Robotics System Toolbox™
User's Guide
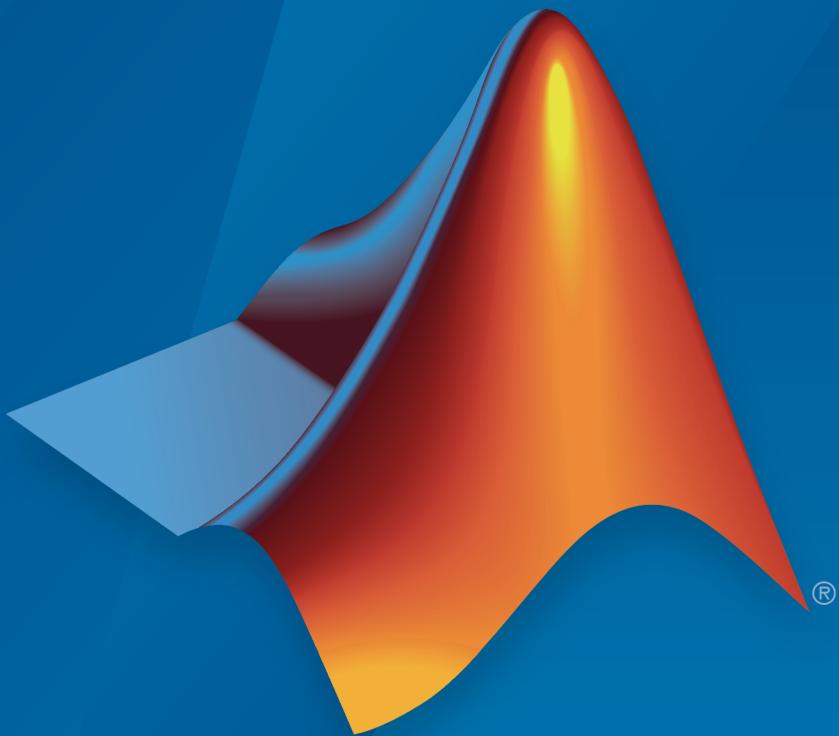
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Coordinate System Transformations

Standard Units for Robotics System Toolbox

Robotics System Toolbox™ uses a fixed set of standards for units to ensure consistency across algorithms and applications. Unless specified otherwise, functions and classes in this toolbox represent all values in units based on the International System of Units (SI). The table below summarizes the relevant quantities and their SI derived units.

Quantity	Unit (abbrev.)
Length	meter (m)
Time	second (s)
Angle	radian (rad)
Velocity	meter/second (m/s)
Angular Velocity	radian/second (rad/s)
Acceleration	meter/second^2 (m/s^2)
Angular Acceleration	radian/second^2 (rad/s^2)
Mass	kilogram (kg)
Force	Newton (N)
Torque	Newton-meter (N-m)
Moment of Inertia	kilogram-meter^2 (kg-m^2)

Coordinate Transformations in Robotics

In this section...

In robotics applications, many different coordinate systems can be used to define where robots, sensors, and other objects are located. In general, the location of an object in 3-D space is defined by its position and orientation. There are multiple possible representations for these quantities, some of which are specific to certain applications. Translation and rotation are alternative terms for position and orientation. Robotics System Toolbox supports representations that are commonly used in robotics and allows you to convert between them. You can transform between coordinate systems when you apply these representations to 3-D points. These supported representations are detailed below with brief explanations of their usage and numeric equivalent in MATLAB®. Each representation has an abbreviation for its name. This is used in the naming of arguments and conversion functions that are supported in this toolbox.

At the end of this section, you can find out about the conversion functions that we offer to convert between these representations.

Robotics System Toolbox assumes that positions and orientations are defined in a right-handed Cartesian coordinate system.

Axis-Angle
Abbreviation: axang

A rotation in 3-D space described by a scalar rotation around a fixed axis defined by a vector.

Numeric Representation: 1-by-3 unit vector and a scalar angle combined as a 1-by-4 vector

For example, a rotation of `pi/2` radians around the *y*-axis would be:

```
axang = [0 1 0 pi/2]
```

Euler Angles
Abbreviation: eul

Euler angles are three angles that describe the orientation of a rigid body. Each angle is a scalar rotation around a given coordinate frame axis. The Robotics System Toolbox supports two rotation orders. The `'ZYZ'` axis order is commonly used for robotics applications. We also support the `'ZYX'` axis order which is also denoted as "Roll Pitch Yaw (rpy)." Knowing which axis order you use is important for apply the rotation to points and in converting to other representations.

Numeric Representation: 1-by-3 vector of scalar angles

For example, a rotation around the *y* -axis of pi would be expressed as:

```
eul = [0 pi 0]
```

Note: The axis order is not stored in the transformation, so you must be aware of what rotation order is to be applied.

Homogeneous Transformation Matrix
Abbreviation: tform

A homogeneous transformation matrix combines a translation and rotation into one matrix.

Numeric Representation: 4-by-4 matrix

For example, a rotation of angle α around the *y* -axis and a translation of 4 units along the *y* -axis would be expressed as:

```
tform =
 cos α  0      sin α  0
 0      1      0      4
-sin α  0      cos α  0
 0      0      0      1
```

You should **pre-multiply** your transformation matrix with your homogeneous coordinates, which are represented as a matrix of row vectors (*n*-by-4 matrix of points). For example:

```
points = rand(100,4);
tformPoints = tform*points;
```

Quaternion
Abbreviation: quat

A quaternion is a four-element vector with a scalar rotation and 3-element vector. Quaternions are advantageous because they avoid singularity issues that are inherent in other representations. The first element, w, is a scalar to normalize the vector with the three other values, *[x y z]* defining the axis of rotation.

Numeric Representation: 1-by-4 vector

For example, a rotation of `pi/2` around the y-axis would be expressed as:

```
quat = [0.7071 0 0.7071 0]
```

Rotation Matrix
Abbreviation: rotm

A rotation matrix describes a rotation in 3-D space. It is a square, orthonormal matrix with a determinant of 1.

Numeric Representation: 3-by-3 matrix

For example, a rotation of **α** degrees around the *x*-axis would be:

```
rotm =

    1      0          0
    0      cos α      -sin α
    0      sin α      cos α
```

You should **pre-multiply** your rotation matrix with your coordinates, which are represented as a matrix of row vectors (*n*-by-3 matrix of points). For example:

```
points = rand(100,3);
rotPoints = rotm*points;
```

Translation Vector
Abbreviation: trvec

A translation vector is represented in 3-D Euclidean space as Cartesian coordinates. It only involves coordinate translation applied equally to all points. There is no rotation involved.

Numeric Representation: 1-by-3 vector

For example, a translation by 3 units along the x -axis and 2.5 units along the z -axis would be expressed as:

```
trvec = [3 0 2.5]
```

Conversion Functions and Transformations

Robotics System Toolbox provides conversion functions for the previously mentioned transformation representations. Not all conversions are supported by a dedicated function. Below is a table showing which conversions are supported (in blue). The abbreviations for the rotation and translation representations are shown as well.

Converting From / Converting To	Axis-Angle (axang)	Euler Angles (eul)	Quaternion (quat)	Rotation Matrix (rotm)	Homogeneous Transformation (tform)	Translation Vector (trvec)
Axis-Angle (axang)	■		▨	▨	▨	
Euler Angles (eul)		■	▨	▨	▨	
Quaternion (quat)	▨	▨	■	▨	▨	
Rotation Matrix (rotm)	▨	▨	▨	■	▨	
Homogeneous Transformation (tform)	▨	▨	▨	▨	■	▨
Translation Vector (trvec)					▨	■

The names of all the conversion functions follow a standard format. They follow the form `alpha2beta` where `alpha` is the abbreviation for what you are converting from and `beta` is what you are converting to as an abbreviation. For example, converting from Euler angles to quaternion would be `eul2quat`.

