: [1x1 validatorOccupancyMap]
    MaxConnectionDistance: Inf
           MaxNumNodes: 50
```

## Input Arguments

**planner1 — Path planner**
plannerPRM object

Path planner, specified as a plannerPRM object.

## Output Arguments

**planner2 — Copy of path planner**
plannerPRM object

Copy of path planner, returned as a plannerPRM object.

# Version History

**Introduced in R2022a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

**Objects**
plannerPRM

**Functions**
graphData | plan

# graphData

Retrieve graph as digraph object

## Syntax

```
graph = graphData(planner)
```

## Description

`graph = graphData(planner)` retrieves graph as a `digraph` object. The `digraph` object is created when the `plannerPRM` object is created with default or user specified values for the `MaxNumNodes` and `MaxConnectionDistance` properties.

## Examples

### Retrieve Graph from Probabilistic Roadmap Path Planner

Load an example map into the workspace, and use it to create an occupancy map with a resolution of 10 cells/meter.

```
load("exampleMaps.mat","simpleMap");
map = occupancyMap(simpleMap,10);
```

Create a state space object and update the state space bounds to match the map limits.

```
ss = stateSpaceSE2;
ss.StateBounds = [map.XWorldLimits; map.YWorldLimits; [-pi pi]];
```

Create a state validator for the occupancy map using the state space object and set the validation distance.

```
sv = validatorOccupancyMap(ss,Map=map);
sv.ValidationDistance = 0.01;
```

Create a probabilistic roadmap path planner object.

```
planner = plannerPRM(ss,sv);
```

Retrieve the network graph as a `digraph` object.

```
graph = graphData(planner);
```

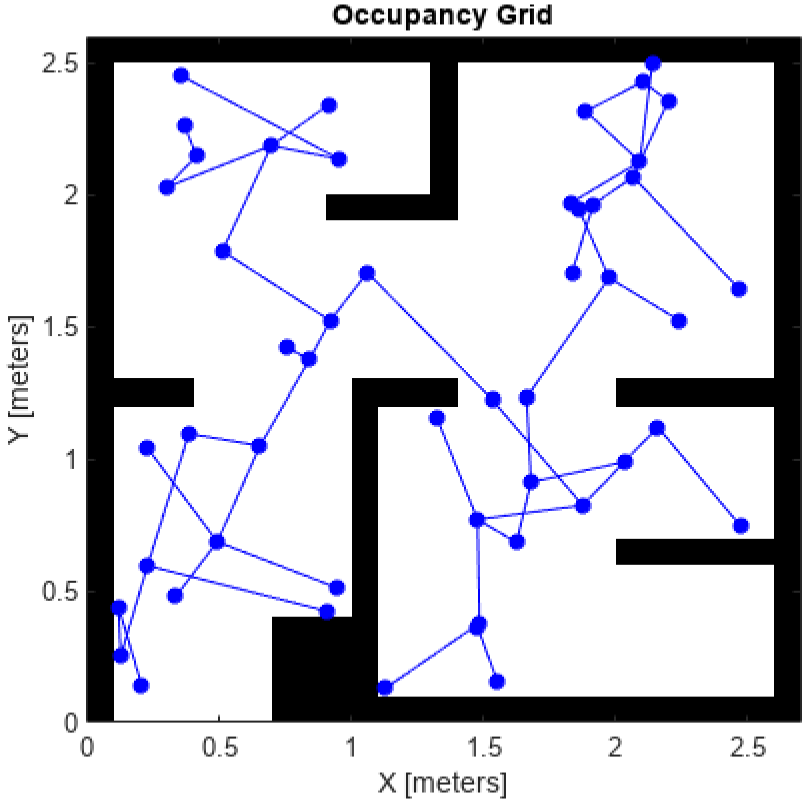
Extract the nodes and edges from the graph.

```
edges = table2array(graph.Edges);
nodes = table2array(graph.Nodes);
```

Plot the map and graph.

```
show(sv.Map)
hold on
```

```
plot(nodes(:,1),nodes(:,2),"*",Color=[0 0 1],LineWidth=2)
for i = 1:size(edges,1)
    % Samples states at distance 0.02 meters.
    states = interpolate(ss,nodes(edges(i,1),:), ...
                         nodes(edges(i,2),:),0:0.02:1);
    plot(states(:,1),states(:,2),Color=[0 0 1])
end
```




## Input Arguments

**planner — Path planner**
plannerPRM object

Path planner, specified as a `plannerPRM` object.

## Output Arguments

**graph — Graph data**
digraph object

Graph data, returned as a `digraph` object.

## Version History

**Introduced in R2022a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using MATLAB® Coder™.

## See Also

### Objects

`plannerPRM` | `digraph`

### Functions

`copy` | `plan`

# plan

Plan path between start and goal states on roadmap

## Syntax

```
path = plan(planner,startState,goalState)
[path,solutionInfo] = plan(planner,startState,goalState)
```

## Description

`path = plan(planner,startState,goalState)` returns an obstacle-free path as a `navPath` object between the start state and the goal state within a roadmap that contains a network graph of connected nodes.

`[path,solutionInfo] = plan(planner,startState,goalState)` also returns `solutionInfo` as a structure that contains the solution information of the path planning.

## Examples

### Plan Obstacle-Free Path Using Probabilistic Roadmap Path Planner

Create an occupancy map from an example map and set the map resolution as 10 cells/meter.

```
map = load("exampleMaps.mat").simpleMap;
map = occupancyMap(map,10);
```

Create a state space and update the state space bounds to be the same as the map limits.

```
ss = stateSpaceSE2;
ss.StateBounds = [map.XWorldLimits; map.YWorldLimits; [-pi pi]];
```

Create a state validator with `stateSpaceSE2` using the map and set the validation distance.

```
sv = validatorOccupancyMap(ss,Map=map);
sv.ValidationDistance = 0.01;
```

Create a `plannerPRM` object.

```
planner = plannerPRM(ss,sv);
```

Retrieve graph as a digraph object.

```
graph = graphData(planner);
```

Extract nodes and edges from graph.

```
edges = table2array(graph.Edges);
nodes = table2array(graph.Nodes);
```

Specify the start and goal states.

```
start = [0.5 0.5 0];
goal = [2.5 0.2 0];
```

Plot map and graph.

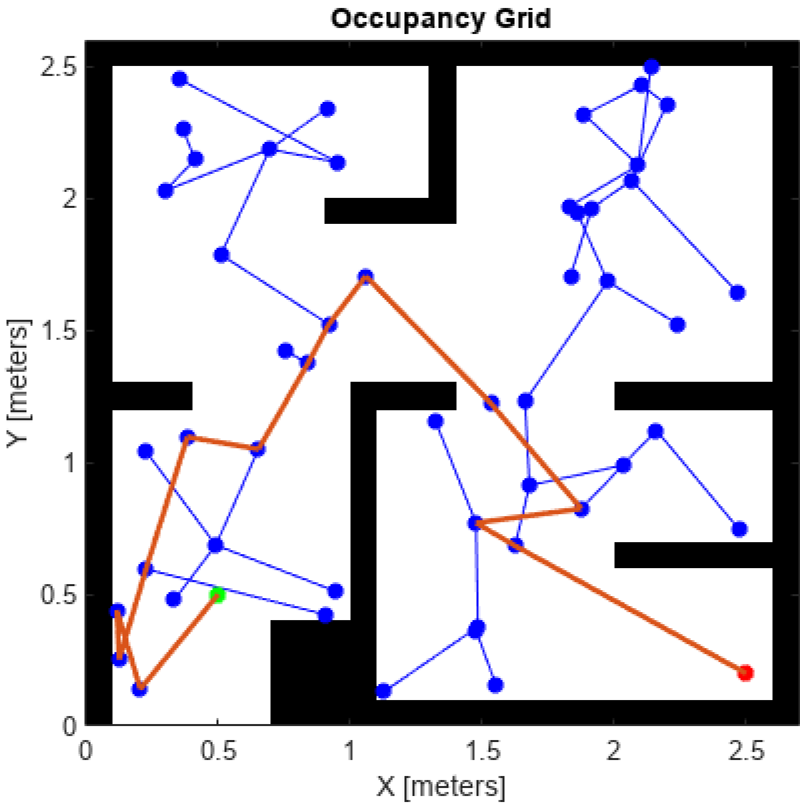
```
show(sv.Map)
hold on
plot(nodes(:,1),nodes(:,2),"*","Color","b","LineWidth",2)
for i = 1:size(edges,1)
    % Samples states at distance 0.02 meters.
    states = interpolate(ss,nodes(edges(i,1),:), ...
                         nodes(edges(i,2),:),0:0.02:1);
    plot(states(:,1),states(:,2),"Color","b")
end
plot(start(1),start(2),"*","Color","g","LineWidth",3)
plot(goal(1),goal(2),"*","Color","r","LineWidth",3)
```

Plan a path with default settings. Set the `rng` seed for repeatability.

```
rng(100,"twister");
[pthObj, solnInfo] = plan(planner,start,goal);
```

Visualize the results.

```
if solnInfo.IsPathFound
    interpolate(pthObj,1000);
    plot(pthObj.States(:,1),pthObj.States(:,2), ...
         "Color",[0.85 0.325 0.098],"LineWidth",2)
else
    disp("Path not found")
end
hold off
```




**Plan Path Through 3-D Occupancy Map Using Probabilistic Roadmap Planner**

Load a 3-D occupancy map of a city block into the workspace. Specify the threshold to consider cells as obstacle-free.

```
mapData = load("dMapCityBlock.mat");
omap = mapData.omap;
omap.FreeThreshold = 0.5;
```

Inflate the occupancy map to add a buffer zone for safe operation around the obstacles.

```
inflate(omap,1)
```

Create an SE(3) state space object with bounds for state variables.

```
ss = stateSpaceSE3([0 220;0 220;0 100;inf inf;inf inf;inf inf;inf inf]);
```

Create a 3-D occupancy map state validator using the created state space. Assign the occupancy map to the state validator object. Specify the sampling distance interval.

```
sv = validatorOccupancyMap3D(ss, ...
     Map = omap, ...
     ValidationDistance = 0.1);
```

Create a probabilistic roadmap path planner with increased maximum connection distance.

```
planner = plannerPRM(ss,sv);
```

Specify start and goal poses.

```
start = [40 180 25 0.7 0.2 0 0.1];
goal = [150 33 35 0.3 0 0.1 0.6];
```

Configure the random number generator for repeatable result.

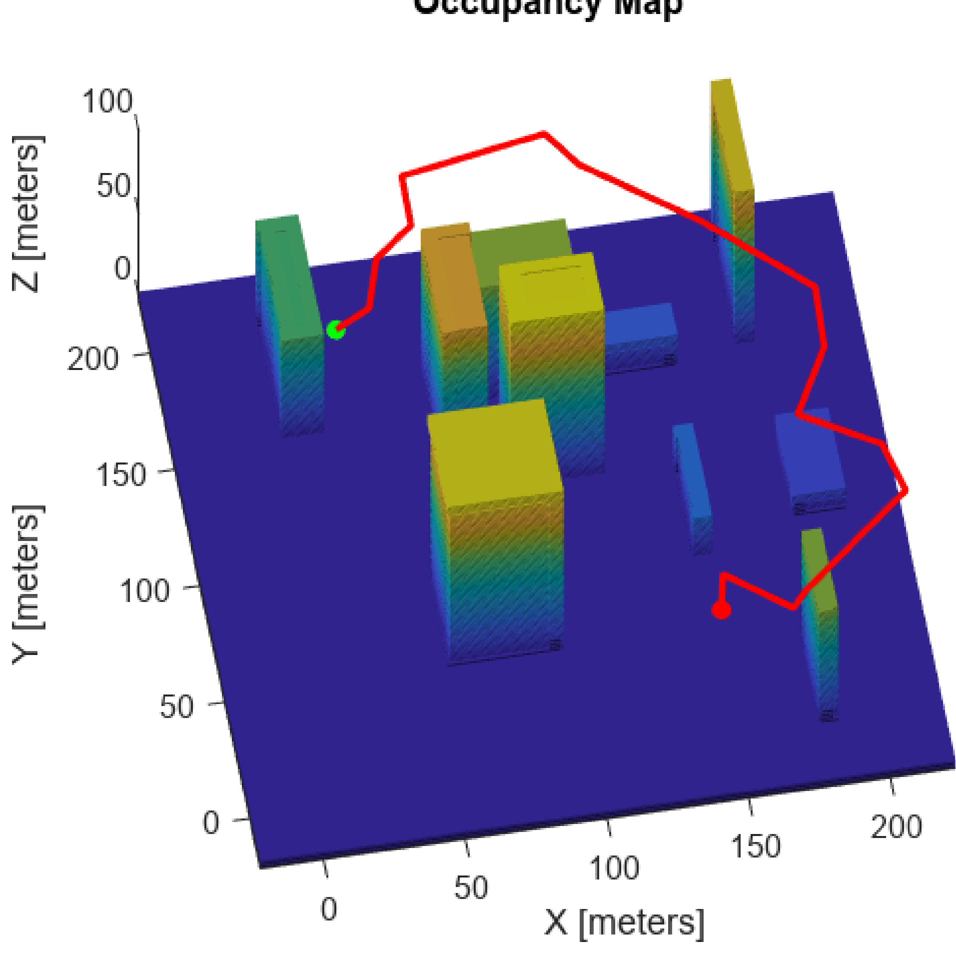
```
rng(1,"twister");
```

Plan the path.

```
[pthObj,solnInfo] = plan(planner,start,goal);
```

Visualize the planned path.

```
show(omap)
axis equal
view([-10 55])
hold on
% Start state
scatter3(start(1,1),start(1,2),start(1,3),"g","filled")
% Goal state
scatter3(goal(1,1),goal(1,2),goal(1,3),"r","filled")
% Path
plot3(pthObj.States(:,1),pthObj.States(:,2),pthObj.States(:,3), ...
      "r-",LineWidth=2)
```




## Input Arguments

**planner — Path planner**
plannerPRM object

Path planner, specified as a plannerPRM object.

**startState — Start state of the path**
*N*-element real-valued row vector

Start state of the path, specified as an *N*-element real-valued row vector. *N* is the dimension of the state space.

Example: [1 1 pi/6]

Data Types: single | double

**goalState — Goal state of the path**
*N*-element real-valued row vector

Goal state of the path, specified as an *N*-element real-valued row vector. *N* is the dimension of the state space.

Example: `[2 2 pi/3]`

Data Types: `single` | `double`

## Output Arguments

**`path` — Planned path information**
`navPath` object

Planned path information, returned as a `navPath` object.

**`solutionInfo` — Solution information**
structure

Solution information, returned as a structure. The structure contains the field:

| Field | Description |
| --- | --- |
| `IsPathFound` | Indicates whether a path is found. It returns as `1` if a path is found. Otherwise, it returns `0`. |

Data Types: `struct`

# Version History

**Introduced in R2022a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using MATLAB® Coder™.

## See Also

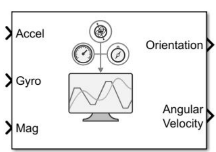
**Objects**
`plannerPRM` | `navPath`

**Functions**
`copy` | `graphData`

# Blocks

# AHRS

Orientation from accelerometer, gyroscope, and magnetometer readings




**Libraries:**
Navigation Toolbox / Multisensor Positioning / Navigation Filters
Sensor Fusion and Tracking Toolbox / Multisensor Positioning / Navigation Filters

## Description

The AHRS Simulink® block fuses accelerometer, magnetometer, and gyroscope sensor data to estimate device orientation.

## Ports

### Input

**Accel** — Accelerometer readings in sensor body coordinate system (m/s$^2$)
*N*-by-3 matrix of real scalar

Accelerometer readings in the sensor body coordinate system in m/s$^2$, specified as an *N*-by-3 matrix of real scalars. *N* is the number of samples, and the three columns of `Accel` represent the [*x y z*] measurements, respectively.

Data Types: `single` | `double`

**Gyro** — Gyroscope readings in sensor body coordinate system (rad/s)
*N*-by-3 matrix of real scalar

Gyroscope readings in the sensor body coordinate system in rad/s, specified as an *N*-by-3 matrix of real scalars. *N* is the number of samples, and the three columns of `Gyro` represent the [*x y z*] measurements, respectively.

Data Types: `single` | `double`

**Mag** — Magnetometer readings in sensor body coordinate system (µT)
*N*-by-3 matrix of real scalar

Magnetometer readings in the sensor body coordinate system in µT, specified as an *N*-by-3 matrix of real scalars. *N* is the number of samples, and the three columns of `magReadings` represent the [*x y z*] measurements, respectively.

Data Types: `single` | `double`

### Output

**Orientation** — Orientation of sensor body frame relative to navigation frame
*M*-by-4 array of scalar | 3-by-3-by-*M*-element rotation matrix

Orientation of the sensor body frame relative to the navigation frame, return as an *M*-by-4 array of scalars or a 3-by-3-by-*M* array of rotation matrices. Each row the of the *N*-by-4 array is assumed to be

the four elements of a `quaternion`. The number of input samples, *N*, and the **Decimation Factor** parameter determine the output size *M*.

Data Types: `single` | `double`

**Angular Velocity** — Angular velocity in sensor body coordinate system (rad/s)
*M*-by-3 array of real scalar (default)

Angular velocity with gyroscope bias removed in the sensor body coordinate system in rad/s, returned as an *M*-by-3 array of real scalars. The number of input samples, *N*, and the **Decimation Factor** parameter determine the output size *M*.

Data Types: `single` | `double`

## Parameters

#### Main

**Reference frame** — Navigation reference frame

`NED` (default) | `ENU`

Navigation reference frame, specified as `NED` (North-East-Down) or `ENU` (East-North-Up).

**Decimation factor** — Decimation factor

`1` (default) | positive integer

Decimation factor by which to reduce the input sensor data rate, specified as a positive integer.

The number of rows of the inputs –– **Accel**, **Gyro** , and **Mag** –– must be a multiple of the decimation factor.

Data Types: `single` | `double`

**Initial process noise** — Initial process noise

`ahrsfilter.defaultProcessNoise` (default) | 12-by-12 matrix of real scalar

Initial process noise, specified as a 12-by-12 matrix of real scalars. The default value, `ahrsfilter.defaultProcessNoise`, is a 12-by-12 diagonal matrix as:

```
  Columns 1 through 6

   0.000006092348396                   0                   0                   0
                   0   0.000006092348396                   0                   0
                   0                   0   0.000006092348396                   0
                   0                   0                   0   0.000076154354947
                   0                   0                   0                   0   0.00007615435
                   0                   0                   0                   0
                   0                   0                   0                   0
                   0                   0                   0                   0
                   0                   0                   0                   0
                   0                   0                   0                   0
                   0                   0                   0                   0
                   0                   0                   0                   0
```

```
  Columns 7 through 12

                 0                  0                  0                  0
                 0                  0                  0                  0
                 0                  0                  0                  0
                 0                  0                  0                  0
                 0                  0                  0                  0
                 0                  0                  0                  0
 0.009623610000000                  0                  0                  0
                 0  0.009623610000000                  0                  0
                 0                  0  0.009623610000000                  0
                 0                  0                  0  0.600000000000000
                 0                  0                  0                  0  0.60000000000
                 0                  0                  0                  0
```

Data Types: single | double

**Orientation format** — Orientation output format

'quaternion' (default) | 'Rotation matrix'

Output orientation format, specified as 'quaternion' or 'Rotation matrix':

- 'quaternion' –– Output is an *M*-by-4 array of real scalars. Each row of the array represents the four components of a quaternion.
- 'Rotation matrix' –– Output is a 3-by-3-by-*M* rotation matrix.

The output size *M* depends on the input dimension *N* and the **Decimation Factor** parameter.

Data Types: char | string

**Simulate using** — Type of simulation to run

Interpreted Execution (default) | Code Generation

- Interpreted execution — Simulate the model using the MATLAB interpreter. This option shortens startup time. In Interpreted execution mode, you can debug the source code of the block.
- Code generation — Simulate the model using generated C code. The first time you run a simulation, Simulink generates C code for the block. The C code is reused for subsequent simulations as long as the model does not change. This option requires additional startup time.

**Measurement Noise**

**Accelerometer noise ((m/s$^2$)$^2$)** — Variance of accelerometer signal noise ((m/s$^2$)$^2$)

0.0001924722 (default) | positive real scalar

Variance of accelerometer signal noise in (m/s$^2$)$^2$, specified as a positive real scalar.

Data Types: single | double

**Gyroscope noise ((rad/s)$^2$)** — Variance of gyroscope signal noise ((rad/s)$^2$)

9.1385e-5 (default) | positive real scalar

Variance of gyroscope signal noise in (rad/s)$^2$, specified as a positive real scalar.

Data Types: single | double

**Magnetometer noise (μT$^2$)** — Variance of magnetometer signal noise (μT$^2$)

0.1 (default) | positive real scalar

Variance of magnetometer signal noise in μT$^2$, specified as a positive real scalar.

Data Types: single | double

**Gyroscope drift noise (rad/s)** — Variance of gyroscope offset drift ((rad/s)$^2$)

3.0462e-13 (default) | positive real scalar

Variance of gyroscope offset drift in (rad/s)$^2$, specified as a positive real scalar.

Data Types: single | double

**Environmental Noise**

**Linear acceleration noise ((m/s$^2$)$^2$)** — Variance of linear acceleration noise (m/s$^2$)$^2$

0.0096236100000000012 (default) | positive real scalar

Variance of linear acceleration noise in (m/s$^2$)$^2$, specified as a positive real scalar. Linear acceleration is modeled as a lowpass-filtered white noise process.

Data Types: single | double

**Magnetic disturbance noise (μT$^2$)** — Variance of magnetic disturbance noise ((μT)$^2$)

0.5 (default) | real finite positive scalar

Variance of magnetic disturbance noise in μT$^2$, specified as a real finite positive scalar.

Data Types: single | double

**Linear acceleration decay factor** — Decay factor for linear acceleration drift

0.5 (default) | scalar in the range [0,1)

Decay factor for linear acceleration drift, specified as a scalar in the range [0,1). If linear acceleration changes quickly, set this parameter to a lower value. If linear acceleration changes slowly, set this parameter to a higher value. Linear acceleration drift is modeled as a lowpass-filtered white noise process.

Data Types: single | double

**Magnetic disturbance decay factor** — Decay factor for magnetic disturbance

0.5 (default) | positive scalar in the range [0,1]

Decay factor for magnetic disturbance, specified as a positive scalar in the range [0,1]. Magnetic disturbance is modeled as a first order Markov process.

Data Types: single | double

**Magnetic field strength (μT)** — Magnetic field strength (μT)

`50` (default) | real positive scalar

Magnetic field strength in μT, specified as a real positive scalar. The magnetic field strength is an estimate of the magnetic field strength of the Earth at the current location.

Data Types: `single` | `double`

## Algorithms

*Note: The following algorithm only applies to an NED reference frame.*

The AHRS block uses the nine-axis Kalman filter structure described in [1]. The algorithm attempts to track the errors in orientation, gyroscope offset, linear acceleration, and magnetic disturbance to output the final orientation and angular velocity. Instead of tracking the orientation directly, the indirect Kalman filter models the error process, $x$, with a recursive update:

$$x_k = \begin{bmatrix} \theta_k \\ b_k \\ a_k \\ d_k \end{bmatrix} = F_k \begin{bmatrix} \theta_{k-1} \\ b_{k-1} \\ a_{k-1} \\ d_{k-1} \end{bmatrix} + w_k$$

where $x_k$ is a 12-by-1 vector consisting of:

- $\theta_k$ -– 3-by-1 orientation error vector, in degrees, at time $k$
- $b_k$ -– 3-by-1 gyroscope zero angular rate bias vector, in deg/s, at time $k$
- $a_k$ -– 3-by-1 acceleration error vector measured in the sensor frame, in g, at time $k$
- $d_k$ -– 3-by-1 magnetic disturbance error vector measured in the sensor frame, in µT, at time $k$

and where $w_k$ is a 12-by-1 additive noise vector, and $F_k$ is the state transition model.

Because $x_k$ is defined as the error process, the *a priori* estimate is always zero, and therefore the state transition model, $F_k$, is zero. This insight results in the following reduction of the standard Kalman equations:

Standard Kalman equations:

$$x_k^- = F_k x_{k-1}^+$$

$$P_k^- = F_k P_{k-1}^+ F_k^T + Q_k$$

$$y_k = z_k - H_k x_k^-$$

$$S_k = R_k + H_k P_k^- H_k{}^T$$

$$K_k = P_k^- H_k^T (S_k)^{-1}$$

$$x_k^+ = x_k^- + K_k y_k$$

$$P_k^+ = P_k{-} - K_k H_k P_k^-$$

Kalman equations used in this algorithm:

$$x_k^- = 0$$

$$P_k^- = Q_k$$

$$y_k = z_k$$

$$S_k = R_k + H_k P_k^- H_k^T$$

$$K_k = P_k^- H_k^T (S_k)^{-1}$$

$$x_k^+ = K_k y_k$$

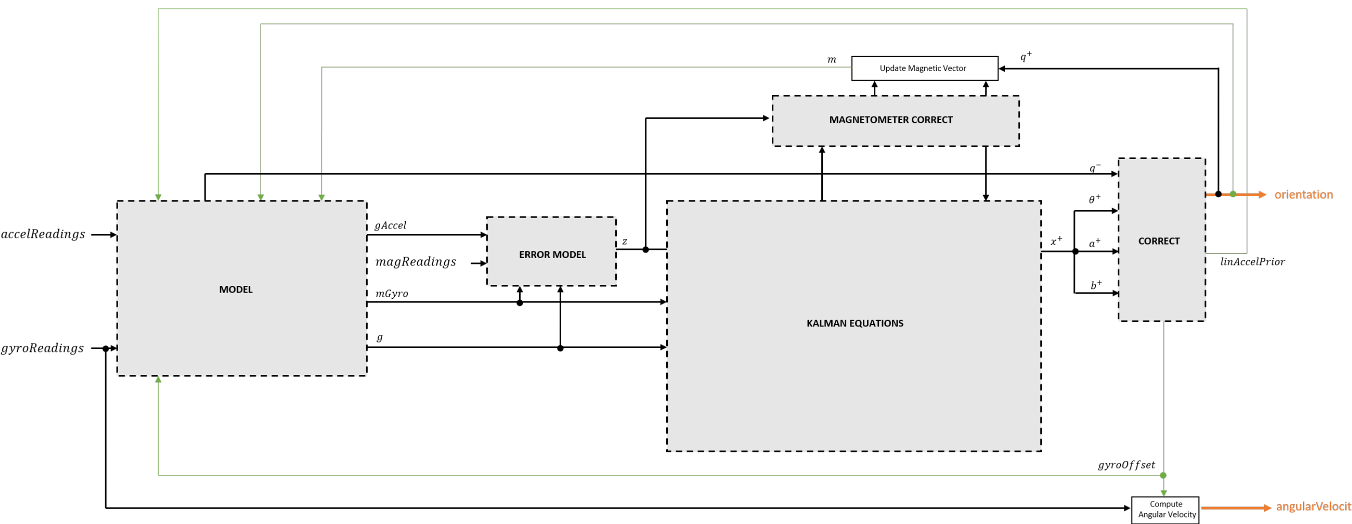
$$P_k^+ = P_k^- - K_k H_k P_k^-$$

where:

- $x_k^-$ –– predicted (*a priori*) state estimate; the error process
- $P_k^-$ –– predicted (*a priori*) estimate covariance
- $y_k$ –– innovation
- $S_k$ –– innovation covariance
- $K_k$ –– Kalman gain
- $x_k^+$ –– updated (*a posteriori*) state estimate
- $P_k^+$ –– updated (*a posteriori*) estimate covariance

$k$ represents the iteration, the superscript $^+$ represents an *a posteriori* estimate, and the superscript $^-$ represents an *a priori* estimate.

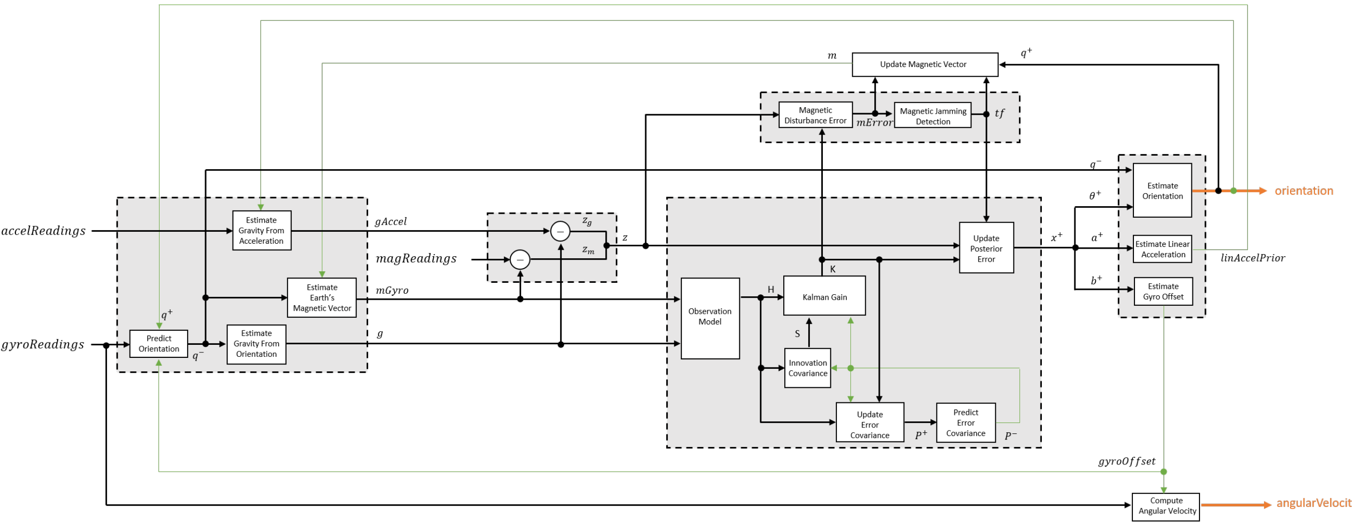
The graphic and following steps describe a single frame-based iteration through the algorithm.




Before the first iteration, the `accelReadings`, `gyroReadings`, and `magReadings` inputs are chunked into `DecimationFactor`-by-3 frames. For each chunk, the algorithm uses the most current accelerometer and magnetometer readings corresponding to the chunk of gyroscope readings.

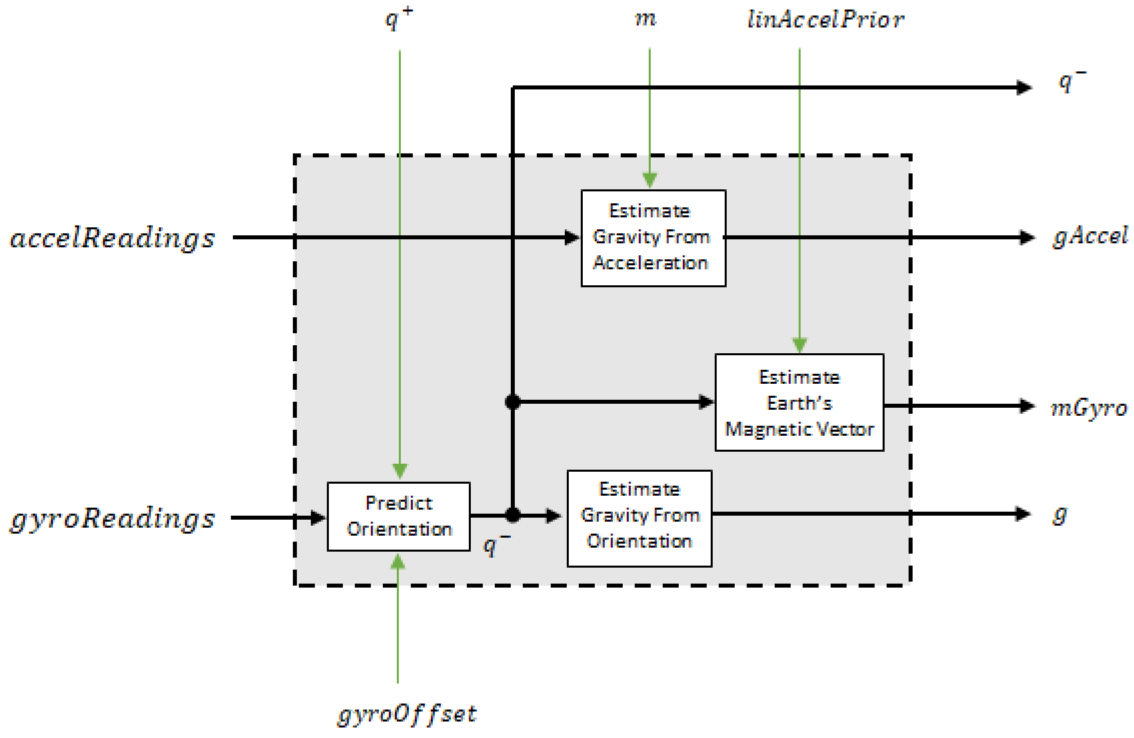
### Detailed Overview

Walk through the algorithm for an explanation of each stage of the detailed overview.




## Model

The algorithm models acceleration and angular change as linear processes.




### Predict Orientation

The orientation for the current frame is predicted by first estimating the angular change from the previous frame:

$$\Delta\varphi_{N \times 3} = \frac{(gyroReadings_{N \times 3} - gyroOffset_{1 \times 3})}{fs}$$

where $N$ is the decimation factor specified by the Decimation factor and $fs$ is the sample rate.

The angular change is converted into quaternions using the `rotvec` `quaternion` construction syntax:

$$\Delta Q_{N \times 1} = \text{quaternion}(\Delta\varphi_{N \times 3}, 'rotvec')$$

The previous orientation estimate is updated by rotating it by $\Delta Q$:

$$q^-_{1 \times 1} = \left(q^+_{1 \times 1}\right)\left(\prod_{n=1}^{N} \Delta Q_n\right)$$

During the first iteration, the orientation estimate, $q^-$, is initialized by `ecompass`.

#### Estimate Gravity from Orientation

The gravity vector is interpreted as the third column of the quaternion, $q^-$, in rotation matrix form:

$$g_{1 \times 3} = (rPrior(:,3))^T$$

#### Estimate Gravity from Acceleration

A second gravity vector estimation is made by subtracting the decayed linear acceleration estimate of the previous iteration from the accelerometer readings:

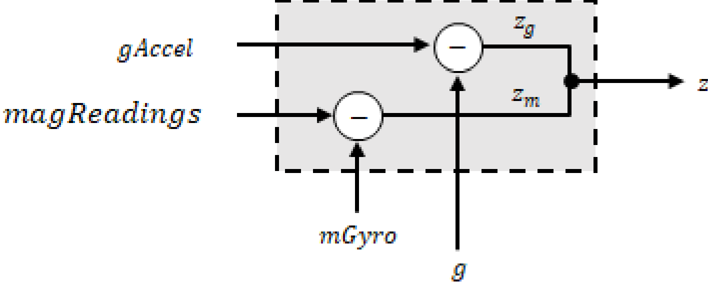
$$gAccel_{1 \times 3} = accelReadings_{1 \times 3} - linAccelprior_{1 \times 3}$$

#### Estimate Earth's Magnetic Vector

Earth's magnetic vector is estimated by rotating the magnetic vector estimate from the previous iteration by the *a priori* orientation estimate, in rotation matrix form:

$$mGyro_{1 \times 3} = \left((rPrior)\left(m^T\right)\right)^T$$

### Error Model

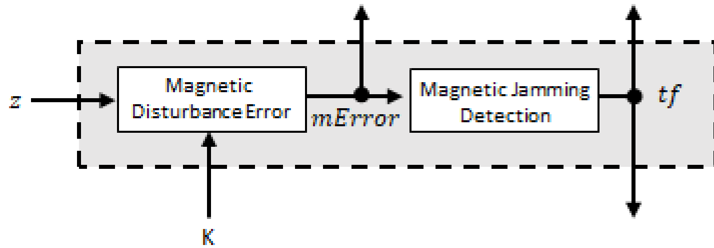



The error model combines two differences:

- The difference between the gravity estimate from the accelerometer readings and the gravity estimate from the gyroscope readings: $z_g = g - gAccel$
- The difference between the magnetic vector estimate from the gyroscope readings and the magnetic vector estimate from the magnetometer:$z_m = mGyro - magReadings$

### Magnetometer Correct

The magnetometer correct estimates the error in the magnetic vector estimate and detects magnetic jamming.




#### Magnetometer Disturbance Error

The magnetic disturbance error is calculated by matrix multiplication of the Kalman gain associated with the magnetic vector with the error signal:

$$mError_{3\times 1} = \left((K(10{:}12,:)_{3\times 6})(z_{1\times 6})^T\right)^T$$

The Kalman gain, *K*, is the Kalman gain calculated in the current iteration.

#### Magnetic Jamming Detection

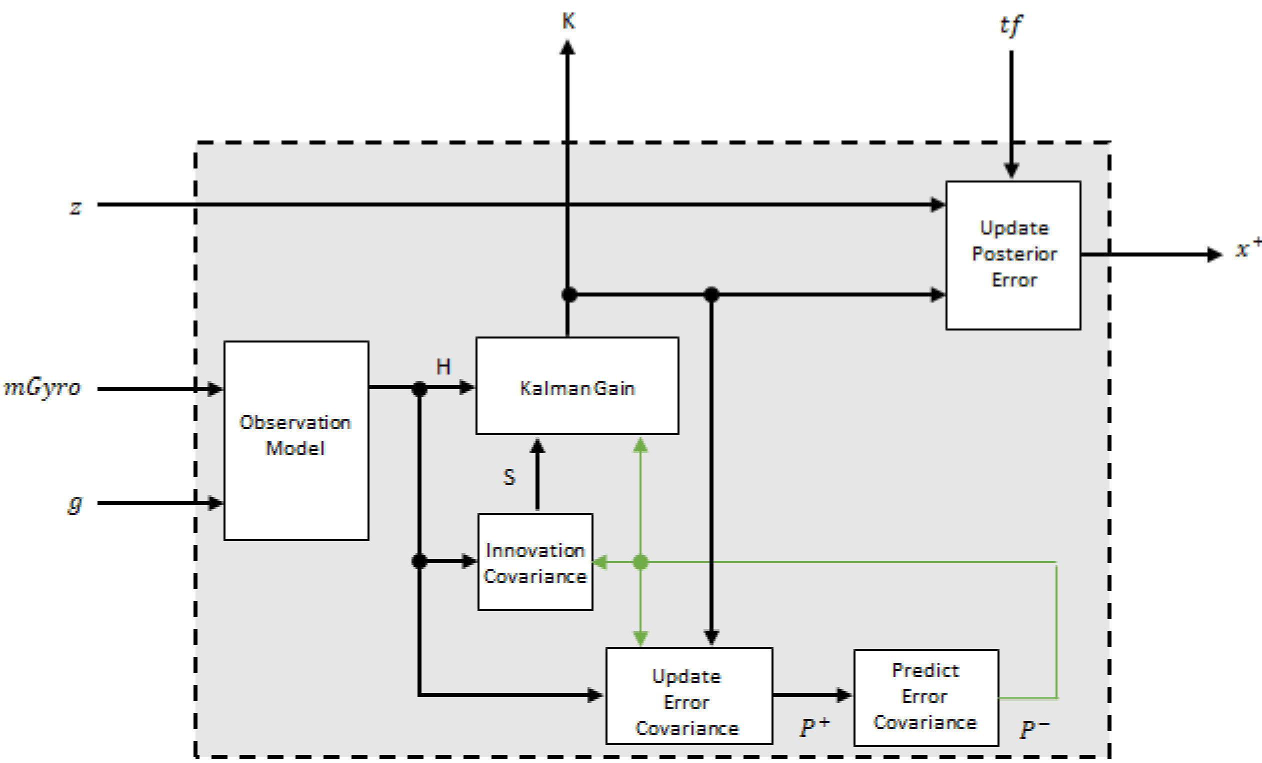
Magnetic jamming is determined by verifying that the power of the detected magnetic disturbance is less than or equal to four times the power of the expected magnetic field strength:

$$tf = \begin{cases} \text{true} & \text{if} \quad \sum |mError|^2 > (4)(\text{ExpectedMagneticFieldStrength})^2 \\ \text{false} & \text{else} \end{cases}$$

ExpectedMagneticFieldStrength is a property of `ahrsfilter`.

### Kalman Equations

The Kalman equations use the gravity estimate derived from the gyroscope readings, *g*, the magnetic vector estimate derived from the gyroscope readings, *mGyro*, and the observation of the error process, *z*, to update the Kalman gain and intermediary covariance matrices. The Kalman gain is applied to the error signal, *z*, to output an *a posteriori* error estimate, $x^+$.




**Observation Model**

The observation model maps the 1-by-3 observed states, $g$ and $mGyro$, into the 6-by-12 true state, $H$.

The observation model is constructed as:

$$H_{3\times 9} = \begin{bmatrix} 0 & g_z & -g_y & 0 & -\kappa g_z & \kappa g_y & 1 & 0 & 0 & 0 & 0 & 0 \\ -g_z & 0 & g_x & \kappa g_z & 0 & -\kappa g_x & 0 & 1 & 0 & 0 & 0 & 0 \\ g_y & -g_x & 0 & -\kappa g_y & \kappa g_x & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & m_z & -m_y & 0 & -\kappa m_z & -\kappa m_y & 0 & 0 & 0 & -1 & 0 & 0 \\ -m_z & 0 & m_x & \kappa m_z & 0 & -\kappa m_x & 0 & 0 & 0 & 0 & -1 & 0 \\ m_y & -m_x & 0 & -\kappa m_y & \kappa m_x & 0 & 0 & 0 & 0 & 0 & 0 & -1 \end{bmatrix}$$

where $g_x$, $g_y$, and $g_z$ are the $x$-, $y$-, and $z$-elements of the gravity vector estimated from the *a priori* orientation, respectively. $m_x$, $m_y$, and $m_z$ are the $x$-, $y$-, and $z$-elements of the magnetic vector estimated from the *a priori* orientation, respectively. $\kappa$ is a constant determined by the Sample rate and Decimation factor properties: $\kappa$ = `Decimation factor/Sample rate`.

**Innovation Covariance**

The innovation covariance is a 6-by-6 matrix used to track the variability in the measurements. The innovation covariance matrix is calculated as:

$$S_{6x6} = R_{6x6} + (H_{6x12})\left(P^{-}_{12x12}\right)(H_{6x12})^T$$

where

- $H$ is the observation model matrix
- $P^-$ is the predicted (*a priori*) estimate of the covariance of the observation model calculated in the previous iteration
- $R$ is the covariance of the observation model noise, calculated as:

$$R_{6 \times 6} = \begin{bmatrix} accel_{\text{noise}} & 0 & 0 & 0 & 0 & 0 \\ 0 & accel_{\text{noise}} & 0 & 0 & 0 & 0 \\ 0 & 0 & accel_{\text{noise}} & 0 & 0 & 0 \\ 0 & 0 & 0 & mag_{\text{noise}} & 0 & 0 \\ 0 & 0 & 0 & 0 & mag_{\text{noise}} & 0 \\ 0 & 0 & 0 & 0 & 0 & mag_{\text{noise}} \end{bmatrix}$$

where

$$accel_{\text{noise}} = \text{AccelerometerNoise} + \text{LinearAccelerationNoise} + \kappa^2 (\text{GyroscopeDriftNoise} + \text{GyroscopeNoise})$$

and

$$mag_{\text{noise}} = \text{MagnetometerNoise} + \text{MagneticDisturbanceNoise} + \kappa^2 (\text{GyroscopeDriftNoise} + \text{GyroscopeNoise})$$

**Update Error Estimate Covariance**

The error estimate covariance is a 12-by-12 matrix used to track the variability in the state.

The error estimate covariance matrix is updated as:

$$P^+_{12 \times 12} = P^-_{12 \times 12} - (K_{12 \times 6})(H_{6 \times 12})\left(P^-_{12 \times 12}\right)$$

where $K$ is the Kalman gain, $H$ is the measurement matrix, and $P^-$ is the error estimate covariance calculated during the previous iteration.

**Predict Error Estimate Covariance**

The error estimate covariance is a 12-by-12 matrix used to track the variability in the state. The *a priori* error estimate covariance, $P^-$, is set to the process noise covariance, $Q$, determined during the previous iteration. $Q$ is calculated as a function of the *a posteriori* error estimate covariance, $P^+$. When calculating $Q$, it is assumed that the cross-correlation terms are negligible compared to the autocorrelation terms, and are set to zero:

$Q =$

$$
\begin{bmatrix}
P^{+}(1) + \kappa^{2}\big(P^{+}(40) + \beta + \eta\big) & 0 & 0 & -\kappa\big(P^{+}(40) + \beta\big) & 0 \\
0 & P^{+}(14) + \kappa^{2}\big(P^{+}(53) + \beta + \eta\big) & 0 & 0 & -\kappa\big(P^{+}(5 \\
0 & 0 & P^{+}(27) + \kappa^{2}\big(P^{+}(66) + \beta + \eta\big) & 0 & 0 \\
-\kappa\big(P^{+}(40) + \beta\big) & 0 & 0 & P^{+}(40) + \beta & 0 \\
0 & -\kappa\big(P^{+}(53) + \beta\big) & 0 & 0 & P^{+}(53) \\
0 & 0 & -\kappa\big(P^{+}(66) + \beta\big) & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0
\end{bmatrix}
$$

where

- $P^{+}$ -– is the updated (*a posteriori*) error estimate covariance
- $\kappa$ -– Decimation factor divided by sample rate.
- $\beta$ -– Gyroscope drift noise.
- $\eta$ -– Gyroscope noise.
- $\nu$ -– Linear acceleration decay factor.
- $\xi$ -– Linear acceleration noise.
- $\sigma$ -– Magnetic disturbance decay factor.
- $\gamma$ -– Magnetic disturbance noise.

#### Kalman Gain

The Kalman gain matrix is a 12-by-6 matrix used to weight the innovation. In this algorithm, the innovation is interpreted as the error process, $z$.

The Kalman gain matrix is constructed as:

$$K_{12 \times 6} = \left(P^{-}_{12 \times 12}\right)(H_{6 \times 12})^{T}\left((S_{6 \times 6})^{T}\right)^{-1}$$

where

- $P^{-}$ -– predicted error covariance
- $H$ -– observation model
- $S$ -– innovation covariance

#### Update a Posteriori Error

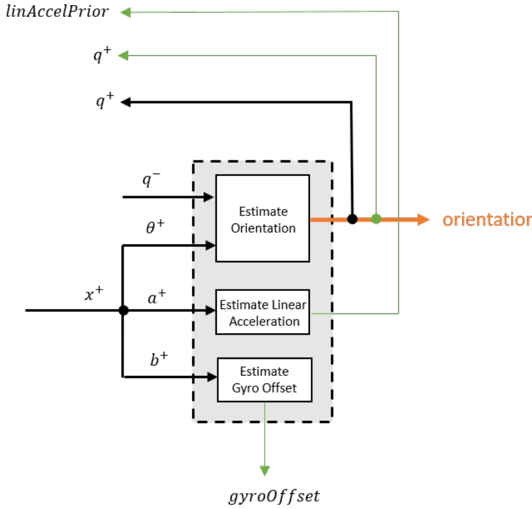
The *a posterior* error estimate is determined by combining the Kalman gain matrix with the error in the gravity vector and magnetic vector estimations:

$$x_{12 \times 1} = (K_{12 \times 6})(z_{1 \times 6})^{T}$$

If magnetic jamming is detected in the current iteration, the magnetic vector error signal is ignored, and the *a posterior* error estimate is calculated as:

$$x_{9 \times 1} = (K(1{:}9, 1{:}3)(z_{g})^{T}$$

### Correct




#### Estimate Orientation

The orientation estimate is updated by multiplying the previous estimation by the error:

$$q^{+} = (q^{-})\left(\theta^{+}\right)$$

#### Estimate Linear Acceleration

The linear acceleration estimation is updated by decaying the linear acceleration estimation from the previous iteration and subtracting the error:

$$linAccelPrior = (linAccelPrior_{k-1})\nu - b^{+}$$

where

- $\nu$ –– Linear acceleration decay factor

#### Estimate Gyroscope Offset

The gyroscope offset estimation is updated by subtracting the gyroscope offset error from the gyroscope offset from the previous iteration:

$$gyroOffset = gyroOffset_{k-1} - a^{+}$$

### Compute Angular Velocity

To estimate angular velocity, the frame of `gyroReadings` are averaged and the gyroscope offset computed in the previous iteration is subtracted:

$$angularVelocity_{1\times3} = \frac{\sum gyroReadings_{N\times3}}{N} - gyroOffset_{1\times3}$$

where $N$ is the decimation factor specified by the `DecimationFactor` property.

The gyroscope offset estimation is initialized to zeros for the first iteration.

#### Update Magnetic Vector

If magnetic jamming was not detected in the current iteration, the magnetic vector estimate, *m*, is updated using the *a posteriori* magnetic disturbance error and the *a posteriori* orientation.

The magnetic disturbance error is converted to the navigation frame:

$$mErrorNED_{1 \times 3} = \left((rPost_{3 \times 3})^T (mError_{1 \times 3})^T\right)^T$$

The magnetic disturbance error in the navigation frame is subtracted from the previous magnetic vector estimate and then interpreted as inclination:

$$M = m - mErrorNED$$

$$inclination = \mathrm{atan2}(M(3), M(1))$$

The inclination is converted to a constrained magnetic vector estimate for the next iteration:

$$m(1) = (\mathrm{ExpectedMagneticFieldStrength})(\cos(inclination))$$
$$m(2) = 0$$
$$m(3) = (\mathrm{ExpectedMagneticFieldStrength})(\sin(inclination))$$

## Version History

**Introduced in R2020a**

### References

[1] Open Source Sensor Fusion. https://github.com/memsindustrygroup/Open-Source-Sensor-Fusion/tree/master/docs

[2] Roetenberg, D., H.J. Luinge, C.T.M. Baten, and P.H. Veltink. "Compensation of Magnetic Disturbances Improves Inertial and Magnetic Sensing of Human Body Segment Orientation." *IEEE Transactions on Neural Systems and Rehabilitation Engineering*. Vol. 13. Issue 3, 2005, pp. 395-405.

### Extended Capabilities

#### C/C++ Code Generation

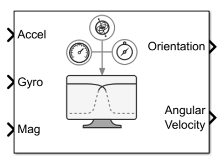
Generate C and C++ code using Simulink® Coder™.

### See Also

`ahrsfilter` | `ecompass` | `imufilter` | `imuSensor` | `gpsSensor`

# Complementary Filter

Estimate orientation using complementary filter




**Libraries:**
Sensor Fusion and Tracking Toolbox / Multisensor Positioning / Navigation Filters
Navigation Toolbox / Multisensor Positioning / Navigation Filters

## Description

The Complementary Filter Simulink block fuses accelerometer, magnetometer, and gyroscope sensor data to estimate device orientation.

## Ports

### Input

**Accel** — Accelerometer readings in sensor body coordinate system (m/s$^2$)
matrix

Accelerometer readings in the sensor body coordinate system in m/s$^2$, specified as an *N*-by-3 matrix of real numbers. *N* is the number of samples, and the each row is of the form [*x y z*].