All the functions expect valid inputs. If you specify invalid inputs, the outputs will be undefined.

There are other conversion functions for converting between radians and degrees, Cartesian and homogeneous coordinates, and for calculating wrapped angle differences. For a full list of conversions, see "Coordinate System Transformations".

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Algorithm Design

Occupancy Grids

Binary Occupancy Grid

Occupancy grids are used to represent a robot's workspace as a discrete grid. Information about the environment can be collected from sensors in real time or be loaded from prior knowledge. For robotics applications, laser range finders, bump sensors, cameras and depth sensors are commonly used to find obstacles. A binary occupancy grid uses simple `true` and `false` values to represent the occupied workspace (obstacles) and free workspace respectively. This shows where obstacles are and whether a robot can move through that space.

World and Grid Coordinates

When working with occupancy grids, you have the option to use either world or grid coordinates. This section describes the difference between these coordinate systems and how to work with them in MATLAB.

The absolute reference frame in which the robot operates is referred to as the "world" frame in the occupancy grid. Most operations using Robotics System Toolbox are performed in the world frame, and this is the default selection when using MATLAB functions in this toolbox. World coordinates are used as an absolute coordinate frame with a fixed origin and have unlimited resolution when specifying locations. However, all locations are converted to grid locations because of data storage and resolution limits.

Grid coordinates define the actual resolution of the occupancy grid and the finite locations of obstacles. The origin of grid coordinates is in the top-left of the grid with the first location having a location of `(1,1)`. However, the location of the grid in world coordinates is defined by the property, `GridLocationInWorld` and specifies the bottom-left location of the grid. When creating a `robotics.BinaryOccupancyGrid` object, other properties such as `XWorldLimits` and `YWorldLimits` are defined by the input `width`, `height`, and `resolution`. The figure below shows a visual representation of these properties and the relation between world and grid coordinates.
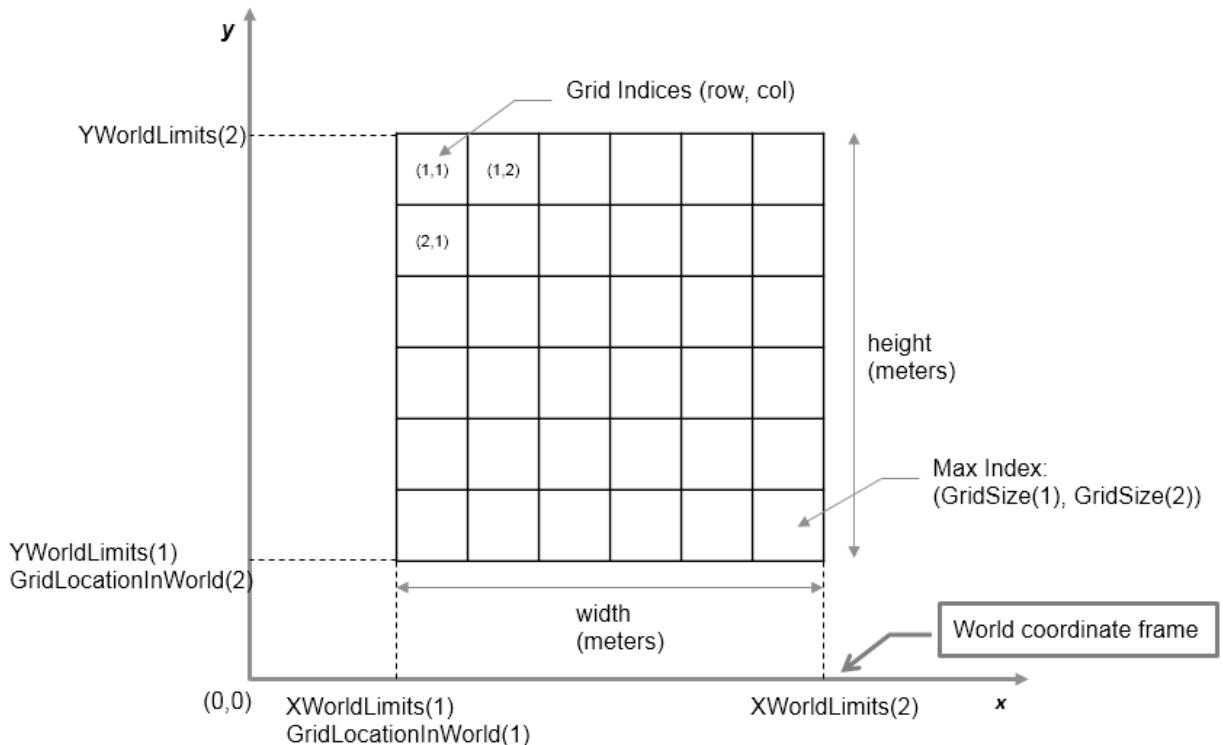
Grid Coordinates from World Coordinate Inputs

When setting occupancy locations, you can input the locations in either grid or world coordinates. However, based on the limits of the grid, the locations are set to the closest grid locations. Edges of the grid belong to the lower left grid location.

This example shows how the locations are interpreted on the grid. An occupancy grid is created and three points are set as occupied by obstacles. The original input points are then plotted over the map to show how they are interpreted. Also note that the entire grid cell is set as occupied if any point within the grid cell is set as occupied.

Create occupancy grid and set obstacle locations.

```
map = robotics.BinaryOccupancyGrid(10,10,5);
xy = [5 5; 4.3 4.4; 5.5 5.4];
setOccupancy(map,xy, 1);
```

Display map, original points and set axes.

```
show(map);
hold on
plot(xy(:,1),xy(:,2),'xr','MarkerSize', 20)
grid on
set(gca,'XTick', 0:0.2:10,'YTick',0:0.2:10)
xlim([4 6])
ylim([4 6])
```
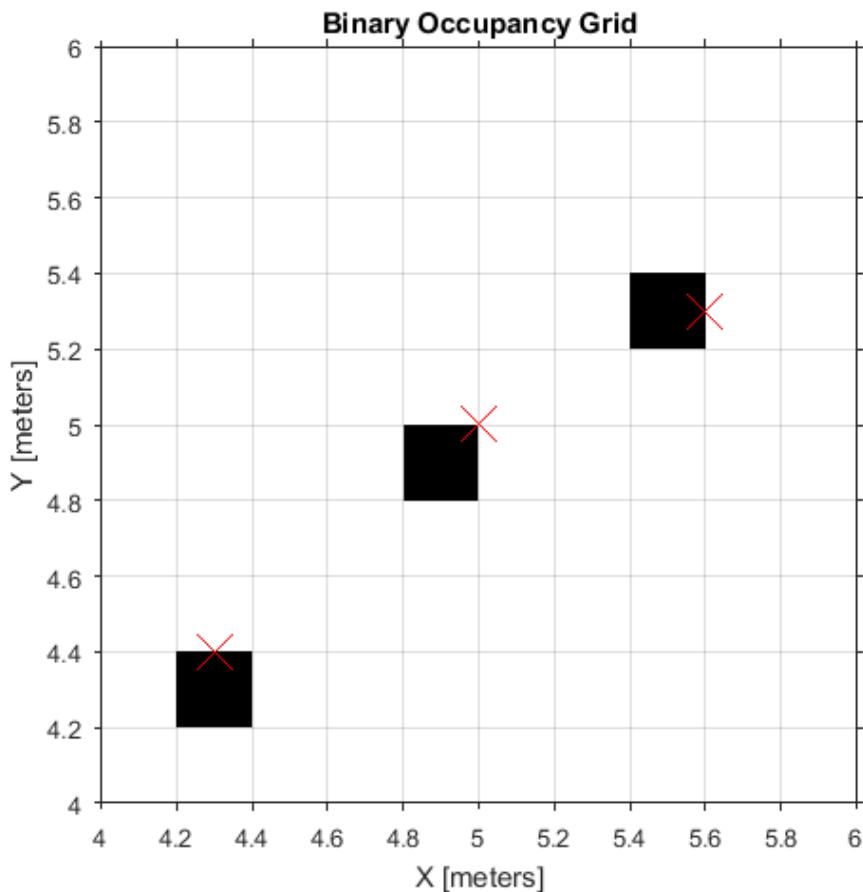
Inflation of Coordinates