Data Types: `single` | `double`

**Gyro** — Gyroscope readings in sensor body coordinate system (rad/s)
matrix

Gyroscope readings in the sensor body coordinate system in rad/s, specified as an *N*-by-3 matrix of real numbers. *N* is the number of samples, and the each row is of the form [*x y z*].

Data Types: `single` | `double`

**Mag** — Magnetometer readings in sensor body coordinate system (µT)
matrix

Magnetometer readings in the sensor body coordinate system in µT, specified as an *N*-by-3 matrix of real numbers. *N* is the number of samples, and the each row is of the form [*x y z*].

#### Dependencies

To enable this input port, select the `Enable Magnetometer input` parameter.

Data Types: `single` | `double`

### Output

**Orientation** — Orientation of sensor body frame relative to navigation frame
matrix | array

Orientation of the sensor body frame relative to the navigation frame, returned as an *M*-by-4 matrix of real numbers or a 3-by-3-by-*M* array. Each row of the *M*-by-4 matrix represents the four

components of a `quaternion`. Each page of the 3-by-3-by-$M$ array represents a 3-by-3 rotation matrix.

The number of input samples, $N$, determines the output size, $M$.

The output format depends on the value of the `Orientation format` parameter.

Data Types: `single` | `double`

**Angular Velocity** — Angular velocity in sensor body coordinate system (rad/s)
matrix

Angular velocity, with gyroscope bias removed, in the sensor body coordinate system in rad/s, returned as an $M$-by-3 matrix of real numbers.

The number of input samples, $N$, determines the output size, $M$.

Data Types: `single` | `double`

## Parameters

**Reference frame** — Navigation reference frame

`NED` (default) | `ENU`

Specify the navigation reference frame as `NED` (North-East-Down) or `ENU` (East-North-Up).

**Orientation format** — Orientation output format

`quaternion` (default) | `Rotation matrix`

Specify the format in which to output `Orientation` as `quaternion` or `Rotation matrix`:

- `quaternion` — `Orientation` outputs an $M$-by-4 matrix of real numbers. Each row of the matrix represents the four components of a `quaternion`.
- `Rotation matrix` — `Orientation` outputs a 3-by-3-by-$M$ array, in which each page of the array is a 3-by-3 rotation matrix.

The number of input samples, $N$, determines the output size, $M$.

**Accelerometer gain** — Accelerometer gain

`0.01` (default) | real scalar in range [0, 1]

Specify the accelerometer gain as a real scalar in the range [0, 1]. The gain determines how much the block trust the accelerometer measurement over the gyroscope measurement for orientation estimation.

Example: `0.02`

Data Types: `single` | `double`

**Enable Magnetometer input** — Accept magnetometer readings input

on (default) | `off`

Select this parameter to enable input of magnetometer readings at the `Mag` port.

**Magnetometer gain** — Magnetometer gain

`0.01` (default) | real scalar in range [0, 1]

Specify the magnetometer gain as a real scalar in the range [0, 1]. The gain determines how much the block trust the magnetometer measurement over the gyroscope measurement for orientation estimation.

Example: `0.02`

Data Types: `single` | `double`

**Simulate using** — Type of simulation to run

`Interpreted Execution` (default) | `Code Generation`

Select the type of simulation to run from these options:

- `Interpreted execution` — Simulate the model using the MATLAB interpreter. This option shortens startup time, but has a slower simulation speed than `Code generation`. In this mode, you can debug the source code of the block.
- `Code generation` — Simulate the model using generated C code. The first time you run a simulation in this mode, Simulink generates C code for the block. Simulink reuses the C code for subsequent simulations, as long as the model does not change. This option requires additional startup time, but the speed of subsequent simulations is comparable to `Interpreted execution`.

# Version History

**Introduced in R2023a**

## Extended Capabilities

**C/C++ Code Generation**
Generate C and C++ code using Simulink® Coder™.

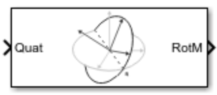
## See Also

**Objects**
`complementaryFilter`

**Blocks**
AHRS

# Coordinate Transformation Conversion

Convert to a specified coordinate transformation representation




**Libraries:**
Robotics System Toolbox / Utilities
Navigation Toolbox / Utilities
ROS Toolbox / Utilities
UAV Toolbox / Utilities

## Description

The Coordinate Transformation Conversion block converts a coordinate transformation from the input representation to a specified output representation. The input and output representations use the following forms:

- Axis-Angle (`AxAng`) – `[x y z theta]`
- Euler Angles (`Eul`) – `[z y x]`, `[z y z]`, or `[x y z]`
- Homogeneous Transformation (`TForm`) – 4-by-4 matrix
- Quaternion (`Quat`) – `[w x y z]`
- Rotation Matrix (`RotM`) – 3-by-3 matrix
- Translation Vector (`TrVec`) – `[x y z]`

All vectors must be **column vectors**.

To accommodate representations that only contain position or orientation information (`TrVec` or `Eul`, for example), you can specify two inputs or outputs to handle all transformation information. When you select the Homogeneous Transformation as an input or output, an optional `Show TrVec input/output port` parameter can be selected on the block mask to toggle the multiple ports.

## Ports

### Input

**Input transformation** — Coordinate transformation
column vector | 3-by-3 matrix | 4-by-4 matrix

Input transformation, specified as a coordinate transformation. The following representations are supported:

- Axis-Angle (`AxAng`) – `[x y z theta]`
- Euler Angles (`Eul`) – `[z y x]`, `[z y z]`, or `[x y z]`
- Homogeneous Transformation (`TForm`) – 4-by-4 matrix
- Quaternion (`Quat`) – `[w x y z]`
- Rotation Matrix (`RotM`) – 3-by-3 matrix
- Translation Vector (`TrVec`) – `[x y z]`

All vectors must be **column vectors**.

To accommodate representations that only contain position or orientation information (`TrVec` or `Eul`, for example), you can specify two inputs or outputs to handle all transformation information. When you select the Homogeneous Transformation as an input or output, an optional `Show TrVec input/output port` parameter can be selected on the block mask to toggle the multiple ports.

**TrVec** — Translation vector
3-element column vector

Translation vector, specified as a 3-element column vector, `[x y z]`, which corresponds to a translation in the *x*, *y*, and *z* axes respectively. This port can be used to input or output the translation information separately from the rotation vector.

#### Dependencies

You must select Homogeneous Transformation (`TForm`) for the opposite transformation port to get the option to show the additional `TrVec` port. Enable the port by clicking `Show TrVec input/output port`.

### Output Arguments

**Output transformation** — Coordinate transformation
column vector | 3-by-3 matrix | 4-by-4 matrix

Output transformation, returned as a coordinate transformation with the specified representation. The following representations are supported:

- Axis-Angle (`AxAng`) – `[x y z theta]`
- Euler Angles (`Eul`) – `[z y x]`, `[z y z]`, or `[x y z]`
- Homogeneous Transformation (`TForm`) – 4-by-4 matrix
- Quaternion (`Quat`) – `[w x y z]`
- Rotation Matrix (`RotM`) – 3-by-3 matrix
- Translation Vector (`TrVec`) – `[x y z]`

To accommodate representations that only contain position or orientation information (`TrVec` or `Eul`, for example), you can specify two inputs or outputs to handle all transformation information. When you select the Homogeneous Transformation as an input or output, an optional `Show TrVec input/output port` parameter can be selected on the block mask to toggle the multiple ports.

**TrVec** — Translation vector
three-element column vector

Translation vector, returned as a three-element column vector, `[x y z]`, which corresponds to a translation in the *x*, *y*, and *z* axes respectively. This port can be used to input or output the translation information separately from the rotation vector.

#### Dependencies

You must select Homogeneous Transformation (`TForm`) for the opposite transformation port to get the option to show the additional `TrVec` port. Enable the port by clicking `Show TrVec input/output port`.

## Parameters

**Representation** — Input or output representation
Axis-Angle | Euler Angles | Homogeneous Transformation | Rotation Matrix | Translation Vector | Quaternion

Select the representation for both the input and output port for the block. If you are using a transformation with only orientation information, you can also select the `Show TrVec input/output port` when converting to or from a homogeneous transformation.

**Axis rotation sequence** — Order of Euler angle axis rotations
ZYX (default) | ZYZ | XYZ

Order of the Euler angle axis rotations, specified as `ZYX`, `ZYZ`, or `XYZ`. The order of the angles in the input or output port `Eul` must match this rotation sequence. The default order `ZYX` specifies an orientation by:

- Rotating about the initial *z*-axis
- Rotating about the intermediate *y*-axis
- Rotating about the second intermediate *x*-axis

#### Dependencies

You must select `Euler Angles` for the `Representation` input or output parameter. The axis rotation sequence only applies to Euler angle rotations.

**Show TrVec input/output port** — Toggle `TrVec` port
off (default) | on

Toggle the `TrVec` input or output port when you want to specify or receive a separate translation vector for position information along with an orientation representation.

#### Dependencies

You must select Homogeneous Transformation (`TForm`) for the opposite transformation port to get the option to show the additional `TrVec` port.

**Simulate using** — Type of simulation to run
Interpreted execution (default) | Code generation

- `Interpreted execution` — Simulate model using the MATLAB interpreter. This option shortens startup time but has a slower simulation speed than `Code generation`. In this mode, you can debug the source code of the block.
- `Code generation` — Simulate model using generated C code. The first time you run a simulation, Simulink generates C code for the block. The C code is reused for subsequent simulations, as long as the model does not change. This option requires additional startup time, but the speed of the subsequent simulations is comparable to `Interpreted execution`.

**Tunable:** No

# Version History

**Introduced in R2017b**

## Extended Capabilities

### C/C++ Code Generation

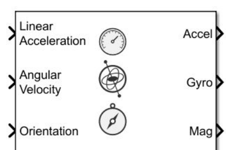
Generate C and C++ code using Simulink® Coder™.

## See Also

`axang2quat` | `eul2tform` | `trvec2tform`

# IMU

IMU simulation model




**Libraries:**
Sensor Fusion and Tracking Toolbox / Multisensor Positioning / Sensor Models
Navigation Toolbox / Multisensor Positioning / Sensor Models

## Description

The IMU Simulink block models receiving data from an inertial measurement unit (IMU) composed of accelerometer, gyroscope, and magnetometer sensors. You can specify the reference frame of the block inputs as the `NED` (North-East-Down) or `ENU` (East-North-Up) frame by using the **Reference Frame** parameter.

## Ports

### Input

**Linear Acceleration** — Acceleration of IMU in local navigation coordinate system (m/s$^2$)
*N*-by-3 matrix of real scalar

Acceleration of the IMU in the local navigation coordinate system, specified as an *N*-by-3 matrix of real scalars in meters per second squared. *N* is the number of samples in the current frame. Do not include the gravitational acceleration in this input since the sensor models gravitational acceleration by default.

To specify the orientation of the IMU sensor body frame with respect to the local navigation frame, use the **Orientation** input port.

Data Types: `single` | `double`

**Angular Velocity** — Angular velocity of IMU in local navigation coordinate system (rad/s)
*N*-by-3 matrix of real scalar

Angular velocity of the IMU sensor body frame in the local navigation coordinate system, specified as an *N*-by-3 matrix of scalars in radians per second. *N* is the number of samples in the current frame. To specify the orientation of the IMU sensor body frame with respect to the local navigation frame, use the **Orientation** input port.

Data Types: `single` | `double`

**Orientation** — Orientation of IMU in local navigation coordinate system
*N*-by-4 array of real scalar | 3-by-3-by-*N*-element rotation matrix

Orientation of the IMU sensor body frame with respect to the local navigation coordinate system, specified as an *N*-by-4 array of real scalars or a 3-by-3-by-*N* rotation matrix. Each row the of the *N*-by-4 array is assumed to be the four elements of a `quaternion`. *N* is the number of samples in the current frame.

Data Types: `single` | `double`

#### Output

**Accel** — Accelerometer measurement of IMU in sensor body coordinate system (m/s$^2$)
*N*-by-3 matrix of real scalar

Accelerometer measurement of the IMU in the sensor body coordinate system, returned as an *N*-by-3 matrix of real scalars in meters per second squared. *N* is the number of samples in the current frame.

Data Types: `single` | `double`

**Gyro** — Gyroscope measurement of IMU in sensor body coordinate system (rad/s)
*N*-by-3 matrix of real scalar

Gyroscope measurement of the IMU in the sensor body coordinate system, returned as an *N*-by-3 matrix of real scalars in radians per second. *N* is the number of samples in the current frame.

Data Types: `single` | `double`

**Mag** — Magnetometer measurement of IMU in sensor body coordinate system (μT)
*N*-by-3 matrix of real scalar

Magnetometer measurement of the IMU in the sensor body coordinate system, returned as an *N*-by-3 matrix of real scalars in microtesla. *N* is the number of samples in the current frame.

Data Types: `single` | `double`

## Parameters

#### Parameters

**Reference frame** — Navigation reference frame

`NED` (default) | `ENU`

Navigation reference frame, specified as `NED` (North-East-Down) or `ENU` (East-North-Up).

---

**Note**

- If you choose the NED reference frame, specify the sensor inputs in the NED reference frame. Additionally, the sensor models the gravitational acceleration as [0 0 9.81] m/s$^2$.
- If you choose the ENU reference frame, specify the sensor inputs in the ENU reference frame. Additionally, the sensor models the gravitational acceleration as [0 0 −9.81] m/s$^2$.

---

**Temperature (°C)** — Operating temperature of IMU (°C)

`25` (default) | real scalar

Operating temperature of the IMU in degrees Celsius, specified as a real scalar.

When the block calculates temperature scale factors and environmental drift noises, 25 °C is used as the nominal temperature.

Data Types: `single` | `double`

**Magnetic field (NED)** — Magnetic field vector expressed in NED navigation frame (μT)

`[27.5550, -2.4169, -16.0849]` (default) | 1-by-3 vector of scalar

Magnetic field vector expressed in the NED navigation frame, specified as a 1-by-3 vector of scalars.

The default magnetic field corresponds to the magnetic field at latitude zero, longitude zero, and altitude zero.

#### Dependencies

To enable this parameter, set **Reference frame** to `NED`.

Data Types: `single` | `double`

**MagneticField (ENU)** — Magnetic field vector expressed in ENU navigation frame (μT)

`[-2.4169, 27.5550, 16.0849]` (default) | 1-by-3 vector of scalar

Magnetic field vector expressed in the ENU navigation frame, specified as a 1-by-3 vector of scalars.

The default magnetic field corresponds to the magnetic field at latitude zero, longitude zero, and altitude zero.

#### Dependencies

To enable this parameter, set **Reference frame** to `ENU`.

Data Types: `single` | `double`

**Seed** — Initial seed for randomization

`67` (default) | nonnegative integer

Initial seed of a random number generator algorithm, specified as a nonnegative integer.

Data Types: `single` | `double`

**Simulate using** — Type of simulation to run

`Interpreted Execution` (default) | `Code Generation`

- `Interpreted execution` — Simulate the model using the MATLAB interpreter. This option shortens startup time. In `Interpreted execution` mode, you can debug the source code of the block.
- `Code generation` — Simulate the model using generated C code. The first time that you run a simulation, Simulink generates C code for the block. The C code is reused for subsequent simulations if the model does not change. This option requires additional startup time.

#### Accelerometer

**Maximum readings (m/s$^2$)** — Maximum sensor reading (m/s$^2$)

`inf` (default) | real positive scalar

Maximum sensor reading in m/s$^2$, specified as a real positive scalar.

Data Types: `single` | `double`

**Resolution ((m/s²)/LSB)** — Resolution of sensor measurements ((m/s²)/LSB)

`0` (default) | real nonnegative scalar

Resolution of sensor measurements in $(m/s^2)$/LSB, specified as a real nonnegative scalar.

Data Types: `single` | `double`

**Constant offset bias (m/s²)** — Constant sensor offset bias (m/s²)

`[0 0 0]` (default) | real scalar | real 3-element row vector

Constant sensor offset bias in $m/s^2$, specified as a real scalar or 3-element row vector. Any scalar input is converted into a real 3-element row vector where each element has the input scalar value.

Data Types: `single` | `double`

**Axis skew (%)** — Sensor axes skew (%)

`diag([100 100 100])` (default) | scalar in the range [0,100] | 3-element row vector in the range [0,100] | 3-by-3 matrix in the range [0,100]

Sensor axes skew in percentage, specified as a scalar, a 3-element row vector, or a 3-by-3 matrix with values ranging from `0` to `100`. The diagonal elements of the matrix account for the misalignment effects for each axes. The off-diagonal elements account for the cross-axes misalignment effects. The measured state $v_{measure}$ is obtained from the true state $v_{true}$ via the misalignment matrix as:

$$v_{measure} = \frac{1}{100} M v_{true} = \frac{1}{100} \begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{bmatrix} v_{true}$$

- If you specify the property as a scalar, then all the off-diagonal elements of the matrix take the value of the specified scalar and all the diagonal elements are 100.
- If you specify the property as a vector [$a$ $b$ $c$], then $m_{21} = m_{31} = a$, $m_{12} = m_{32} = b$, and $m_{13} = m_{23} = c$. All the diagonal elements are 100.

Data Types: `single` | `double`

**Velocity random walk (m/s²/√Hz)** — Velocity random walk (m/s²/√Hz)

`[0 0 0]` (default) | real scalar | real 3-element row vector

Velocity random walk in $(m/s^2/\sqrt{Hz})$, specified as a real scalar or 3-element row vector. This property corresponds to the power spectral density of sensor noise. Any scalar input is converted into a real 3-element row vector where each element has the input scalar value.

Data Types: `single` | `double`

**Bias Instability (m/s²)** — Instability of the bias offset (m/s²)

`[0 0 0]` (default) | real scalar | real 3-element row vector

Instability of the bias offset in m/s$^2$, specified as a real scalar or 3-element row vector. Any scalar input is converted into a real 3-element row vector where each element has the input scalar value.

Data Types: `single` | `double`

**Acceleration random walk ((m/s$^2$)(√Hz))** — Acceleration random walk ((m/s$^2$)(√Hz))

`[0 0 0]` (default) | real scalar | real 3-element row vector