The `inflate` method (`robotics.BinaryOccupancyGrid.inflate`) is used to account for the robot's dimensions. By inflating the obstacle locations, you can create buffer zones for the robot to have space to navigate without hitting obstacles. When inflating obstacles, the specified `radius` is converted to the number of cells rounded up from the value `resolution*radius`. Each occupied cell is then inflated by this cell value. This inflation can have some important effects if the accuracy of the map at individual grid locations is extremely important. A basic inflation example is shown to illustrate how the radius value is used. The result of `inflate` by *1m* on an obstacle at world location `[5 5]` is shown. The input `radius` is plotted as a circle from the obstacle grid location. ***Note:*** *The center location of the obstacle is converted to a grid location (from [5 5] in blue to [4.9 4.9] in red), which accounts for a small shift in the circle center as well.*

This example shows how to create the map, set the obstacle locations and inflate it by a radius of 1m. Extra plots on the figure help illustrate the inflation and shifting due to conversion to grid locations.

```
map = robotics.BinaryOccupancyGrid(10,10,5);
setOccupancy(map,[5 5], 1);
inflate(map,1);
show(map)
hold on
theta = linspace(0,2*pi);
x = 4.9+cos(theta);
y = 4.9+sin(theta);
plot(5,5,'*b','MarkerSize',10)
plot(4.9,4.9,'xr','MarkerSize',10)
plot(x,y,'-r','LineWidth',2);
xlim([3.6 6.2])
ylim([3.6 6.2])
grid on
legend('Original Location','Grid Center','Inflation')
```
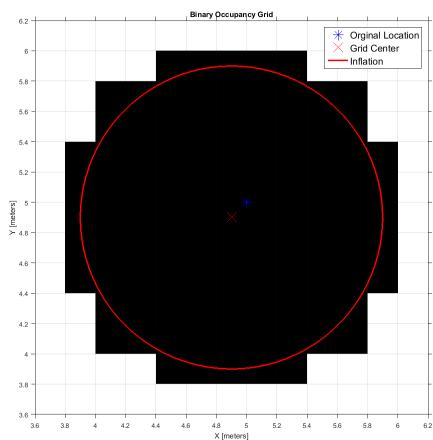
As you can see from the above figure, even cells that barely overlap with the inflation radius are labeled as occupied.

Pure Pursuit Controller

In this section...
"Reference Coordinate System" on page 2-7
"Look Ahead Distance" on page 2-8
"Limitations" on page 2-9

PurePursuit is a path tracking algorithm. It computes the angular velocity command that will move the robot from its current position to reach some look-ahead point in front of the robot. The linear velocity is assumed constant, hence you can change the linear velocity of the robot at any point. The algorithm then moves the look-ahead point on the path based on the current position of the robot until the last point of the path. You can think of this as the robot constantly chasing a point in front of it. The property LookAheadDistance will decide how far the look-ahead point is placed.

The `PurePursuit` class (`robotics.PurePursuit`) is not a traditional controller, but acts as a tracking algorithm for path following purposes. In the Robotics System Toolbox, you create a `PurePursuit` controller and specify a list of waypoints. The desired linear and maximum angular velocities can be specified. These properties are usually determined based on the robot's specifications. Given the pose (position and orientation) of the robot as an input, the `step` function can be used to calculate the linear and angular velocities commands for the robot. How the robot uses these commands is dependant on the system you are using, so consider how robots can execute a motion given these commands. The final important property is the `LookAheadDistance`, which tells the robot how far along on the path to track towards. This property is explained in more detail in a section below.

Reference Coordinate System

It is important to understand the reference coordinate frame used by the `PurePursuit` algorithm for its inputs and outputs. The figure below shows the reference coordinate system. The input waypoints are [x y] coordinates, which are used to compute the robot velocity commands. The robot's pose is input as a pose and orientation (theta) list of points as [x y theta]. The positive *x* and *y* directions are in the right and up directions respectively (blue in figure). The *theta* value is the angular orientation of the robot measured counterclockwise in radians from the *x*-axis (robot currently at 0 radians).
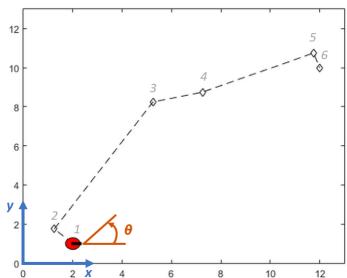
Look Ahead Distance

The `LookAheadDistance` property is the main tuning property for the `PurePursuit` controller. The look ahead distance is how far along the path the robot should look from the current location to compute the angular velocity commands. The figure below shows the robot and the look-ahead point. As displayed in this image, note that the actual path does not match the direct line between waypoints.
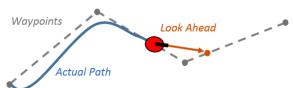
The effect of changing this parameter can change how your robot tracks the path and there are two major goals: regaining the path and maintaining the path. In order to quickly regain the path between waypoints, a small `LookAheadDistance` will cause your robot to move quickly towards the path. However, as can be seen in the figure below, the robot overshoots the path and oscillates along the desired path. In order to reduce the oscillations along the path, a larger look ahead distance can be chosen, however, it might result in larger curvatures near the corners.
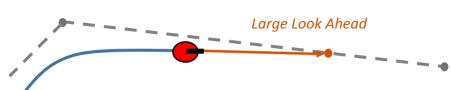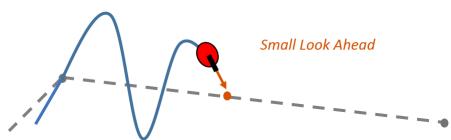
The `LookAheadDistance` property should be tuned for your application and robot system. Different linear and angular velocities will affect this response as well and should be considered for the path following controller.

Limitations

There are a few limitations to note about this `PurePursuit` algorithm:

- As shown above, the controller cannot exactly follow direct paths between waypoints. Parameters must be tuned to optimize the performance and to converge to the path over time.
- This `PurePursuit` algorithm does not stabilize the robot at a point. In your application, a distance threshold for a goal location should be applied to stop the robot near the desired goal. This can be seen in the path following example: "Path Following for a Differential Drive Robot".

References

[1] Coulter, R. *Implementation of the Pure Pursuit Path Tracking Algorithm*. Carnegie Mellon University, Pittsburgh, Pennsylvania, Jan 1990.

ROS Network Concepts

ROS Network Setup

In this section...
"Introduction" on page 3-2
"Network Connection Layout" on page 3-2
"Examples" on page 3-3

Introduction

Setting up a ROS network allows for communication between different devices. Different participants or *nodes* all register with a ROS master to share information. The ROS master is unique and each ROS network only has one master. Each node is usually a separate device, although one device can have multiple nodes running. MATLAB acts as one of these nodes when using it to communicate with ROS.

All devices must be connected to the same actual or virtual network for ROS connections to work. You can create a new ROS master in MATLAB, or you can connect to an existing ROS master that is running on a different device. If you connect to an external master, you have to know the IP address or hostname of the device. The initial ROS master connection is done by calling `rosinit`. For more information on setting up and using the ROS network, see "Network Connection and Exploration".

Data communication is achieved by sending messages using entities called publishers, subscribers, and services. Publishers send data via topic names, which subscribers then receive over the network. Services use clients to request information from a server. For more information on sending messages, see "Publishers, Subscribers, and Services"

Network Connection Layout

The ROS network is a collection of nodes that are all connected to the ROS master. The number of nodes can be quite large depending on your application and devices. When nodes get registered with the master, communication with all other nodes becomes possible. Each node registers different publishers, subscribers, and services on the ROS master to send and receive information between nodes. Even though all nodes in the ROS network are registered with the master, data is exchanged directly between nodes. The following figure shows the layout of a ROS network with two ROS nodes. It is important that all nodes have bidirectional connectivity to share data across the network. Verifying these connections is important during setup.
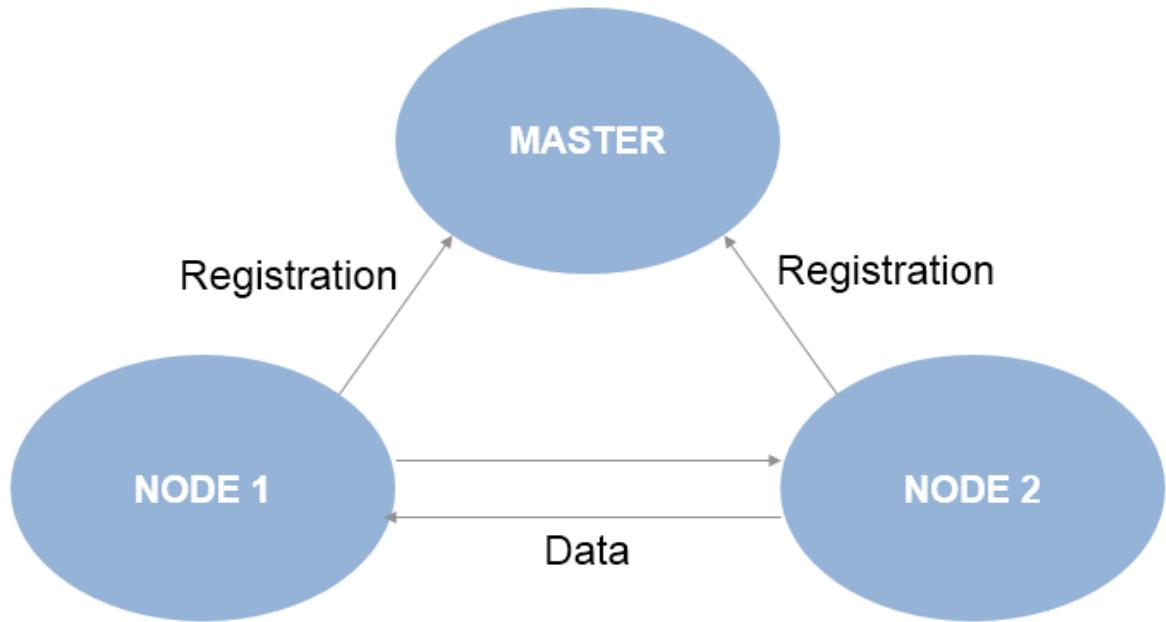
Each node registers its own Node URI with the master. Other participants in the ROS network will use this URI to contact the node. Again, this URI must be reachable by every other node in the ROS network. To create a node in MATLAB, call rosinit. If a ROS master is already set up, MATLAB detects it and sets the Node URI appropriately. Otherwise, it creates both a ROS master and node that are connected.

By default, each MATLAB instance has a single "global" node. The node has a randomly-generated name assigned to it for uniqueness. All publishers, subscribers, service clients, and service servers will operate on this global node.

Examples

To better understand how the ROS network is set up in MATLAB, see the following examples:

- "Getting Started with ROS"
- "Connecting to a ROS Network"

ROS Messages

Built-In Message Support

In this section...
"ROS Message Structure" on page 4-2
"Limitations of ROS Messages in MATLAB" on page 4-3
"ROS Data Type Conversions" on page 4-3
"Supported Message List" on page 4-4

MATLAB has support for a large library of ROS message types. How messages are structured, limitations for ROS messages, and supported ROS data types are described in order to understand how MATLAB works with ROS messages. Also, a full list of built-in message types are shown.

ROS Message Structure

In MATLAB, ROS messages are stored as handle objects. Therefore, all the rules of handle objects apply including copying, modifying and other performance considerations. For more information on handle objects, see "Handle Objects". Each handle points to the object for that specific message, which contains the information relevant to that message type. The message type has a built in structure for the data it contains.

ROS messages are similar to *structure arrays* with how they store the data relevant to that message type. Each message type has a specific set of properties with their corresponding values that are individually stored and accessed. You can specifically point to and modify each property on its own. All messages have the MessageType property to view the message type as a string. Also, you can use the showdetails function to view the contents of the message.

Here is a sample 'geometry_msgs/Point' created in MATLAB using rosmessage. It contains 3 properties corresponding to a 3-D point in XYZ coordinates.

```
pointMsg = rosmessage('geometry_msgs/Point')

pointMsg =

  ROS Point message with properties:

    MessageType: 'geometry_msgs/Point'
              X: 0
              Y: 0
```

```
             Z: 0

  Use showdetails to show the contents of the message
```

You can access and modify each property by using the created `pointMsg` handle.

```
pointMsg.Y = 2

pointMsg =

  ROS Point message with properties:

    MessageType: 'geometry_msgs/Point'
              X: 0
              Y: 2
              Z: 0

  Use showdetails to show the contents of the message
```

To explore further the ROS message structure in MATLAB, see "Working with Basic ROS Messages".

Limitations of ROS Messages in MATLAB

Because ROS messages use structure arrays, this creates a limitation on the validation of certain messages with multiple values. Because each value can be set separately, the message does not validate the properties as a whole entity. For example, a quaternion message contains w, x, y, and z properties, but the message does not enforce that the quaternion as a whole is valid. When modifying properties, you should ensure you are maintaining the rules required for that message.

Message properties can also have a variety of data types. MATLAB uses the rules set by ROS to determine what these data types are. However, if they are to be used in calculations, you might have to cast them to another value. The ROS data types do not convert directly to MATLAB data types, so the next section described the corresponding types.

ROS Data Type Conversions

ROS message types have predetermined properties and data types for the values of those properties. These data types must be mapped to MATLAB data types to be used in MATLAB. This table summarizes how ROS data types are converted to MATLAB data types.

ROS Data Type	Description	MATLAB
bool	Boolean / Unsigned 8-bit integer	`logical`
int8	Signed 8-bit integer	`int8`
uint8	Unsigned 8-bit integer	`uint8`
int16	Signed 16-bit integer	`int16`
uint16	Unsigned 16-bit integer	`uint16`
int32	Signed 32-bit integer	`int32`
uint32	Unsigned 32-bit integer	`uint32`
int64	Signed 64-bit integer	`int64`
uint64	Unsigned 64-bit integer	`uint64`
float32	32-bit IEEE floating point	`single`
float64	64-bit IEEE floating point	`double`
string	ASCII string (utf-8 only)	`char`
time	Seconds and nanoseconds as signed 32-bit integers	`Time` object
duration	Seconds and nanoseconds as signed 32-bit integers	`Duration` object