Acceleration random walk of sensor in (m/s$^2$)(√Hz), specified as a real scalar or 3-element row vector. Any scalar input is converted into a real 3-element row vector where each element has the input scalar value.

Data Types: `single` | `double`

**Bias from temperature ((m/s$^2$)/°C)** — Sensor bias from temperature ((m/s$^2$)/°C)

`[0 0 0]` (default) | real scalar | real 3-element row vector

Sensor bias from temperature in (m/s$^2$)/°C, specified as a real scalar or 3-element row vector. Any scalar input is converted into a real 3-element row vector where each element has the input scalar value.

Data Types: `single` | `double`

**Temperature scale factor (%/°C)** — Scale factor error from temperature (%/°C)

`[0 0 0]` (default) | real scalar in the range [0,100] | real 3-element row vector in the range [0,100]

Scale factor error from temperature in %/°C, specified as a real scalar or real 3-element row vector with values ranging from 0 to 100. Any scalar input is converted into a real 3-element row vector where each element has the input scalar value.

Data Types: `single` | `double`

#### Gyroscope

**Maximum readings (rad/s)** — Maximum sensor reading (rad/s)

`inf` (default) | real positive scalar

Maximum sensor reading in rad/s, specified as a real positive scalar.

Data Types: `single` | `double`

**Resolution ((rad/s)/LSB)** — Resolution of sensor measurements ((rad/s)/LSB)

`0` (default) | real nonnegative scalar

Resolution of sensor measurements in (rad/s)/LSB, specified as a real nonnegative scalar.

Data Types: `single` | `double`

**Constant offset bias (rad/s)** — Constant sensor offset bias (rad/s)

`[0 0 0]` (default) | real scalar | real 3-element row vector

Constant sensor offset bias in rad/s, specified as a real scalar or 3-element row vector. Any scalar input is converted into a real 3-element row vector where each element has the input scalar value.

Data Types: `single` | `double`

**Axis skew (%)** — Sensor axes skew (%)

`diag([100 100 100])` (default) | scalar in the range [0,100] | 3-element row vector in the range [0,100] | 3-by-3 matrix in the range [0,100]

Sensor axes skew in percentage, specified as a scalar, a 3-element row vector, or a 3-by-3 matrix with values ranging from `0` to `100`. The diagonal elements of the matrix account for the misalignment effects for each axes. The off-diagonal elements account for the cross-axes misalignment effects. The measured state $v_{measure}$ is obtained from the true state $v_{true}$ via the misalignment matrix as:

$$v_{measure} = \frac{1}{100} M v_{true} = \frac{1}{100} \begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{bmatrix} v_{true}$$

- If you specify the property as a scalar, then all the off-diagonal elements of the matrix take the value of the specified scalar and all the diagonal elements are 100.
- If you specify the property as a vector [$a$ $b$ $c$], then $m_{21} = m_{31} = a$, $m_{12} = m_{32} = b$, and $m_{13} = m_{23} = c$. All the diagonal elements are 100.

Data Types: `single` | `double`

**Bias from acceleration ((rad/s)/(m/s²))** — Sensor bias from linear acceleration (rad/s)/(m/s²)

`[0 0 0]` (default) | real scalar | real 3-element row vector

Sensor bias from linear acceleration in (rad/s)/(m/s²), specified as a real scalar or 3-element row vector. Any scalar input is converted into a real 3-element row vector where each element has the input scalar value.

Data Types: `single` | `double`

**Angle random walk ((rad/s)/(√Hz))** — Angle random walk ((rad/s)/(√Hz))

`[0 0 0]` (default) | real scalar | real 3-element row vector

Angle random walk of sensor in (rad/s)/(√Hz), specified as a real scalar or 3-element row vector. Any scalar input is converted into a real 3-element row vector where each element has the input scalar value.

Data Types: `single` | `double`

**Bias Instability (rad/s)** — Instability of the bias offset (rad/s)

`[0 0 0]` (default) | real scalar | real 3-element row vector

Instability of the bias offset in rad/s, specified as a real scalar or 3-element row vector. Any scalar input is converted into a real 3-element row vector where each element has the input scalar value.

Data Types: `single` | `double`

**Rate random walk ((rad/s)(√Hz))** — Integrated white noise of sensor ((rad/s)(√Hz))

`[0 0 0]` (default) | real scalar | real 3-element row vector

Integrated white noise of sensor in (rad/s)(√Hz), specified as a real scalar or 3-element row vector. Any scalar input is converted into a real 3-element row vector where each element has the input scalar value.

Data Types: `single` | `double`

**Bias from temperature ((rad/s)/°C)** — Sensor bias from temperature ((rad/s)/℃)

`[0 0 0]` (default) | real scalar | real 3-element row vector

Sensor bias from temperature in (rad/s)/℃, specified as a real scalar or 3-element row vector. Any scalar input is converted into a real 3-element row vector where each element has the input scalar value.

Data Types: `single` | `double`

**Temperature scale factor (%/°C)** — Scale factor error from temperature (%/℃)

`[0 0 0]` (default) | real scalar in the range [0,100] | real 3-element row vector in the range [0,100]

Scale factor error from temperature in %/℃, specified as a real scalar or real 3-element row vector with values ranging from 0 to 100. Any scalar input is converted into a real 3-element row vector where each element has the input scalar value.

Data Types: `single` | `double`

**Magnetometer**

**Maximum readings (µT)** — Maximum sensor reading (µT)

`inf` (default) | real positive scalar

Maximum sensor reading in µT, specified as a real positive scalar.

Data Types: `single` | `double`

**Resolution ((µT)/LSB)** — Resolution of sensor measurements ((µT)/LSB)

`0` (default) | real nonnegative scalar

Resolution of sensor measurements in (µT)/LSB, specified as a real nonnegative scalar.

Data Types: `single` | `double`

**Constant offset bias (µT)** — Constant sensor offset bias (µT)

`[0 0 0]` (default) | real scalar | real 3-element row vector

Constant sensor offset bias in µT, specified as a real scalar or 3-element row vector. Any scalar input is converted into a real 3-element row vector where each element has the input scalar value.

Data Types: `single` | `double`

**Axis skew (%)** — Sensor axes skew (%)

`diag([100 100 100])` (default) | scalar in the range [0,100] | 3-element row vector in the range [0,100] | 3-by-3 matrix in the range [0,100]

Sensor axes skew in percentage, specified as a scalar, a 3-element row vector, or a 3-by-3 matrix with values ranging from `0` to `100`. The diagonal elements of the matrix account for the misalignment effects for each axes. The off-diagonal elements account for the cross-axes misalignment effects. The measured state $v_{measure}$ is obtained from the true state $v_{true}$ via the misalignment matrix as:

$$v_{measure} = \frac{1}{100} M v_{true} = \frac{1}{100} \begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{bmatrix} v_{true}$$

- If you specify the property as a scalar, then all the off-diagonal elements of the matrix take the value of the specified scalar and all the diagonal elements are 100.
- If you specify the property as a vector [$a$ $b$ $c$], then $m_{21} = m_{31} = a$, $m_{12} = m_{32} = b$, and $m_{13} = m_{23} = c$. All the diagonal elements are 100.

**White noise PSD (μT/√Hz)** — Power spectral density of sensor noise (μT/√Hz)

`[0 0 0]` (default) | real scalar | real 3-element row vector

Power spectral density of sensor noise in μT/√Hz, specified as a real scalar or 3-element row vector. Any scalar input is converted into a real 3-element row vector where each element has the input scalar value.

Data Types: `single` | `double`

**Bias Instability (μT)** — Instability of the bias offset (μT)

`[0 0 0]` (default) | real scalar | real 3-element row vector

Instability of the bias offset in μT, specified as a real scalar or 3-element row vector. Any scalar input is converted into a real 3-element row vector where each element has the input scalar value.

Data Types: `single` | `double`

**Random walk ((μT)*√Hz)** — Integrated white noise of sensor ((μT)*√Hz)

`[0 0 0]` (default) | real scalar | real 3-element row vector

Integrated white noise of sensor in (μT)*√Hz, specified as a real scalar or 3-element row vector. Any scalar input is converted into a real 3-element row vector where each element has the input scalar value.

Data Types: `single` | `double`

**Bias from temperature (μT/℃)** — Sensor bias from temperature (μT/℃)

`[0 0 0]` (default) | real scalar | real 3-element row vector

Sensor bias from temperature in μT/℃, specified as a real scalar or 3-element row vector. Any scalar input is converted into a real 3-element row vector where each element has the input scalar value.

Data Types: `single` | `double`

**Temperature scale factor (%/°C)** — Scale factor error from temperature (%/℃)

`[0 0 0]` (default) | real scalar in the range [0,100] | real 3-element row vector in the range [0,100]

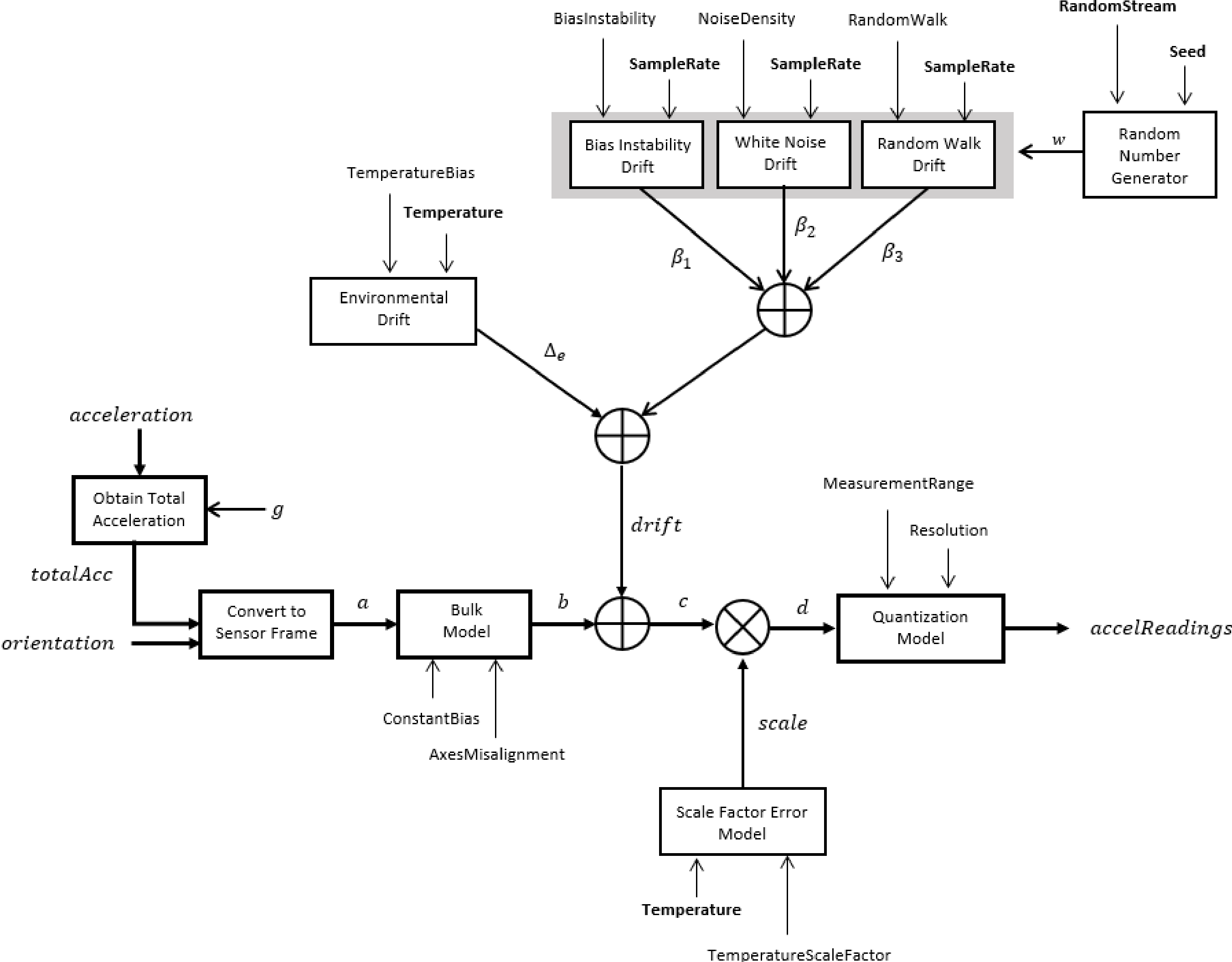
Scale factor error from temperature in %/℃, specified as a real scalar or real 3-element row vector with values ranging from 0 to 100. Any scalar input is converted into a real 3-element row vector where each element has the input scalar value.

Data Types: `single` | `double`

## Algorithms

### Accelerometer

The following algorithm description assumes an NED navigation frame. The accelerometer model uses the ground-truth orientation and acceleration inputs and the `imuSensor` and `accelparams` properties to model accelerometer readings.



#### Obtain Total Acceleration

To obtain the total acceleration (*totalAcc*), the acceleration is preprocessed by negating and adding the gravity constant vector ($g$= [0; 0; 9.8] m/s$^2$ assuming an NED frame) as:

$$totalAcc = -acceleration + g$$

The `acceleration` term is negated to obtain zero total acceleration readings when the accelerometer is in a free fall. The `acceleration` term is also known as the specific force.

#### Convert to Sensor Frame

Then the total acceleration is converted from the local navigation frame to the sensor frame using:

$$a = (orientation)(totalAcc)^T$$

If the orientation is input in quaternion form, it is converted to a rotation matrix before processing.

#### Bulk Model

The ground-truth acceleration in the sensor frame, $a$, passes through the bulk model, which adds axes misalignment and bias:

$$b = \left( \begin{bmatrix} 1 & \frac{\alpha_2}{100} & \frac{\alpha_3}{100} \\ \frac{\alpha_1}{100} & 1 & \frac{\alpha_3}{100} \\ \frac{\alpha_1}{100} & \frac{\alpha_2}{100} & 1 \end{bmatrix} \left(a^T\right) \right)^T + \text{ConstantBias}$$

where ConstantBias is a property of `accelparams`, and $\alpha_1$, $\alpha_2$, and $\alpha_3$ are given by the first, second, and third elements of the AxesMisalignment property of `accelparams`.

#### Bias Instability Drift

The bias instability drift is modeled as white noise biased and then filtered:

$$\beta_1(k) = \frac{1}{2}\beta_1(k-1) + (\text{BiasInstability})w(k)$$

where $k$ is the discrete time step index, BiasInstability is a property of `accelparams`, $w$ is white noise that follows a normal distribution of mean 0 and variance of 1. The discrete time step size is the reciprocal of the SampleRate property.

#### White Noise Drift

White noise drift is modeled by multiplying elements of the white noise random stream by the standard deviation:

$$\beta_2 = (w)\left(\sqrt{\frac{\text{SampleRate}}{2}}\right)(\text{NoiseDensity})$$

where $w$ is white noise that follows a normal distribution of mean 0 and variance of 1, SampleRate is an `imuSensor` property, and NoiseDensity is an `accelparams` property.

#### Random Walk Drift

The random walk drift is modeled by biasing elements of the white noise random stream and then filtering:

$$\beta_2(k) = \beta_2(k-1) + w(k)\left(\frac{\text{RandomWalk}}{\sqrt{\frac{\text{SampleRate}}{2}}}\right)$$

where $k$ is the discrete time step index, RandomWalk is a property of `accelparams`, SampleRate is a property of `imuSensor`, $w$ is white noise that follows a normal distribution of mean 0 and variance of 1. The discrete time step size is the reciprocal of the SampleRate property.

#### Environmental Drift Noise

The environmental drift noise is modeled by multiplying the temperature difference from a standard with the temperature bias:

$$\Delta_e = (\text{Temperature} - 25)(\text{TemperatureBias})$$

where Temperature is a property of `imuSensor`, and TemperatureBias is a property of `accelparams`. The constant 25 corresponds to a standard temperature.

#### Scale Factor Error Model

The temperature scale factor error is modeled as:

$$scaleFactorError = 1 + \left(\frac{\text{Temperature}-25}{100}\right)(\text{TemperatureScaleFactor})$$

where Temperature is a property of `imuSensor`, and TemperatureScaleFactor is a property of `accelparams`. The constant 25 corresponds to a standard temperature.

#### Quantization Model

The quantization is modeled by first saturating the continuous signal model:

$$e = \begin{cases} \text{MeasurementRange} & \text{if} \quad d > \text{MeasurementRange} \\ -\text{MeasurementRange} & \text{if} \quad -d > \text{MeasurementRange} \\ d & \text{else} \end{cases}$$

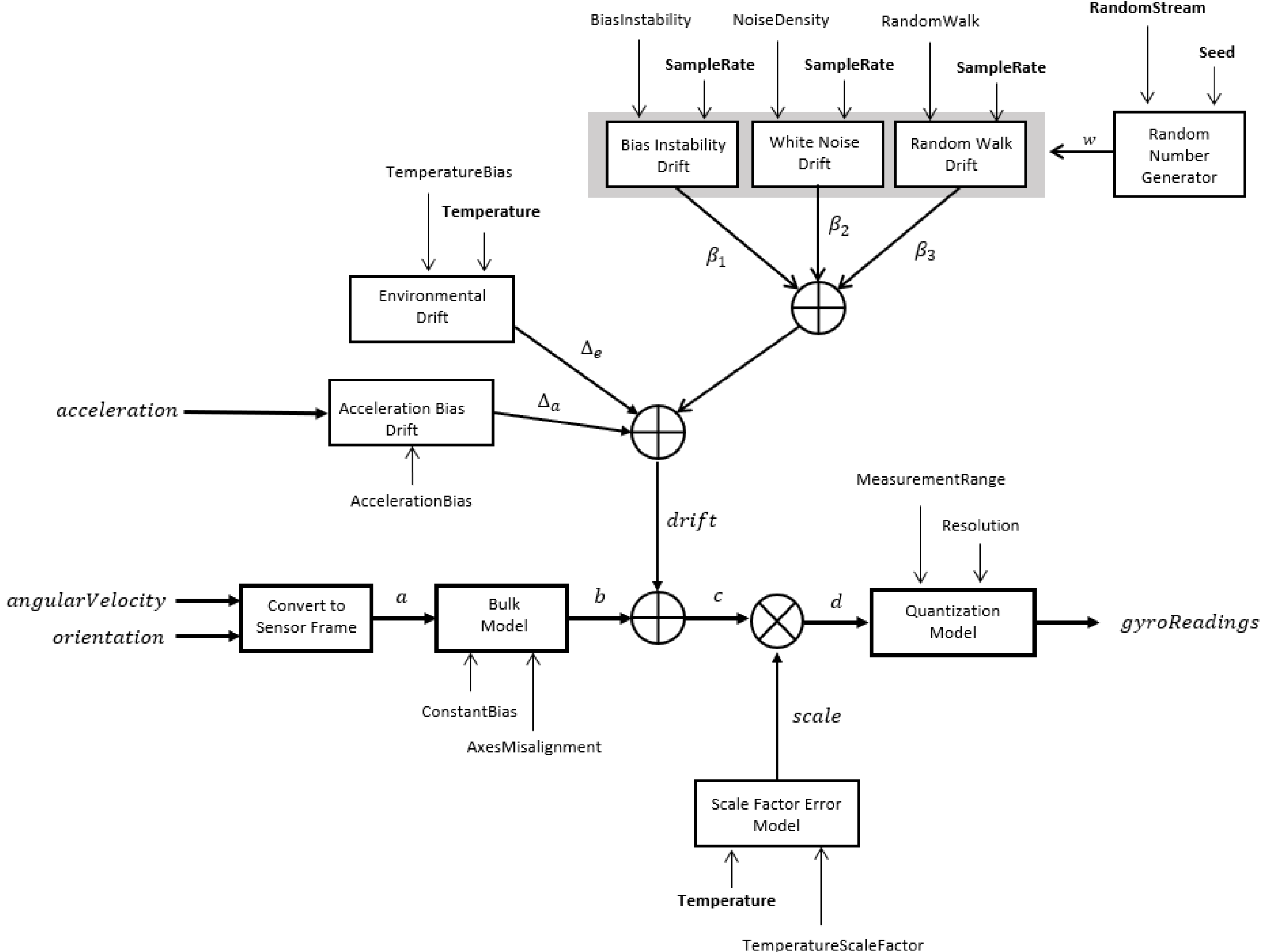
and then setting the resolution:

$$accelReadings = (\text{Resolution})\left(\text{round}\left(\frac{e}{\text{Resolution}}\right)\right)$$

where MeasurementRange is a property of `accelparams`.

### Gyroscope

The following algorithm description assumes an NED navigation frame. The gyroscope model uses the ground-truth orientation, acceleration, and angular velocity inputs, and the `imuSensor` and `gyroparams` properties to model accelerometer readings.




**Convert to Sensor Frame**

The ground-truth angular velocity is converted from the local frame to the sensor frame using the ground-truth orientation:

$$a = (orientation)(angularVelocity)^T$$

If the orientation is input in quaternion form, it is converted to a rotation matrix before processing.

**Bulk Model**

The ground-truth angular velocity in the sensor frame, $a$, passes through the bulk model, which adds axes misalignment and bias:

$$b = \left( \begin{bmatrix} 1 & \frac{\alpha_2}{100} & \frac{\alpha_3}{100} \\ \frac{\alpha_1}{100} & 1 & \frac{\alpha_3}{100} \\ \frac{\alpha_1}{100} & \frac{\alpha_2}{100} & 1 \end{bmatrix} (a^T) \right)^T + \text{ConstantBias}$$

where ConstantBias is a property of `gyroparams`, and $\alpha_1$, $\alpha_2$, and $\alpha_3$ are given by the first, second, and third elements of the AxesMisalignment property of `gyroparams`.

#### Bias Instability Drift

The bias instability drift is modeled as white noise biased and then filtered:

$$\beta_1(k) = \frac{1}{2}\beta_1(k-1) + (\text{BiasInstability})w(k)$$

where $k$ is the discrete time step index, BiasInstability is a property of `gyroparams`, $w$ is white noise that follows a normal distribution of mean 0 and variance of 1. The discrete time step size is the reciprocal of the SampleRate property.

#### White Noise Drift

White noise drift is modeled by multiplying elements of the white noise random stream by the standard deviation:

$$\beta_2 = (w)\left(\sqrt{\frac{\text{SampleRate}}{2}}\right)(\text{NoiseDensity})$$

where $w$ is white noise that follows a normal distribution of mean 0 and variance of 1, SampleRate is an `imuSensor` property, and NoiseDensity is an `gyroparams` property.

#### Random Walk Drift

The random walk drift is modeled by biasing elements of the white noise random stream and then filtering:

$$\beta_2(k) = \beta_2(k-1) + w(k)\left(\frac{\text{RandomWalk}}{\sqrt{\frac{\text{SampleRate}}{2}}}\right)$$

where $k$ is the discrete time step index, RandomWalk is a property of `gyroparams`, SampleRate is a property of `imuSensor`, and $w$ is white noise that follows a normal distribution of mean 0 and variance of 1. The discrete time step size is the reciprocal of the SampleRate property.

#### Environmental Drift Noise

The environmental drift noise is modeled by multiplying the temperature difference from a standard with the temperature bias:

$$\Delta_e = (\text{Temperature} - 25)(\text{TemperatureBias})$$

where Temperature is a property of `imuSensor`, and TemperatureBias is a property of `gyroparams`. The constant 25 corresponds to a standard temperature.

#### Acceleration Bias Drift

The acceleration bias drift is modeled by multiplying the acceleration input and acceleration bias:

$$\Delta_a = acceleration * \text{AccelerationBias}$$

where AccelerationBias is a property of `gyroparams`.

#### Scale Factor Error Model

The temperature scale factor error is modeled as:

$$scaleFactorError = 1 + \left(\frac{\text{Temperature} - 25}{100}\right)(\text{TemperatureScaleFactor})$$

where Temperature is a property of `imuSensor`, and TemperatureScaleFactor is a property of `gyroparams`. The constant 25 corresponds to a standard temperature.

#### Quantization Model

The quantization is modeled by first saturating the continuous signal model:

$$e = \begin{cases} \text{MeasurementRange} & \text{if} \quad d > \text{MeasurementRange} \\ -\text{MeasurementRange} & \text{if} \quad -d > \text{MeasurementRange} \\ d & \text{else} \end{cases}$$

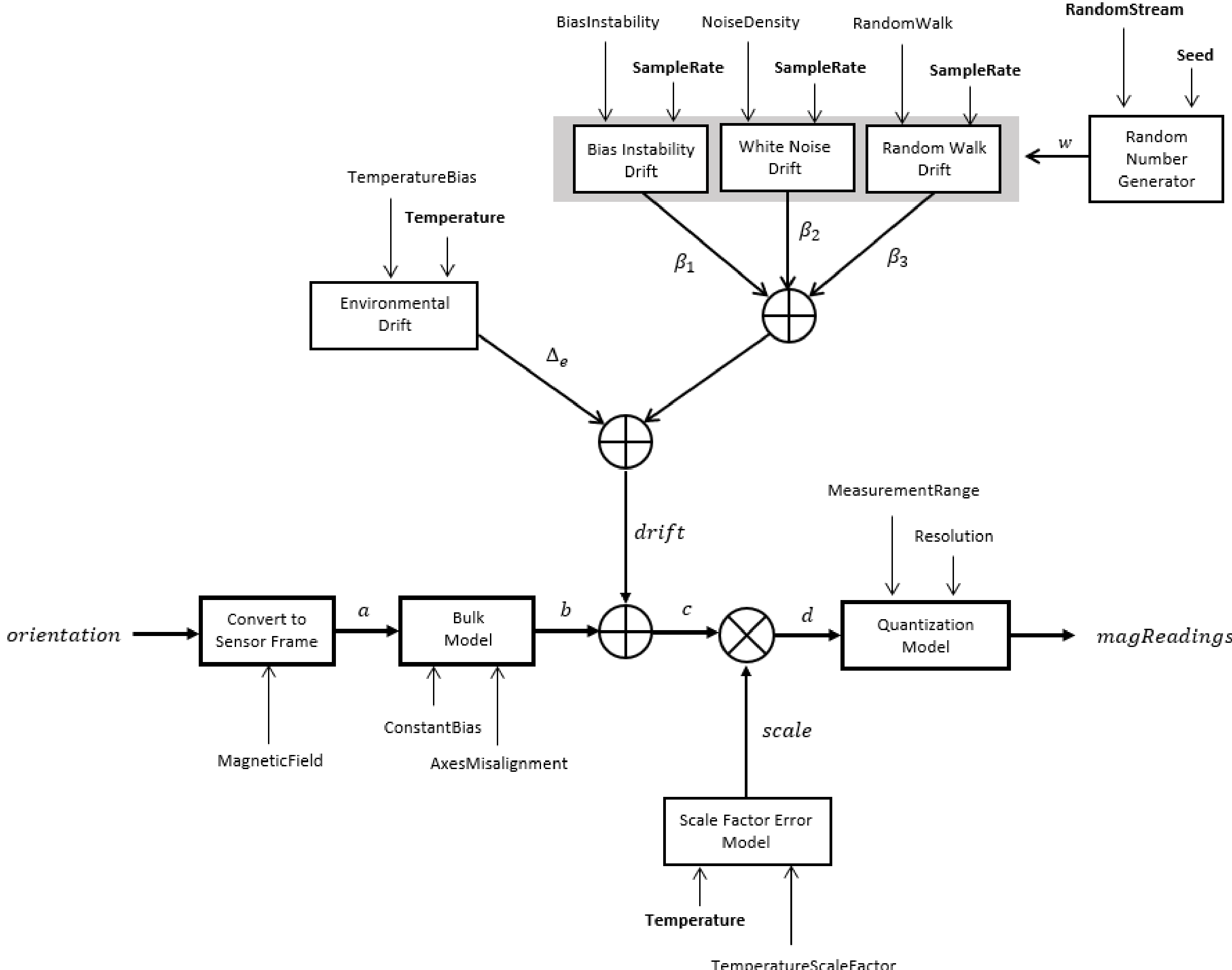
and then setting the resolution:

$$gyroReadings = (\text{Resolution})\left(\text{round}\left(\frac{e}{\text{Resolution}}\right)\right)$$

where MeasurementRange is a property of `gyroparams`.

### Magnetometer

The following algorithm description assumes an NED navigation frame. The magnetometer model uses the ground-truth orientation and acceleration inputs, and the `imuSensor` and `magparams` properties to model magnetometer readings.




**Convert to Sensor Frame**

The ground-truth acceleration is converted from the local frame to the sensor frame using the ground-truth orientation:

$$a = (orientation)(totalAcc)^T$$

If the orientation is input in quaternion form, it is converted to a rotation matrix before processing.

**Bulk Model**

The ground-truth acceleration in the sensor frame, $a$, passes through the bulk model, which adds axes misalignment and bias:

$$b = \left( \begin{bmatrix} 1 & \frac{\alpha_2}{100} & \frac{\alpha_3}{100} \\ \frac{\alpha_1}{100} & 1 & \frac{\alpha_3}{100} \\ \frac{\alpha_1}{100} & \frac{\alpha_2}{100} & 1 \end{bmatrix} \left(a^T\right) \right)^T + \text{ConstantBias}$$

where ConstantBias is a property of `magparams`, and $\alpha_1$, $\alpha_2$, and $\alpha_3$ are given by the first, second, and third elements of the AxesMisalignment property of `magparams`.

**Bias Instability Drift**

The bias instability drift is modeled as white noise biased and then filtered:

$$\beta_1(k) = \frac{1}{2}\beta_1(k-1) + (\text{BiasInstability})w(k)$$

where $k$ is the discrete time step index, BiasInstability is a property of `magparams`, $w$ is white noise that follows a normal distribution of mean 0 and variance of 1. The discrete time step size is the reciprocal of the SampleRate property.

**White Noise Drift**

White noise drift is modeled by multiplying elements of the white noise random stream by the standard deviation:

$$\beta_2 = (w)\left(\sqrt{\frac{\text{SampleRate}}{2}}\right)(\text{NoiseDensity})$$

where $w$ is white noise that follows a normal distribution of mean 0 and variance of 1, SampleRate is an `imuSensor` property, and NoiseDensity is an `magparams` property.