Supported Message List

Here is an alphabetized list of messages types supported. You can get this list by calling `rosmsg list` in the MATLAB command prompt. When specifying message types, input strings must match the following strings exactly. To enable you to use custom message type that are not listed here, MATLAB also provides a custom message support package. For more information, see `roboticsSupportPackages` to install the support package.

```
'ackermann_msgs/AckermannDrive'
'ackermann_msgs/AckermannDriveStamped'
'actionlib_msgs/GoalID'
'actionlib_msgs/GoalStatus'
'actionlib_msgs/GoalStatusArray'
'adhoc_communication/BroadcastCMgrRobotUpdate'
'adhoc_communication/BroadcastCMgrRobotUpdateRequest'
'adhoc_communication/BroadcastCMgrRobotUpdateResponse'
```

```
'adhoc_communication/BroadcastString'
'adhoc_communication/BroadcastStringRequest'
'adhoc_communication/BroadcastStringResponse'
'adhoc_communication/CMgrDimensions'
'adhoc_communication/CMgrRobotUpdate'
'adhoc_communication/ChangeMCMembership'
'adhoc_communication/ChangeMCMembershipRequest'
'adhoc_communication/ChangeMCMembershipResponse'
'adhoc_communication/ExpAuction'
'adhoc_communication/ExpCluster'
'adhoc_communication/ExpFrontier'
'adhoc_communication/ExpFrontierElement'
'adhoc_communication/GetGroupState'
'adhoc_communication/GetGroupStateRequest'
'adhoc_communication/GetGroupStateResponse'
'adhoc_communication/GetNeighbors'
'adhoc_communication/GetNeighborsRequest'
'adhoc_communication/GetNeighborsResponse'
'adhoc_communication/MmControl'
'adhoc_communication/MmListOfPoints'
'adhoc_communication/MmMapUpdate'
'adhoc_communication/MmPoint'
'adhoc_communication/MmRobotPosition'
'adhoc_communication/RecvString'
'adhoc_communication/SendCMgrRobotUpdate'
'adhoc_communication/SendCMgrRobotUpdateRequest'
'adhoc_communication/SendCMgrRobotUpdateResponse'
'adhoc_communication/SendExpAuction'
'adhoc_communication/SendExpAuctionRequest'
'adhoc_communication/SendExpAuctionResponse'
'adhoc_communication/SendExpCluster'
'adhoc_communication/SendExpClusterRequest'
'adhoc_communication/SendExpClusterResponse'
'adhoc_communication/SendExpFrontier'
'adhoc_communication/SendExpFrontierRequest'
'adhoc_communication/SendExpFrontierResponse'
'adhoc_communication/SendMmControl'
'adhoc_communication/SendMmControlRequest'
'adhoc_communication/SendMmControlResponse'
'adhoc_communication/SendMmMapUpdate'
'adhoc_communication/SendMmMapUpdateRequest'
'adhoc_communication/SendMmMapUpdateResponse'
'adhoc_communication/SendMmPoint'
'adhoc_communication/SendMmPointRequest'
```

```
'adhoc_communication/SendMmPointResponse'
'adhoc_communication/SendMmRobotPosition'
'adhoc_communication/SendMmRobotPositionRequest'
'adhoc_communication/SendMmRobotPositionResponse'
'adhoc_communication/SendOccupancyGrid'
'adhoc_communication/SendOccupancyGridRequest'
'adhoc_communication/SendOccupancyGridResponse'
'adhoc_communication/SendQuaternion'
'adhoc_communication/SendQuaternionRequest'
'adhoc_communication/SendQuaternionResponse'
'adhoc_communication/SendString'
'adhoc_communication/SendStringRequest'
'adhoc_communication/SendStringResponse'
'adhoc_communication/SendTwist'
'adhoc_communication/SendTwistRequest'
'adhoc_communication/SendTwistResponse'
'adhoc_communication/ShutDown'
'adhoc_communication/ShutDownRequest'
'adhoc_communication/ShutDownResponse'
'app_manager/App'
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'app_manager/AppList'
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'app_manager/GetAppDetailsRequest'
'app_manager/GetAppDetailsResponse'
'app_manager/GetInstallationState'
'app_manager/GetInstallationStateRequest'
'app_manager/GetInstallationStateResponse'
'app_manager/Icon'
'app_manager/InstallApp'
'app_manager/InstallAppRequest'
'app_manager/InstallAppResponse'
'app_manager/KeyValue'
'app_manager/ListApps'
'app_manager/ListAppsRequest'
'app_manager/ListAppsResponse'
'app_manager/StartApp'
'app_manager/StartAppRequest'
'app_manager/StartAppResponse'
'app_manager/StatusCodes'
'app_manager/StopApp'
```

```
'app_manager/StopAppRequest'
'app_manager/StopAppResponse'
'app_manager/UninstallApp'
'app_manager/UninstallAppRequest'
'app_manager/UninstallAppResponse'
'applanix_msgs/Ack'
'applanix_msgs/AidingSensorIntegrationControl'
'applanix_msgs/AidingSensorParams'
'applanix_msgs/BaseGNSSModemStatus'
'applanix_msgs/BaseGNSSSetup'
'applanix_msgs/BinaryMessageSelect'
'applanix_msgs/COMPortMessages'
'applanix_msgs/COMPortParams'
'applanix_msgs/COMPortSetup'
'applanix_msgs/CalibratedInstallationParameters'
'applanix_msgs/CommonFooter'
'applanix_msgs/CommonHeader'
'applanix_msgs/DGPSSourceControl'
'applanix_msgs/DMIData'
'applanix_msgs/Event'
'applanix_msgs/EventSetup'
'applanix_msgs/GAMS'
'applanix_msgs/GAMSCalibrationControl'
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'turtlesim/SetPenResponse'
'turtlesim/Spawn'
'turtlesim/SpawnRequest'
'turtlesim/SpawnResponse'
'turtlesim/TeleportAbsolute'
'turtlesim/TeleportAbsoluteRequest'
'turtlesim/TeleportAbsoluteResponse'
```

```
'turtlesim/TeleportRelative'
'turtlesim/TeleportRelativeRequest'
'turtlesim/TeleportRelativeResponse'
'um6/Reset'
'um6/ResetRequest'
'um6/ResetResponse'
'underwater_sensor_msgs/DVL'
'underwater_sensor_msgs/Pressure'
'universal_teleop/Control'
'universal_teleop/Event'
'uuid_msgs/UniqueID'
'velodyne_msgs/VelodynePacket'
'velodyne_msgs/VelodyneScan'
'view_controller_msgs/CameraPlacement'
'visp_camera_calibration/CalibPoint'
'visp_camera_calibration/CalibPointArray'
'visp_camera_calibration/ImageAndPoints'
'visp_camera_calibration/ImagePoint'
'visp_camera_calibration/calibrate'
'visp_camera_calibration/calibrateRequest'
'visp_camera_calibration/calibrateResponse'
'visp_hand2eye_calibration/TransformArray'
'visp_hand2eye_calibration/compute_effector_camera'
'visp_hand2eye_calibration/compute_effector_cameraRequest'
'visp_hand2eye_calibration/compute_effector_cameraResponse'
'visp_hand2eye_calibration/compute_effector_camera_quick'
'visp_hand2eye_calibration/compute_effector_camera_quickRequest'
'visp_hand2eye_calibration/compute_effector_camera_quickResponse'
'visp_hand2eye_calibration/reset'
'visp_hand2eye_calibration/resetRequest'
'visp_hand2eye_calibration/resetResponse'
'visp_tracker/Init'
'visp_tracker/InitRequest'
'visp_tracker/InitResponse'
'visp_tracker/KltPoint'
'visp_tracker/KltPoints'
'visp_tracker/KltSettings'
'visp_tracker/MovingEdgeSettings'
'visp_tracker/MovingEdgeSite'
'visp_tracker/MovingEdgeSites'
'visualization_msgs/ImageMarker'
'visualization_msgs/InteractiveMarker'
'visualization_msgs/InteractiveMarkerControl'
'visualization_msgs/InteractiveMarkerFeedback'
```

```
'visualization_msgs/InteractiveMarkerInit'
'visualization_msgs/InteractiveMarkerPose'
'visualization_msgs/InteractiveMarkerUpdate'
'visualization_msgs/Marker'
'visualization_msgs/MarkerArray'
'visualization_msgs/MenuEntry'
'wfov_camera_msgs/WFOVCompressedImage'
'wfov_camera_msgs/WFOVImage'
'wfov_camera_msgs/WFOVTrigger'
'wge100_camera/BoardConfig'
'wge100_camera/BoardConfigRequest'
'wge100_camera/BoardConfigResponse'
'wifi_ddwrt/Network'
'wifi_ddwrt/SiteSurvey'
'wireless_msgs/Connection'
'wireless_msgs/Network'
'wireless_msgs/Quality'
'wireless_msgs/Scan'
'yocs_msgs/Column'
'yocs_msgs/ColumnList'
'yocs_msgs/Wall'
'yocs_msgs/WallList'
'zeroconf_msgs/AddListener'
'zeroconf_msgs/AddListenerRequest'
'zeroconf_msgs/AddListenerResponse'
'zeroconf_msgs/AddService'
'zeroconf_msgs/AddServiceRequest'
'zeroconf_msgs/AddServiceResponse'
'zeroconf_msgs/DiscoveredService'
'zeroconf_msgs/ListDiscoveredServices'
'zeroconf_msgs/ListDiscoveredServicesRequest'
'zeroconf_msgs/ListDiscoveredServicesResponse'
'zeroconf_msgs/ListPublishedServices'
'zeroconf_msgs/ListPublishedServicesRequest'
'zeroconf_msgs/ListPublishedServicesResponse'
'zeroconf_msgs/Protocols'
'zeroconf_msgs/PublishedService'
'zeroconf_msgs/RemoveListener'
'zeroconf_msgs/RemoveListenerRequest'
'zeroconf_msgs/RemoveListenerResponse'
'zeroconf_msgs/RemoveService'
'zeroconf_msgs/RemoveServiceRequest'
'zeroconf_msgs/RemoveServiceResponse'
```

ROS Log Files

ROS Log Files (rosbags)

In this section...
"Introduction" on page 5-2
"MATLAB rosbag Structure" on page 5-2
"Workflow for rosbag Selection" on page 5-3
"Limitations" on page 5-5

Introduction

A rosbag or bag is a file format in ROS for storing ROS message data. These bags are often created by subscribing to one or more ROS topics, and storing the received message data in an efficient file structure. MATLAB® can read these rosbag files and help with filtering and extracting message data. The following sections detail the structure of rosbags in MATLAB and the workflow for extracting data from them.

MATLAB rosbag Structure

When accessing rosbag log files, call `rosbag` and specify the file path to the object. MATLAB then creates a `BagSelection` object that contains an index of all the messages from the rosbag.

The `BagSelection` object has the following properties related to the rosbag:

- `FilePath`: a string of the absolute path to the rosbag file.

- `StartTime`: a scalar indicating the time the first message was recorded

- `EndTime`: a scalar indicating the time the last message was recorded

- `NumMessages`: a scalar indicating how many messages are contained in the file

- `AvailableTopics`: a list of what topic and message types were recorded in the bag. This is stored as table data that lists the number of messages, message type, and message definition for each topic. For more information on table data types, see "Access Data in a Table". Here is an example output of this table:

    ```
    ans =
    ```

	NumMessages	MessageType	MessageDefinitio
/clock	12001	rosgraph_msgs/Clock	[1x185 char]
/gazebo/link_states	11999	gazebo_msgs/LinkStates	[1x1247 char]
/odom	11998	nav_msgs/Odometry	[1x2918 char]
/scan	965	sensor_msgs/LaserScan	[1x2123 char]

- `MessageList`: a list of every message in the bag with rows sorted by time stamp of when the message was recorded. This list can be indexed and you can select a portion of the list this way. Calling `select` allows you to select subsets based on time stamp, topic or message type.

Also, note that the `BagSelection` object contains an index for all the messages. However, you must still use functions to extract the data. For extracting this information, see `readMessages` for getting messages based on indices as a cell array or see `timeseries` for reading the data of specified properties as a time series.

Workflow for rosbag Selection

When working with rosbags, there is a general procedure of how you should extract data.

- **Load a rosbag**: Call `rosbag` and the file path to load file and create `BagSelection`.
- **Examine available messages**: Examine `BagSelection` properties (`AvailableTopics`, `NumMessages`, `StartTime`, `EndTime`, and `MessageList`) to determine how to select a subset of messages for analysis.
- **Select messages**: Call `select` to create a selection of messages based on your desired properties.
- **Extract message data**: Call `readMessages` or `timeseries` to get message data as either a cell array or time series data structure.
- **Visualize, analyze or process data**: Use the extracted data for your specific application. You can plot data or develop algorithms to process data.

The following figure also shows the workflow.

Load a rosbag

```
>> filePath = fullfile('rosbags','bag1.bag');
>> bagSelect = rosbag(filePath);
```

Examine available messages

Topic Name	Message Type	Time-stamped Messages

/scan   sensor_msgs/LaserScan

/odom   nav_msgs/Odometry

Select messages

Select Topic: /odom
Select Time Interval: [0, 2]

`select()`
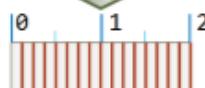
/odom   nav_msgs/Odometry

Extract message data

Select Message
Indices

Select Property: Pose.X
Select Property: Pose.Y
Select Property: Orient.Z

`readMessages()`

`timeseries()`

Message Object(s)
(nav_msgs/Odometry)

. . .

Timeseries Object

Time	Pose.X	Pose.Y	Orient.Z
0.125	0.000	1.254	0.000
0.250	0.123	1.254	1.571
...	...	...	...
2.000	0.297	1.254	3.142

Visualize, analyze, or process data

Time Series Plot:/odom Properties
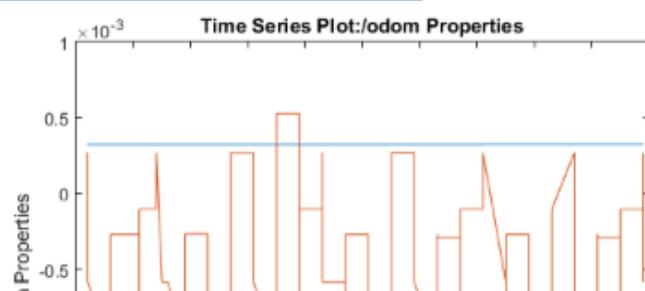
Limitations

There are a few limitations in the rosbag support within MATLAB:

- MATLAB can only parse uncompressed rosbags. See the ROS Wiki for a tool to decompress a compressed rosbag.
- Only rosbags in the v2.0 format are supported. See the ROS Wiki for more information on different bag formats
- The file path to the rosbag must always be accessible. Because the message selection process does not retrieve any data, the file needs to be available for reading when the message data is accessed.