**Random Walk Drift**

The random walk drift is modeled by biasing elements of the white noise random stream and then filtering:

$$\beta_2(k) = \beta_2(k-1) + w(k)\left(\frac{\text{RandomWalk}}{\sqrt{\frac{\text{SampleRate}}{2}}}\right)$$

where $k$ is the discrete time step index, RandomWalk is a property of `magparams`, SampleRate is a property of `imuSensor`, $w$ is white noise that follows a normal distribution of mean 0 and variance of 1. The discrete time step size is the reciprocal of the SampleRate property.

**Environmental Drift Noise**

The environmental drift noise is modeled by multiplying the temperature difference from a standard with the temperature bias:

$$\Delta_e = (\text{Temperature} - 25)(\text{TemperatureBias})$$

where Temperature is a property of `imuSensor`, and TemperatureBias is a property of `magparams`. The constant 25 corresponds to a standard temperature.

#### Scale Factor Error Model

The temperature scale factor error is modeled as:

$$scaleFactorError = 1 + \left(\frac{\text{Temperature} - 25}{100}\right)(\text{TemperatureScaleFactor})$$

where Temperature is a property of `imuSensor`, and TemperatureScaleFactor is a property of `magparams`. The constant 25 corresponds to a standard temperature.

#### Quantization Model

The quantization is modeled by first saturating the continuous signal model:

$$e = \begin{cases} \text{MeasurementRange} & \text{if} \quad d > \text{MeasurementRange} \\ -\text{MeasurementRange} & \text{if} \quad -d > \text{MeasurementRange} \\ d & \text{else} \end{cases}$$

and then setting the resolution:

$$magReadings = (\text{Resolution})\left(\text{round}\left(\frac{e}{\text{Resolution}}\right)\right)$$

where MeasurementRange is a property of `magparams`.

# Version History

**Introduced in R2020a**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using Simulink® Coder™.

## See Also

### Classes

`accelparams` | `gyroparams` | `magparams`

### Objects

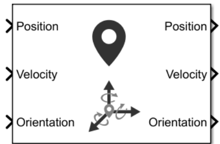
`imuSensor` | `gpsSensor`

### Topics

"Model IMU, GPS, and INS/GPS"

# INS

Simulate INS sensor




**Libraries:**
Navigation Toolbox / Multisensor Positioning / Sensor Models
Automated Driving Toolbox / Driving Scenario and Sensor Modeling
Sensor Fusion and Tracking Toolbox / Multisensor Positioning / Sensor Models
UAV Toolbox / UAV Scenario and Sensor Modeling

## Description

The block simulates an INS sensor, which outputs noise-corrupted position, velocity, and orientation based on the corresponding inputs. The block can also optionally output acceleration and angular velocity based on the corresponding inputs. To change the level of noise present in the output, you can vary the roll, pitch, yaw, position, velocity, acceleration, and angular velocity accuracies. The accuracy is defined as the standard deviation of the noise.

## Ports

### Input

**Position** — Position of INS sensor
*N*-by-3 real-valued matrix

Position of the INS sensor relative to the navigation frame, in meters, specified as an *N*-by-3 real-valued matrix. *N* is the number of samples.

Data Types: `single` | `double`

**Velocity** — Velocity of INS sensor
*N*-by-3 real-valued matrix of scalar

Velocity of the INS sensor relative to the navigation frame, in meters per second, specified as an *N*-by-3 real-valued matrix. *N* is the number of samples.

Data Types: `single` | `double`

**Orientation** — Orientation of INS sensor
3-by-3-by-*N* real-valued array | *N*-by-4 real-valued matrix | *N*-by-3 matrix of Euler angles

Orientation of the INS sensor relative to the navigation frame, specified as one of these formats:

- A 3-by-3-by-*N* real-valued array, where each page of the array (3-by-3 matrix) is a rotation matrix.
- An *N*-by-4 real-valued matrix, where each row of the matrix is the four elements of a quaternion.
- An *N*-by-3 matrix of Euler angles, where each row of the matrix is the three Euler angles corresponding to the z-y-x rotation convention.

*N* is the number of samples.

Data Types: `single` | `double`

**Acceleration** — Acceleration of INS sensor
*N*-by-3 real-valued matrix

Acceleration of the INS sensor relative to the navigation frame, in meters per second squared, specified as an *N*-by-3 real-valued matrix. *N* is the number of samples.

#### Dependencies

To enable this input port, select **Use acceleration and angular velocity**.

Data Types: `single` | `double`

**AngularVelocity** — Angular velocity of INS sensor
*N*-by-3 real-valued matrix

Angular velocity of the INS sensor relative to the navigation frame, in degrees per second, specified as an *N*-by-3 real-valued matrix. *N* is the number of samples.

#### Dependencies

To enable this input port, select **Use acceleration and angular velocity**.

Data Types: `single` | `double`

**HasGNSSFix** — Enable GNSS fix
*N*-by-1 logical vector

Enable GNNS fix, specified as an *N*-by-1 logical vector. *N* is the number of samples. Specify this input as `false` to simulate the loss of a GNSS receiver fix. When a GNSS receiver fix is lost, position measurements drift at a rate specified by the **Position error factor** parameter.

#### Dependencies

To enable this input port, select **Enable HasGNSSFix port**.

Data Types: `single` | `double`

### Output

**Position** — Position of INS sensor
*N*-by-3 real-valued matrix

Position of the INS sensor relative to the navigation frame, in meters, returned as an *N*-by-3 real-valued matrix. *N* is the number of samples in the input.

Data Types: `single` | `double`

**Velocity** — Velocity of INS sensor
*N*-by-3 real-valued matrix

Velocity of the INS sensor relative to the navigation frame, in meters per second, returned as an *N*-by-3 real-valued matrix. *N* is the number of samples in the input.

Data Types: `single` | `double`

**Orientation** — Orientation of INS sensor
3-by-3-by-*N* real-valued array | *N*-by-4 real-valued matrix

Orientation of the INS sensor relative to the navigation frame, returned as one of the formats:

- A 3-by-3-by-*N* real-valued array, where each page of the array (3-by-3 matrix) is a rotation matrix.
- An *N*-by-4 real-valued matrix, where each row of the matrix is the four elements of a quaternion.
- An *N*-by-3 matrix of Euler angles, where each row of the matrix is the three Euler angles corresponding to the z-y-x rotation convention.

*N* is the number of samples in the input.

Data Types: `single` | `double`

**Acceleration** — Acceleration of INS sensor
*N*-by-3 real-valued matrix

Acceleration of the INS sensor relative to the navigation frame, in meters per second squared, returned as an *N*-by-3 real-valued matrix. *N* is the number of samples.

#### Dependencies

To enable this output port, select **Use acceleration and angular velocity**.

Data Types: `single` | `double`

**AngularVelocity** — Angular velocity of INS sensor
*N*-by-3 real-valued matrix

Angular velocity of the INS sensor relative to the navigation frame, in degrees per second, returned as an *N*-by-3 real-valued matrix. *N* is the number of samples.

#### Dependencies

To enable this output port, select **Use acceleration and angular velocity**.

Data Types: `single` | `double`

## Parameters

**Mounting location (m)** — Location of sensor on platform (m)

`[0 0 0]` (default) | three-element real-valued vector of form [*x y z*]

Location of the sensor on the platform, in meters, specified as a three-element real-valued vector of the form [*x y z*]. The vector defines the offset of the sensor origin from the origin of the platform.

Data Types: `single` | `double`

**Roll (X-axis) accuracy (deg)** — Accuracy of roll measurement (deg)

`0.2` (default) | nonnegative real scalar

Accuracy of the roll measurement of the sensor body in degrees, specified as a nonnegative real scalar.

Roll is defined as rotation around the *x*-axis of the sensor body. Roll noise is modeled as white process noise with standard deviation equal to the specified **Roll accuracy** in degrees.

Data Types: `single` | `double`

**Pitch (Y-axis) accuracy (deg)** — Accuracy of pitch measurement (deg)

`0.2` (default) | nonnegative real scalar

Accuracy of the pitch measurement of the sensor body in degrees, specified as a nonnegative real scalar.

Pitch is defined as rotation around the *y*-axis of the sensor body. Pitch noise is modeled as white process noise with standard deviation equal to the specified **Pitch accuracy** in degrees.

Data Types: `single` | `double`

**Yaw (Z-axis) accuracy (deg)** — Accuracy of yaw measurement (deg)

`1` (default) | nonnegative real scalar

Accuracy of the yaw measurement of the sensor body in degrees, specified as a nonnegative real scalar.

Yaw is defined as rotation around the *z*-axis of the sensor body. Yaw noise is modeled as white process noise with standard deviation equal to the specified **Yaw accuracy** in degrees.

Data Types: `single` | `double`

**Position accuracy (m)** — Accuracy of position measurement (m)

`1` (default) | nonnegative real scalar | 1-by-3 vector of nonnegative values

Accuracy of the position measurement of the sensor body in meters, specified as a nonnegative real scalar or a 1-by-3 vector of nonnegative values. If you specify the parameter as a scalar value, then the block sets the accuracy of all three position components to this value.

Position noise is modeled as white process noise with a standard deviation equal to the specified **Position accuracy** in meters.

Data Types: `single` | `double`

**Velocity accuracy (m/s)** — Accuracy of velocity measurement (m/s)

`0.05` (default) | nonnegative real scalar

Accuracy of the velocity measurement of the sensor body in meters per second, specified as a nonnegative real scalar.

Velocity noise is modeled as white process noise with a standard deviation equal to the specified **Velocity accuracy** in meters per second.

Data Types: `single` | `double`

**Use acceleration and angular velocity** — Use acceleration and angular velocity

off (default) | on

Select this check box to enable the block inputs of acceleration and angular velocity through the **Acceleration** and **AngularVelocity** input ports, respectively. Meanwhile, the block outputs the acceleration and angular velocity measurements through the **Acceleration** and **AngularVelocity**

output ports, respectively. Additionally, selecting this parameter enables you to specify the **Acceleration accuracy** and **Angular velocity accuracy** parameters.

**Acceleration accuracy (m/s²)** — Accuracy of acceleration measurement (m/s²)

0 (default) | nonnegative real scalar

Accuracy of the acceleration measurement of the sensor body in meters, specified as a nonnegative real scalar.

Acceleration noise is modeled as white process noise with a standard deviation equal to the specified **Acceleration accuracy** in meters per second squared.

#### Dependencies

To enable this parameter, select **Use acceleration and angular velocity**.

Data Types: `single` | `double`

**Angular velocity accuracy (deg/s)** — Accuracy of angular velocity measurement (deg/s)

0 (default) | nonnegative real scalar

Accuracy of the angular velocity measurement of the sensor body in meters, specified as a nonnegative real scalar.

Angular velocity noise is modeled as white process noise with a standard deviation equal to the specified **Angular velocity accuracy** in degrees per second.

#### Dependencies

To enable this parameter, select **Use acceleration and angular velocity**.

Data Types: `single` | `double`

**Enable HasGNSSFix port** — Enable `HasGNSSFix` input port

off (default) | on

Select this check box to enable the **HasGNSSFix** input port. When the **HasGNSSFix** input is specified as `false`, position measurements drift at a rate specified by the **Position error factor** parameter.

**Position error factor** — Position error factor (m)

`[0 0 0]` (default) | nonnegative scalar | 1-by-3 real-valued vector

Position error factor without GNSS fix, specified as a scalar or a 1-by-3 real-valued vector. If you specify the parameter as a scalar value, then the block sets the position error factors of all three position components to this value.

When the **HasGNSSFix** input is specified as `false`, the position error grows at a quadratic rate due to constant bias in the accelerometer. The position error for a position component $E(t)$ can be expressed as $E(t) = 1/2\alpha t^2$, where $\alpha$ is the position error factor for the corresponding component and $t$ is the time since the GNSS fix is lost. The computed $E(t)$ values for the $x$, $y$, and $z$ components are added to the corresponding position components of the **Position** output.

#### Dependencies

To enable this parameter, select **Enable HasGNSSFix port**.

Data Types: `double`

**Seed** — Initial seed for randomization

`67` (default) | nonnegative integer

Initial seed of a random number generator algorithm, specified as a nonnegative integer.

Data Types: `single` | `double`

**Simulate using** — Type of simulation to run

`Code Generation` (default) | `Interpreted Execution`

- `Interpreted execution` — Simulate the model using the MATLAB interpreter. This option shortens startup time. In `Interpreted execution` mode, you can debug the source code of the block.
- `Code generation` — Simulate the model using generated C code. The first time that you run a simulation, Simulink generates C code for the block. The C code is reused for subsequent simulations if the model does not change. This option requires additional startup time.

## Version History

**Introduced in R2020b**

## Extended Capabilities

#### C/C++ Code Generation

Generate C and C++ code using Simulink® Coder™.

## See Also

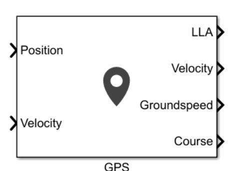
IMU | `insSensor`

#### Topics

"Model IMU, GPS, and INS/GPS"

# GPS

Simulate GPS sensor readings with noise




**Libraries:**
UAV Toolbox / UAV Scenario and Sensor Modeling
Navigation Toolbox / Multisensor Positioning / Sensor Models
Sensor Fusion and Tracking Toolbox / Multisensor Positioning / Sensor Models

## Description

The block outputs noise-corrupted GPS measurements based on the input position and velocity in the local coordinate frame or geodetic frame. It uses the WGS84 earth model to convert local coordinates to latitude-longitude-altitude LLA coordinates.

## Ports

### Input

**Position** — Position of GPS receiver in navigation coordinate system
matrix

Specify the input position of the GPS receiver in the navigation coordinate system as a real, finite *N*-by-3 matrix. *N* is the number of samples in the current frame. The format of the matrix rows differs depending on the value of the **Position input format** parameter.

- If the value of the **Position input format** parameter is `Local`, specify each row of the **Position** as Cartesian coordinates in meters with respect to the local navigation reference frame, specified by the **Reference frame** parameter, with the origin specified by the **Reference location** parameter.
- If the value of the **Position input format** parameter is `Geodetic`, specify each row of the **Position** input as geodetic coordinates of the form `[latitude longitude altitude]`. The values of `latitude` and `longitude` are in degrees. `Altitude` is the height above the WGS84 ellipsoid model in meters.

Data Types: `single` | `double`

**Velocity** — Velocity in local navigation coordinate system (m/s)
matrix

Specify the input velocity of the GPS receiver in the navigation coordinate system in meters per second as a real, finite *N*-by-3 matrix. *N* is the number of samples in the current frame. The format of the matrix rows differs depending on the value of the **Position input format** parameter.

- If the value of the **Position input format** parameter is `Local`, specify each row of the **Velocity** with respect to the local navigation reference frame (NED or ENU), specified by the **Reference frame** parameter, with the origin specified by the **Reference location** parameter.

- If the value of the **Position input format** parameter is `Geodetic`, specify each row of the **Velocity** with respect to the navigation reference frame (NED or ENU), specified by the **Reference frame** parameter, with the origin specified by **Position**.

Data Types: `single` | `double`

**Output**

**LLA** — Position in LLA coordinate system
matrix

Position of the GPS receiver in the geodetic latitude, longitude, and altitude (LLA) coordinate system, returned as a real, finite *N*-by-3 array. Latitude and longitude are in degrees with North and East being positive. Altitude is in meters.

*N* is the number of samples in the current frame.

Data Types: `single` | `double`

**Velocity** — Velocity in local navigation coordinate system (m/s)
matrix

Velocity of the GPS receiver in the local navigation coordinate system in meters per second, returned as a real, finite *N*-by-3 matrix. *N* is the number of samples in the current frame. The format of the matrix rows differs depending on the value of the **Position input format** parameter.

- If the value of the **Position input format** parameter is `Local`, the **Velocity** output is with respect to the local navigation reference frame (NED or ENU), specified by the **Reference frame** parameter, with the origin specified by the **Reference location** parameter.
- If the value of the **Position input format** parameter is `Geodetic`, the **Velocity** output is with respect to the navigation reference frame (NED or ENU), specified by the **Reference frame** parameter, with the origin specified by **LLA**.

Data Types: `single` | `double`

**Groundspeed** — Magnitude of horizontal velocity in local navigation coordinate system (m/s)
vector

Magnitude of the horizontal velocity of the GPS receiver in the local navigation coordinate system in meters per second, returned as a real, finite *N*-element column vector.

*N* is the number of samples in the current frame.

Data Types: `single` | `double`

**Course** — Direction of horizontal velocity in local navigation coordinate system (°)
vector

Direction of the horizontal velocity of the GPS receiver in the local navigation coordinate system, in degrees, returned as a real, finite *N*-element column vector of values from 0 to 360. North corresponds to 0 degrees and East corresponds to 90 degrees.

*N* is the number of samples in the current frame.

Data Types: `single` | `double`

## Parameters

**Reference frame** — Reference frame
NED (default) | ENU

Specify the reference frame as NED (North-East-Down) or ENU(East-North-Up).

**Position input format** — Position coordinate input format
Local (default) | Geodetic

Specify the position coordinate input format as Local or Geodetic.

- If you set this parameter to Local, then the input to the **Position** port must be in the form of Cartesian coordinates with respect to the local navigation frame, specified by the **Reference Frame** parameter, with the origin fixed and defined by the **Reference location** parameter. The input to the **Velocity** input port must also be with respect to this local navigation frame.
- If you set this parameter to Geodetic, then the input to the **Position** port must be geodetic coordinates in [latitude longitude altitude]. The input to the **Velocity** input port must also be with respect to the navigation frame specified by the **Reference frame** parameter, with the origin corresponding to the **Position** port.