6

Simulink ROS Concepts

# Selecting ROS Topics and Messages

In this section...
"Selecting ROS Topics" on page 6-2
"Selecting ROS Message Types" on page 6-3

Selecting ROS Topics

When using Simulink® with ROS, you can publish or subscribe to topics on the ROS network. In the dialog boxes for the Publish and Subscribe blocks, you can select from a list of topics on the ROS network. You must be currently connected to a ROS network to get a list of topics. You can select a topic using the following:
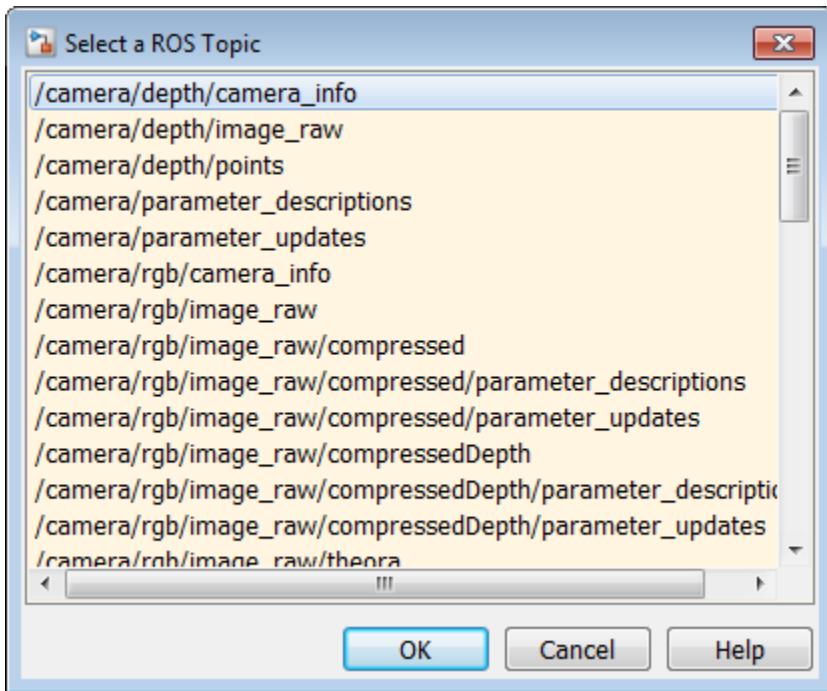
This dialog shows the list of topics available on the ROS master. Selecting a topic from the list automatically populates the **Topic** and **Message type** parameters for the

corresponding block mask dialog. If the message type is not supported in MATLAB ROS, Simulink will throw an error. Once the topic is selected, it is saved with the block. Even if the topic is not longer available on the network, the block will still use that topic name.

To refresh the list, close and open the dialog again.

To use a topic not currently posted on the ROS network or if you are not currently connected, use the "Specify your own" option under the **Topic Source** parameter in your block mask dialog.

Selecting ROS Message Types

Simulink ROS allows you to select from a list of message types currently supported by MATLAB ROS when setting the **Message type** for Publish, Subscribe, or BlankMessage blocks.
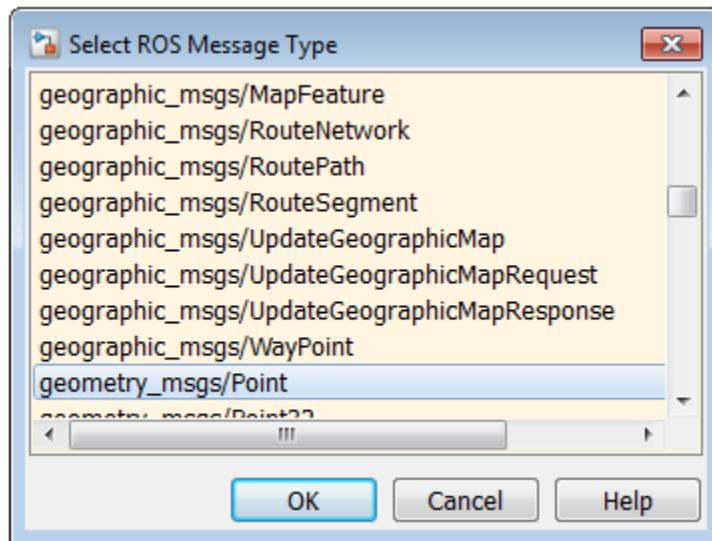

This is the list of all message types supported in MATLAB ROS including any custom message types. You can begin typing in the name of your desired message type or manually search through the list.

The selected message type is stored with the block and saved with the model.

Note: When using code generation, message type information is not included. You must ensure that your Linux ROS environment has the ROS packages installed that contain the necessary message type definitions.

Configuring ROS Network Addresses

During model initialization, Simulink connects to a ROS master and also creates a node associated with the model. The ROS master URI and Node Host are specified in the "Configure ROS Network Addresses" dialog. You can access this in the menu under *Tools>>Robot Operating System (ROS)* by selecting "Configure ROS Network Addresses".
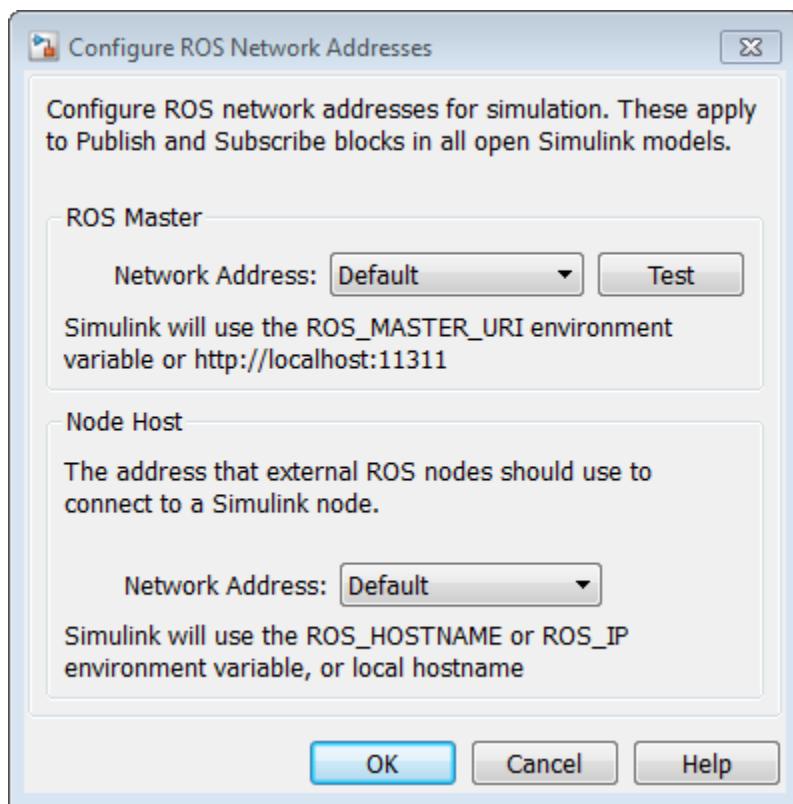
The **Network Address** parameter can be set to "Default" or "Custom".

For the ROS master URI, if **Network Address** is set to "Default", Simulink uses the following rules to set the ROS Master URI:

- Use `ROS_MASTER_URI` environment variable if it is set.

- If a MATLAB global ROS node exists, use the Master URI associated with the global node. The global node is created automatically when `rosinit` is called.

- Use address `http://localhost:11311` if other two rules do not apply.

For the Node Host, if **Network Address** is set to "Default", Simulink uses the following rules to set the ROS Node Host:

- Use `ROS_HOSTNAME` environment variable if it is set.

- Use `ROS_IP` environment variable if it is set.

- Use hostname or IP address of the first network interface on the system if available.

- Use address `http://localhost:11311` if other rules do not apply.

For both, these are the same rules that MATLAB uses to resolve its ROS network addresses.

Otherwise, if you chose "Custom", you can set all the variables as shown below. This overrides the environment variables.