**Reference location** — Origin of local navigation reference frame
[0,0,0] (default) | three-element vector

Specify the origin of the local reference frame as a three-element row vector in geodetic coordinates [latitude longitude altitude], where altitude is the height above the reference ellipsoid model WGS84. The reference location values are in degrees, degrees, and meters, respectively. The degree format is decimal degrees (DD).

#### Dependencies

To enable this parameter, set the **Position input format** parameter to Local.

**Horizontal position accuracy** — Horizontal position accuracy (m)
1.6 (default) | nonnegative real scaler

Specify horizontal position accuracy as a nonnegative real scalar in meters. The horizontal position accuracy specifies the standard deviation of the noise in the horizontal position measurement. Increasing this value adds noise to the measurement, decreasing its accuracy.

**Tunable:** Yes

**Vertical position accuracy** — Vertical position accuracy (m)
3 (default) | nonnegative real scaler

Specify vertical position accuracy as a nonnegative real scalar in meters. The vertical position accuracy specifies the standard deviation of the noise in the vertical position measurement. Increasing this value adds noise to the measurement, decreasing its accuracy.

**Tunable:** Yes

**Velocity accuracy** — Velocity accuracy (m/s)
0.1 (default) | nonnegative real scalar

Specify velocity accuracy per second as a nonnegative real scalar in meters. The velocity accuracy specifies the standard deviation of the noise in the velocity measurement. Increasing this value adds noise to the measurement, decreasing its accuracy.

**Tunable:** Yes

**Decay factor** — Global position noise decay factor
`0.999` (default) | scalar in range [0, 1]

Specify the global position noise decay factor as a numeric scalar in the range [0, 1]. A decay factor of `0` models the global position noise as a white noise process. A decay factor of 1 models the global position noise as a random walk process.

**Tunable:** Yes

**Seed** — Initial seed
`67` (default) | nonnegative integer

Specify the initial seed of an mt19937ar random number generator algorithm as a nonnegative integer.

**Simulate using** — Type of simulation to run
`Interpreted execution` (default) | `Code generation`

Select the type of simulation to run from these options:

- `Interpreted execution` — Simulate the model using the MATLAB interpreter. For more information, see “Simulation Modes”.
- `Code generation` — Simulate the model using generated C code. The first time you run a simulation, Simulink generates C code for the block. The C code is reused for subsequent simulations, as long as the model does not change.

# Version History

**Introduced in R2021b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using Simulink® Coder™.

## See Also

### Objects

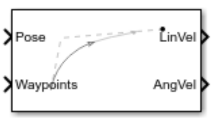
`gpsSensor`

### Topics

“Model IMU, GPS, and INS/GPS”

# Pure Pursuit

Linear and angular velocity control commands




**Libraries:**
Robotics System Toolbox / Mobile Robot Algorithms
Navigation Toolbox / Control Algorithms

## Description

The Pure Pursuit block computes linear and angular velocity commands for following a path using a set of waypoints and the current pose of a differential drive vehicle. The block takes updated poses to update velocity commands for the vehicle to follow a path along a desired set of waypoints. Use the **Max angular velocity** and **Desired linear velocity** parameters to update the velocities based on the performance of the vehicle.

The **Lookahead distance** parameter computes a look-ahead point on the path, which is an instantaneous local goal for the vehicle. The angular velocity command is computed based on this point. Changing **Lookahead distance** has a significant impact on the performance of the algorithm. A higher look-ahead distance results in a smoother trajectory for the vehicle, but can cause the vehicle to cut corners along the path. Too low of a look-ahead distance can result in oscillations in tracking the path, causing unstable behavior. For more information on the pure pursuit algorithm, see “Pure Pursuit Controller”.

## Input/Output Ports

### Input

**Pose** — Current vehicle pose
`[x y theta]` vector

Current vehicle pose, specified as an `[x y theta]` vector, which corresponds to the *x*-*y* position and orientation angle, *theta*. Positive angles are measured counterclockwise from the positive *x*-axis.

**Waypoints** — Waypoints
[ ] (default) | *n*-by-2 array

Waypoints, specified as an *n*-by-2 array of `[x y]` pairs, where *n* is the number of waypoints. You can generate the waypoints using path planners like `mobileRobotPRM` or specify them as an array in Simulink.

### Output

**LinVel** — Linear velocity
scalar in meters per second

Linear velocity, returned as a scalar in meters per second.

Data Types: `double`

**AngVel** — Angular velocity
scalar in radians per second

Angular velocity, returned as a scalar in radians per second.

Data Types: `double`

**TargetDir** — Target direction for vehicle
scalar in radians

Target direction for the vehicle, returned as a scalar in radians. The forward direction of the vehicle is considered zero radians, with positive angles measured counterclockwise. This output can be used as the input to the **TargetDir** port for the Vector Field Histogram block.

#### Dependencies

To enable this port, select the **Show TargetDir output port** parameter.

## Parameters

**Desired linear velocity (m/s)** — Linear velocity
`0.1` (default) | scalar

Desired linear velocity, specified as a scalar in meters per second. The controller assumes that the vehicle drives at a constant linear velocity and that the computed angular velocity is independent of the linear velocity.

**Maximum angular velocity (rad/s)** — Angular velocity
`1.0` (default) | scalar

Maximum angular velocity, specified as a scalar in radians per second. The controller saturates the absolute angular velocity output at the given value.

**Lookahead distance (m)** — Look-ahead distance
`1.0` (default) | scalar

Look-ahead distance, specified as a scalar in meters. The look-ahead distance changes the response of the controller. A vehicle with a higher look-ahead distance produces smooth paths but takes larger turns at corners. A vehicle with a smaller look-ahead distance follows the path closely and takes sharp turns, but oscillate along the path. For more information on the effects of look-ahead distance, see “Pure Pursuit Controller”.

**Show TargetDir output port** — Target direction indicator
off (default) | on

Select this parameter to enable the **TargetDir** out port. This port gives the target direction as an angle in radians from the forward position, with positive angles measured counterclockwise.

**Simulate using** — Type of simulation to run
`Code generation` (default) | `Interpreted execution`

- `Interpreted execution` — Simulate model using the MATLAB interpreter. This option shortens startup time but has a slower simulation speed than `Code generation`. In this mode, you can debug the source code of the block.

- `Code generation` — Simulate model using generated C code. The first time you run a simulation, Simulink generates C code for the block. The C code is reused for subsequent simulations, as long as the model does not change. This option requires additional startup time, but the speed of the subsequent simulations is comparable to `Interpreted execution`.

**Tunable:** No

# Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using Simulink® Coder™.

## See Also

### Blocks

Vector Field Histogram

### Classes

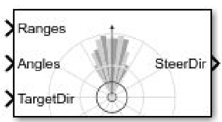
`binaryOccupancyMap` | `occupancyMap` | `controllerVFH`

### Topics

"Plan Path for a Differential Drive Robot in Simulink" (Robotics System Toolbox)
"Path Following with Obstacle Avoidance in Simulink®"
"Pure Pursuit Controller"

# Vector Field Histogram

Avoid obstacles using vector field histogram




**Libraries:**
Navigation Toolbox / Control Algorithms

## Description

The Vector Field Histogram (VFH) block enables your vehicle to avoid obstacles based on range sensor data. Given a range sensor reading in terms of ranges and angles, and a target direction to drive toward, the VFH controller computes an obstacle-free steering direction.

For more information on the algorithm details, see "Vector Field Histogram" on page 4-56 under Algorithms.

## Limitations

- The `Ranges` and `Angles` inputs are limited to 4000 elements when generating code for models that use this block.

## Input/Output Ports

### Input

**Ranges** — Range values from scan data
vector of scalars

Range values from scan data, specified as a vector of scalars in meters. These range values are distances from a sensor at specified angles. The vector must be the same length as the corresponding **Angles** vector.

**Angles** — Angle values from scan data
vector of scalars

Angle values from scan data, specified as a vector of scalars in radians. These angle values are the specific angles of the specified ranges. The vector must be the same length as the corresponding **Ranges** vector.

**TargetDir** — Target direction for vehicle
scalar

Target direction for the vehicle, specified as a scalar in radians. The forward direction of the vehicle is considered zero radians, with positive angles measured counterclockwise. You can use the **TargetDir** output from the Pure Pursuit block when generating controls from a set of waypoints.

### Output

**SteerDir** — Steering direction for vehicle
scalar

Steering direction for the vehicle, specified as a scalar in radians. This obstacle-free direction is calculated based on the VFH+ algorithm. The forward direction of the vehicle is considered zero radians, with positive angles measured counterclockwise.

## Parameters

### Main

**Number of angular sectors** — Number of bins used to create the histograms
`180` (default) | scalar

Number of bins used to create the histograms, specified as a scalar. This parameter is nontunable. You can set this parameter only when the object is initialized.

**Range distance limits (m)** — Limits for range readings
`[0.05 2]` (default) | two-element vector of scalars

Limits for range readings in meters, specified as a two-element vector of scalars. The range readings input are only considered if they fall within the distance limits. Use the lower distance limit to ignore false positives from poor sensor performance at lower ranges. Use the upper limit to ignore obstacles that are too far away from the vehicle.

**Histogram thresholds** — Thresholds for computing binary histogram
`[3 10]` (default) | two-element vector of scalars

Thresholds for computing binary histogram, specified as a two-element vector of scalars. The algorithm uses these thresholds to compute the binary histogram from the polar obstacle density. Polar obstacle density values higher than the upper threshold are represented as occupied space (1) in the binary histogram. Values smaller than the lower threshold are represented as free space (0). Values that fall between the limits are set to the values of a previous computed binary histogram if one exists from previous iterations. If a previous histogram does not exist, the value is set as free space (0).

**vehicle radius (m)** — Radius of the vehicle
`0.1` (default) | scalar

Radius of the vehicle, specified as a scalar in meters. This dimension defines the smallest circle that can circumscribe your vehicle. The vehicle radius is used to account for vehicle size when computing the obstacle-free direction.

**Safety distance (m)** — Safety distance around the vehicle
`0.1` (default) | scalar

Safety distance left around the vehicle position in addiction to **vehicle radius**, specified as a scalar in meters. The vehicle radius and safety distance are used to compute the obstacle-free direction.

**Minimum turning radius (m)** — Minimum turning radius at current speed
`0.1` (default) | scalar

Minimum turning radius for the vehicle moving at its current speed, specified as a scalar in meters.

**Simulate using** — Specify type of simulation to run
`Code generation` (default) | `Interpreted execution`

- `Code generation` — Simulate model using generated C code. The first time you run a simulation, Simulink generates C code for the block. The C code is reused for subsequent simulations, as long as the model does not change. This option requires additional startup time but the speed of the subsequent simulations is comparable to `Interpreted execution`.
- `Interpreted execution` — Simulate model using the MATLAB interpreter. This option shortens startup time but has a slower simulation speed than `Code generation`. In this mode, you can debug the source code of the block.

**Tunable:** No

#### Cost Function Weights

**Target direction weight** — Cost function weight for target direction
5 (default) | scalar

Cost function weight for moving toward the target direction, specified as a scalar. To follow a target direction, set this weight to be higher than the sum of **Current direction weight** and **Previous direction weight**. To ignore the target direction cost, set this weight to `0`.

**Current direction weight** — Cost function weight for current direction
2 (default) | scalar

Cost function weight for moving the vehicle in the current heading direction, specified as a scalar. Higher values of this weight produce efficient paths. To ignore the current direction cost, set this weight to `0`.

**Previous direction weight** — Cost function weight for previous direction
2 (default) | scalar

Cost function weight for moving in the previously selected steering direction, specified as a scalar. Higher values of this weight produce smoother paths. To ignore the previous direction cost, set this weight to `0`.

## Algorithms

### Vector Field Histogram

The block uses the VFH+ algorithm to compute the obstacle-free direction. First, the algorithm takes the ranges and angles from range sensor data and builds a polar histogram for obstacle locations. Then, it uses the input histogram thresholds to calculate a binary histogram that indicates occupied and free directions. Finally, the algorithm computes a masked histogram, which is computed from the binary histogram based on the minimum turning radius of the vehicle.

The algorithm selects multiple steering directions based on the open space and possible driving directions. A cost function, with weights corresponding to the previous, current, and target directions, calculates the cost of different possible directions. The algorithm then returns an obstacle-free direction with minimal cost. Using the obstacle-free direction, you can input commands to move your vehicle in that direction.

To use this block for your own application and environment, you must tune the algorithm parameters. Parameter values depend on the type of vehicle, the range sensor, and the hardware you use. For more information on the VFH algorithm, see `controllerVFH`.

# Version History

**Introduced in R2019b**

## Extended Capabilities

### C/C++ Code Generation

Generate C and C++ code using Simulink® Coder™.

## See Also

### Blocks

Pure Pursuit | Publish | Subscribe

### Classes

`controllerVFH`

### Topics

"Vector Field Histogram"

# 5

# Apps

# SLAM Map Builder

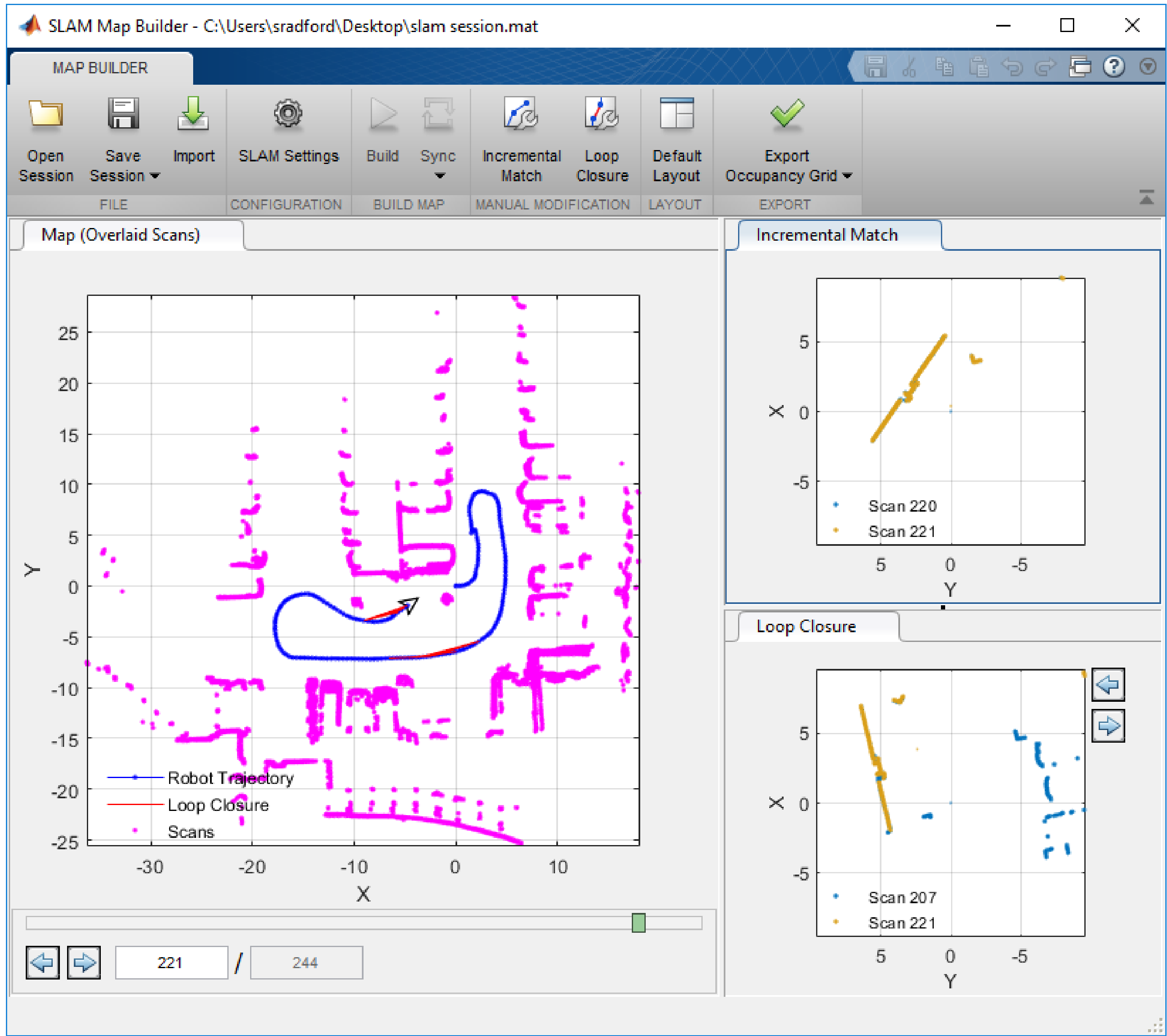
Build 2-D grid maps using lidar-based SLAM

## Description

The **SLAM Map Builder** app loads recorded lidar scans and odometry sensor data to build a 2-D occupancy grid using simultaneous localization and mapping (SLAM) algorithms. Incremental scan matching aligns and overlays scans to build the map. Loop closure detection adjusts for drift of the vehicle odometry by detecting previously visited locations and adjusting the overall map. Sometimes, the scan matching algorithm and loop closure detection require manual adjustment. Use the app to manually align scans and modify loop closures to improve the overall map accuracy. You can also tune the SLAM algorithm settings to improve the automatic map building.

**To use the app:**

| | |
|---|---|
| Import | To load rosbag log files, select **Import** > **Import from rosbag**. Select the rosbag file and click **Open**. This opens the **Import** tab. For more information, see Import and Filter a rosbag on page 5-13.<br><br>To load data from the workspace, **Import** > **Import from workspace**. Select your **Scans** and **Poses** variables using the drop downs provided. You can also specify the variables in the `slamMapBuilder` function. See Programmatic Use on page 5-12. |
| SLAM Settings | Use **SLAM Settings** to adjust the SLAM algorithm settings. Default values are provided, but your specific sensors and data may require tuning of these settings. The most important value to tune is the **Loop Closure Threshold**. For more information, see Tune SLAM Settings on page 5-13. |
| Build | Click **Build** to begin the SLAM map building process. The building process aligns scans in the map using incremental scan matching, identifies loop closures when visiting previous locations, and adjusts poses. Click **Pause** at any time during the map building process to manually align incremental scans or modify loop closures. |
| Incremental Match Loop Closure | Click **Incremental Match** to modify the relative pose of the currently selected frame and align the scan with the previous scan. Click **Loop Closure** to modify or ignore the detected loop closure for the current frame. Use the slider on the bottom to scroll back to areas where scan matching or loop closures are not accurate. You can modify any number of scans or loop closures. For more information, see Modify Increment Scans and Loop Closures on page 5-14. |
| Sync | After modifying your map, click **Sync** to update all the poses in the scan map. The two options under **Sync** are **Sync**, which searches for new loop closures, or **Sync Fast**, which skips loop closure searching and just updates the scan map. For more information, see Sync the Map on page 5-15. |
| Export Occupancy Grid | When you are satisfied with how the map looks, click **Export to OccupancyGrid** to either export the map to an m-file or save the map in the workspace. The map is output as a 2-D probabilistic occupancy grid in an `occupancyMap` object. |
| Open Session Save Session | You can open existing app sessions you have saved using **Open Session**. When you are in the **Map Builder** tab, you can save your progress to an m-file using **Save Session**. |




## Open the SLAM Map Builder App

- MATLAB Toolstrip: In the **Apps** tab, under **ROBOTICS AND AUTONOMOUS SYSTEMS**, click **SLAM Map Builder**.
- MATLAB Command Window: Enter `slamMapBuilder`

### Examples

### Build and Tune a Map Using Lidar Scans with SLAM

The **SLAM Map Builder** app helps you build an occupancy grid from lidar scans using simultaneous localization and mapping (SLAM) algorithms. The map is built by estimating poses through scan matching and using loop closures for pose graph optimization. This example shows you the workflow for loading a rosbag of lidar scan data, filtering the data, and building the map. Tune the scan map by adjusting incremental scan matches and modifying loop closures.

#### Load Lidar Scan Data

Load the example `.mat` file into the workspace, which contains a variable, `scans`, as a cell array of `lidarScan` objects.

```
load slamLidarScans.mat
```

#### Open the App

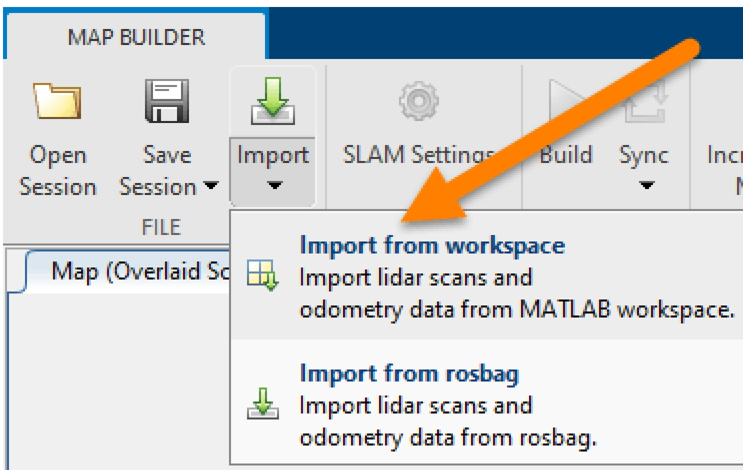
In the **Apps** tab, under **Control System Design and Analysis,** click **SLAM Map Builder**.

Also, you can call the `slamMapBuilder` function:

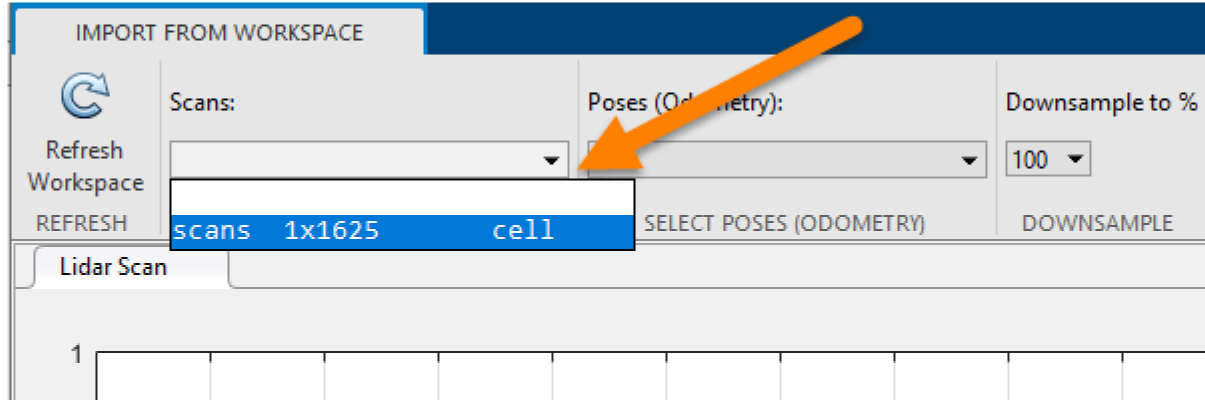
```
slamMapBuilder
```

#### Import Lidar Scans

Click **Import > Import from workspace** to load the scans. Data stored as a rosbag can be loaded with a ROS Toolbox license.




Select the `scans` variable in the **Scans** drop down.



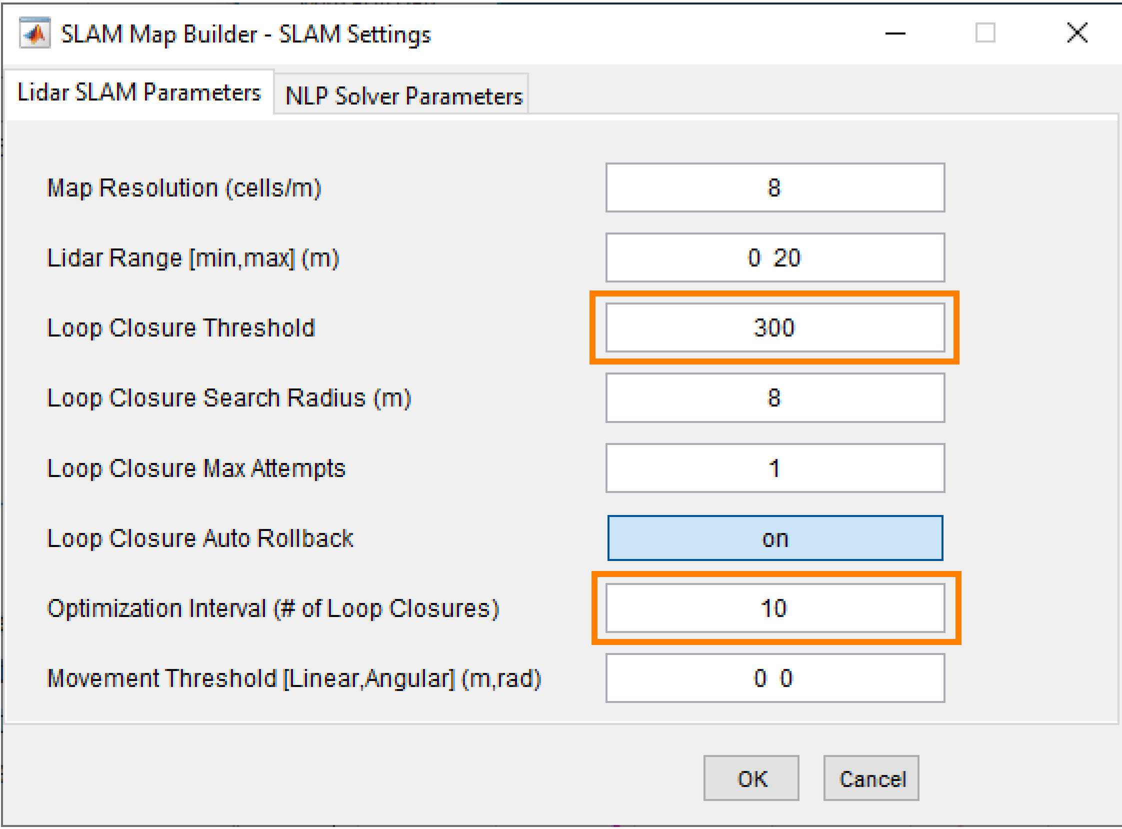

In the tool bar, set **Downsample to (%)** to 10. Downsampling evenly samples from the data to reduce computation time for the SLAM algorithm. For this example, 10% is every 5th scan. Click **Apply**.

Use the slider or arrow keys at the bottom to preview the scans.

Once you are done importing, click **Close.**

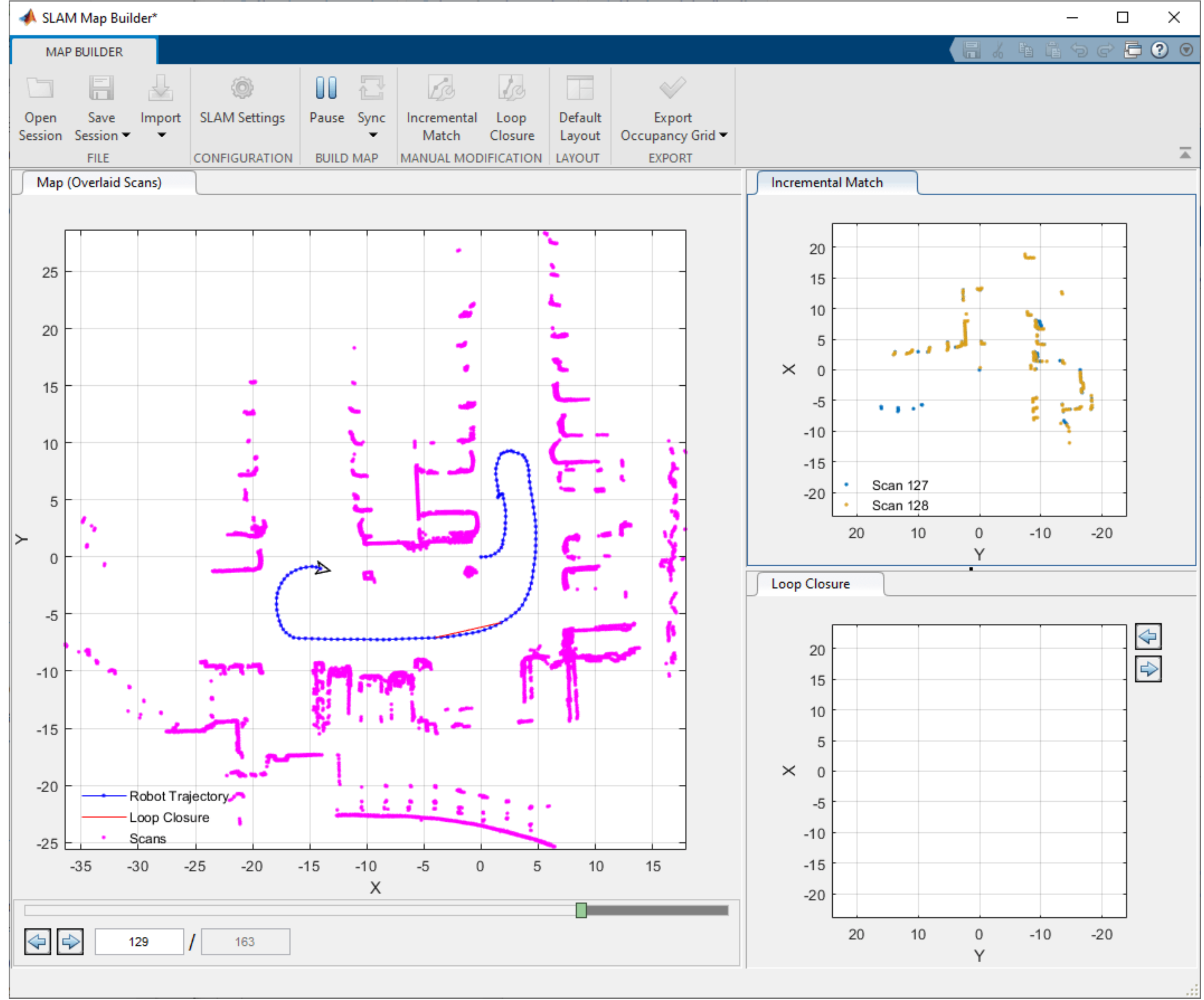
#### Tune SLAM Settings

The SLAM algorithm can be tuned using the **SLAM Settings** dialog. The parameters should be adjusted based on your sensor specifications, the environment, and your application. For this example, increase **Loop Closure Threshold** from `200` to `300`. This increased threshold decreases the likelihood of accepting and using a detected loop closure. Set the **Optimization Interval** to `10`. With every 10th loop closure accepted, the pose graph is optimized to account for drift.




### Build the Map

After filtering your data and setting the SLAM algorithm settings, click **Build**. The app begins processing scans to build the map. You should see the slider progressing and scans being overlaid in the map. The estimated robot trajectory is plotted on the same scan map. Incremental scan matches are shown in the **Incremental Match** pane. Whenever a loop closure is detected, the **Loop Closure** pane shows the two scans overlaid on each other.



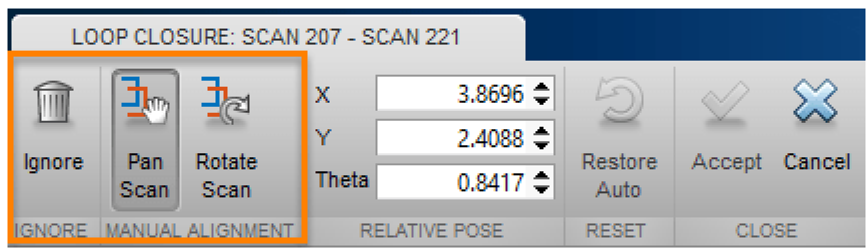

### Adjust Scan Matches or Loop Closures

At any time during the build process, if you notice the map is distorted or an incremental match or loop closure looks off, click **Pause** to select scans for adjustment. You can modify scans at the end of the build process as well. Navigate using the arrow keys or slider to the point in the file where the distortion first occurs. Click the **Incremental Match** or **Loop Closure** buttons to adjust the currently displayed scan poses. In this section, the bad loop closure is artificial and only for illustration purposes.

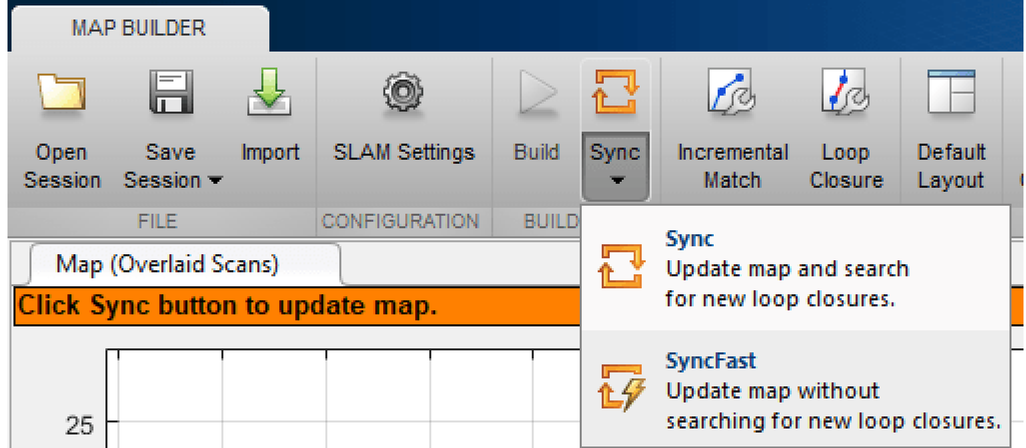
Click the **Loop Closure** button. This opens a tab for modifying the loop closure relative pose.

To ignore the loop closure completely, click **Ignore**. Otherwise, manually modify the relative scan pose until the scans line up.

Click **Pan Scan** or **Rotate Scan**, then click and drag in the figure to align the two scans. Click **Accept** when you are done. You can do this for multiple scans.

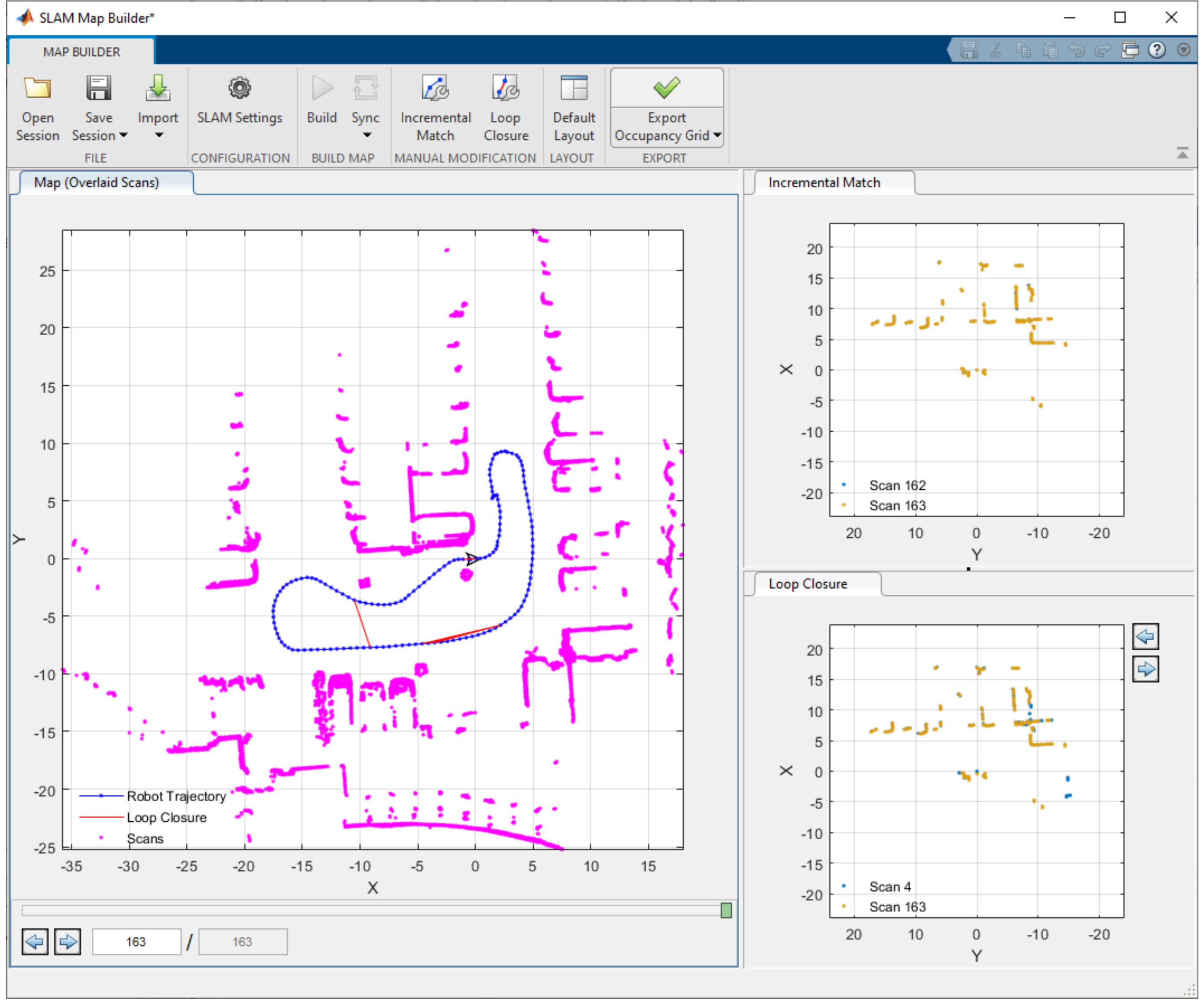



After you modify your scan poses for incremental matches and loop closures, click **Sync** to apply changes. **SyncFast** updates the map without searching for new loop closures and reduces computation time if you have already processed all the scans.




### Export Occupancy Grid

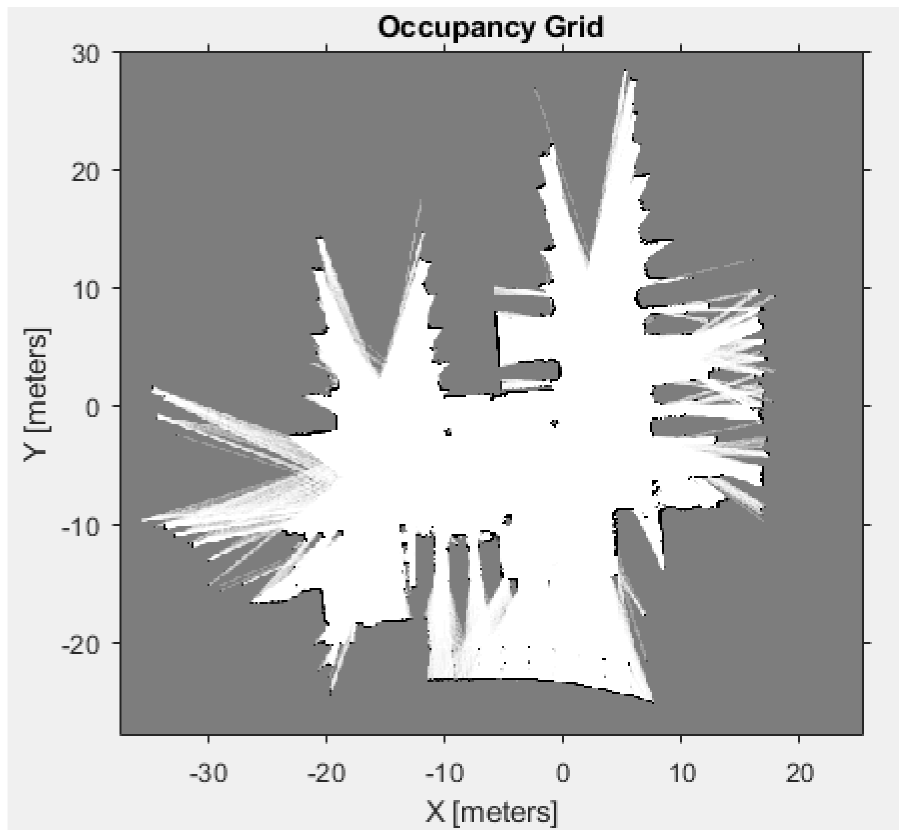
Once you have synced your changes and finished building the map, you should see a fully overlaid scan map with a robot trajectory.




Click **Export Occupancy Grid** to get a final occupancy map of your environment as a `occupancyMap` object. Specify the variable name to export the map to the workspace. You can create a map from a subset of scans by scrolling back to the desired frame before exporting and selecting **Up to currently selected scan**.

Call `show` on the stored map to visualize the occupancy map.

```
show(myOccMap)
```




You can also save a SLAM Map Builder app session using the **Save Session** button. The app writes the current state of the app to a `.mat` file that can be loaded later using **Open Session**.

- "Implement Simultaneous Localization And Mapping (SLAM) with Lidar Scans"
- "Implement Online Simultaneous Localization And Mapping (SLAM) with Lidar Scans"

## Programmatic Use

`slamMapBuilder(bag)` opens the **SLAM Map Builder** app and imports the rosbag log file specified in `bag`, a `BagSelection` object created using the `rosbag` function. The app opens to the **Import** tab to filter the sensor data in your rosbag.

`slamMapBuilder(sessionFile)` opens the **SLAM Map Builder** app from a saved session file name, `sessionFile`. An app session file is created through the **Save Session** button in the app toolstrip.

`slamMapBuilder(scans)` opens the **SLAM Map Builder** app and imports the scans specified in `scans`, a cell array of `lidarScan` objects. The app assumes you have prefiltered your scans and skips the import process. Click **Build** to start building the map.

`slamMapBuilder(scans,poses)` opens the **SLAM Map Builder** app and imports the scans and poses. `scans` is specified as a cell array of `lidarScan` objects. `poses` is a matrix of `[x y theta]` vectors that correspond to the poses of `scans`. The app assumes you have prefiltered your scans and skips the import process. Click **Build** to start building the map.

## More About

### Import and Filter a rosbag

When you click the **Import** button, specify the parameters for your rosbag and how you want to filter the data in the toolstrip. You must **Apply** your settings to see the scans updated in the figures.

- Select the ROS topic for the lidar scans and odometry (if available).
- In **Odom Topic**, if you select `Use TF`, specify the frame of the lidar scan sensor, **Lidar Frame**, and the base fixed frame of the vehicle, **Fixed Frame**. The items in the drop down menu are generated based on the available frames in the `tf` transformation tree of the rosbag. The app only supports `/tf` and `/tf2` topics.
- Specify the **Start Time** and **End Time** if you want to trim data from rosbag. You can use the sliders or manually type in your time values.
- Select the desired downsample percentage of scans in **Downsample to (%)** . This evenly downsamples the scans based on the percentage. For example, a value of 25% would only select every fourth scan.
- Click **Apply** to see the new filtered scans and apply all settings. **Close** the tab when you are done.

If you'd like more control over filtering scans in the rosbag, import your rosbag into MATLAB using `rosbag`. Filter the rosbag using `select`. To open the app using your custom filtered rosbag, see Programmatic Use on page 5-12.

### Tune SLAM Settings

To improve the automatic map building process, the SLAM algorithm has tunable parameters. Click **SLAM Settings** to tune the parameters. Use **Lidar SLAM Parameters** to affect different aspects of the scan alignment and loop closure detection processes. Also, tune the **NLP Solver Parameters** to change how the map optimization algorithm improves the overall map based on loop closures.

**Lidar SLAM Parameters**:

- **Map Resolution (cells/m)** –– Resolution of the map. The resolution affects the location accuracy of the scan alignment and defines the output size of the occupancy grid.
- **Lidar Range [min,max] (m)** –– Range of lidar sensor readings. When processing the lidar scans, readings outside of the lidar range are ignored.
- **Loop Closure Threshold** –– Unitless threshold for accepting loop closures. Depending on your lidar scans, the average loop closure score varies. If the build process does not find loop closures and the vehicle revisits locations in the map, consider lowering this threshold.
- **Loop Closure Search Radius (m)** –– Radius to search for loop closures. Based on the odometry pose, the algorithm searches for loop closures in the existing map within the given radius in meters.
- **Loop Closure Max Attempts** –– Number of attempts at finding loop closures. When this number increases, the algorithm makes more attempts to find loop closures in the map but increases computation time.
- **Loop Closure Auto Rollback** –– Allow automatic rejection of loop closures. The algorithm tracks the residual error from the map optimization. If it detects a sudden change in the error and this parameter is set to `on`, the loop closure is rejected.
- **Optimization Interval (# of Loop Closures)** –– Number of detected loop closures accepted to trigger optimization. By default, the map is optimized with every loop closure found.

- **Movement Threshold [Linear,Angular] (m,rad)** –– Minimum change in pose required to accept a new scan. If the pose of the vehicle does not exceed this threshold, the next scan is discarded from the map building process.

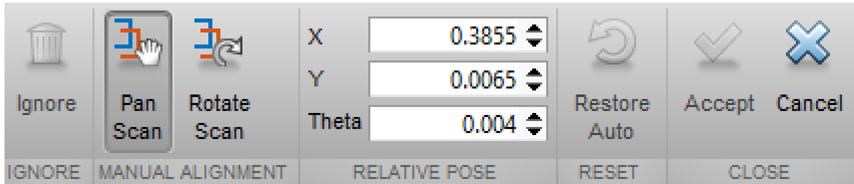
**NLP Solver Parameters**:

- **Max Iterations** –– Maximum number of iterations for map optimization. Increasing this value may improve map accuracy but increases computation time.
- **Max Time (s)** –– Maximum time allowed for map optimization specified in seconds. Increasing this value may improve map accuracy but increases computation time.
- **Gradient Tolerance** –– Lower bound on the norm of the gradient of the cost function for optimization. Lowering this value causes the optimization to run longer to search for a local minimum but increases the computation time.
- **Function Tolerance** –– Lower bound on the change in the cost function for optimization. Lowering this value causes the optimization to run longer to search for a local minimum but increases the computation time.
- **Step Tolerance** –– Lower bound on the step size for optimization. Lowering this value causes the optimization to run longer to search for a local minimum but increases the computation time.
- **First Node Pose [x,y,theta] (m,rad)** –– Pose of the first node in the graph. If you need to offset the position of the scans in the map, specify the position, `[x y]`, in meters and orientation, `theta`, in radians.

After changing any of these settings, the map building process must be restarted to rebuild the map with the new parameters.

### Modify Incremental Matches and Loop Closures

This app allows you to manually modify incremental scans and adjust detected loop closures. If you notice scans are not properly aligned after you build the map, use the **Incremental Match** and **Loop Closure** buttons to open their modification tabs. Use the modification toolstrip buttons to adjust the relative pose between scans.




- **Ignore** –– When modifying loop closures, you can simply ignore loop closures if they are inaccurate. The algorithm always discards ignored loop closure if detected in the same app session. You cannot ignore incremental scan matches.
- **Pan Scan** –– Click this button to manually shift the pose. After selecting, click and drag inside the map to shift the scans and overlay them properly. Align all the points of the scans until you are satisfied. You can manually specify the **X**, **Y** location in the **Relative Pose** section as well.
- **Rotate Scan** –– Click this button to manually rotate the pose. After selecting, click and drag inside the map to rotate the scans and overlay them properly. Align all the points of the scans until you are satisfied. You can manually specify the **Theta** location in the **Relative Pose** section as well.

#### Sync the Map

After making modifications to the map building process using **Incremental Scans** and **Loop Closures**, you must sync the map to apply the changes. Based on the changes you make to properly align scans, the overall map shifts and alignments change for every scan after your modification. You have two options after making your modifications, **Sync** or **Sync Fast**. If you click **Sync Fast**, the changes to the poses are automatically applied and no other changes to the map occur. **Sync** restarts the entire map building and loop closure detection processes starting at the first modification. The specified modifications are applied, but the algorithm attempts to realign other scans and search for new loop closures as well.

# Version History

**Introduced in R2019b**

## See Also

#### Functions

`buildMap` | `matchScans` | `matchScansGrid` | `rosbag` | `optimizePoseGraph`

#### Objects

`lidarSLAM` | `lidarScan` | `occupancyMap` | `poseGraph`

#### Topics

“Implement Simultaneous Localization And Mapping (SLAM) with Lidar Scans”
“Implement Online Simultaneous Localization And Mapping (SLAM) with Lidar Scans”