Note: These addresses are saved in MATLAB preferences, not the model. Therefore, this information is shared across all Simulink models and multiple MATLAB installs of the same release.
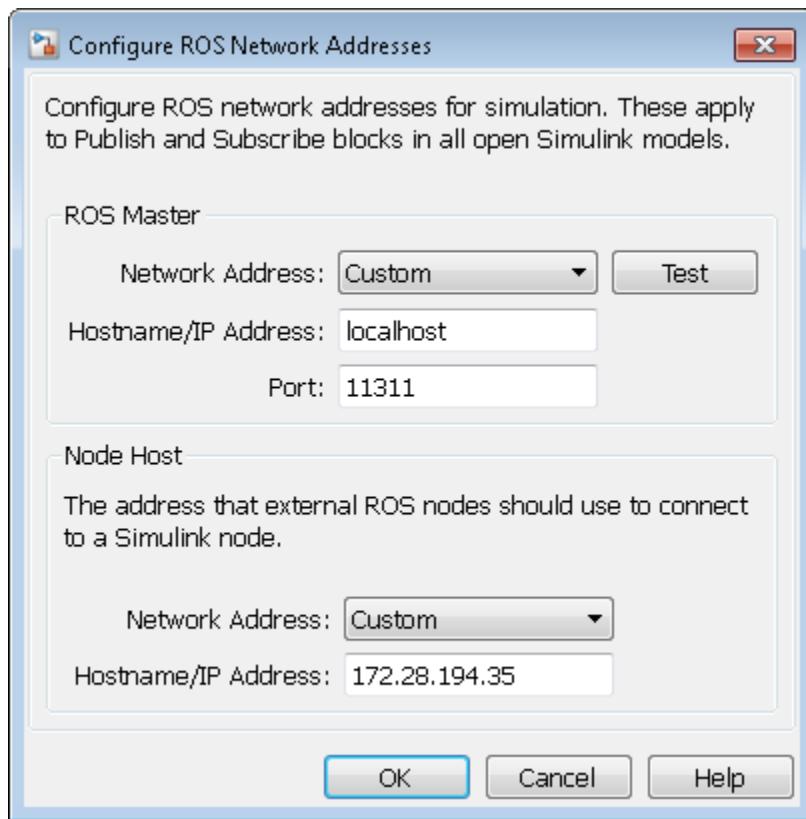
You can also use the "Test" button to ensure you can connect to the ROS master. If you get an error, call `rosinit` to setup a local ROS network, or if you specified a remote ROS master, check your settings are correct.

The custom ROS master or node host settings are not used in generated code when deploying a standalone node.

Managing Array Sizes in Simulink ROS

A ROS message is represented as a bus signal. For more information on bus signals, see "Buses".

If you are working with variable-length signals in Simulink, the non-virtual bus used for messages cannot contain variable-length arrays as properties. All variable-length arrays are converted to fixed-length arrays for non-virtual buses. Therefore, you must manage the maximum size for these fixed-size arrays. To manage array sizes, select *Tools>>Robot Operating System* in the menu and select "Manage Array Sizes". If your model uses ROS messages with variable-length arrays, the following dialog box opens. Otherwise, Simulink displays a message.
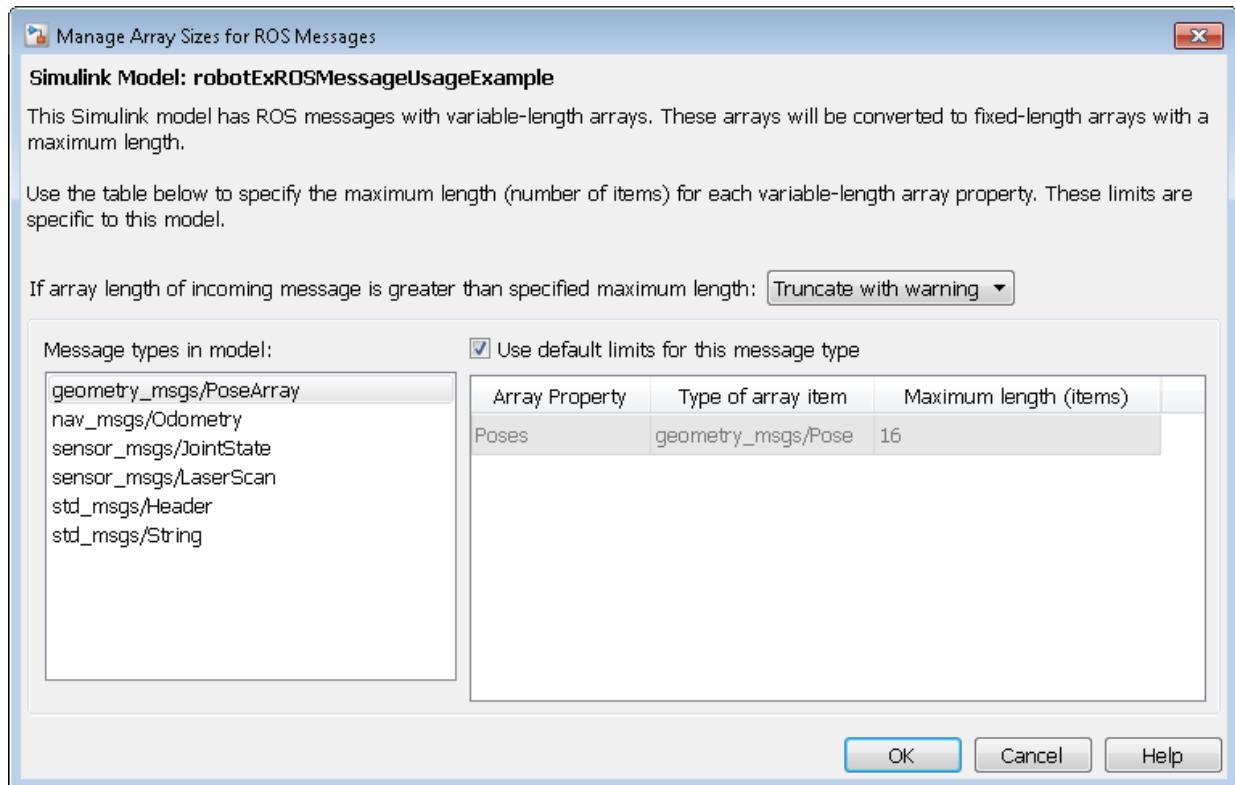
Because the message properties have a variable length, it is possible that they can be truncated if they exceed the maximum size set for that array. You have the option of

`Truncate with warning` or `Truncate silently`. Either way, the simulation will run, but `Truncate with warning` displays a warning in the Diagnostic Viewer that the message property has been truncated. When using generated code, the warning will be emitted using Log Statements in ROS. The warning will be a `ROS_WARN_NAMED` log statement and the *name* is the model name.

The **Message types in model** section shows all the ROS message types that are currently used by Publish, Subscribe and Blank Message blocks in your Simulink model. You have the option to use the default limits for this message type by clicking the check box. Otherwise, select each message type individually to set the **Maximum length (items)** of each **Array Property** as desired. This maximum length is applied to all instances of that message type for that model. The maximum length is also stored with the model. Therefore, it is possible to have two models accessing the same message type with different maximum length limits.

Managing the size of your variable-length arrays can help improve performance. If you limit the size of the array to only include relevant data, you can process data more effectively. However, when running these models, consider possible issues associated with truncation and what could happen to your system if some data is ignored.

Note: If you would like to know the appropriate maximum lengths for different message types. You can simulate the model and observe the sizes output in the warning. To see an example of using ROS messages and working with variable-length arrays, see "Working with ROS messages in Simulink®".

Simulink and ROS Interaction

When using Simulink to communicate with a ROS network or work with ROS functionality, there are several points to note regarding its interaction with MATLAB and the ROS network.

In this section...
"MATLAB ROS Information" on page 6-10
"Simulink ROS Node" on page 6-10
"Differences Between Simulation and Generated Code" on page 6-11
"Publishers and Subscribers in Simulink" on page 6-11

MATLAB ROS Information

Simulink uses the functionality built into MATLAB to communicate with the ROS network during simulation. When trying to debug issues in Simulink, you can use MATLAB to view topics or messages available on the ROS master. For more information on ROS topics and messages, see `rosnode`, `rostopic`, or `rosmsg`.

By default, Simulink uses MATLAB ROS capabilities to resolve network information such as the address of the ROS master. This network information can also be specified in Simulink using the "Configuring ROS Network Addresses" on page 6-5 dialog.

Simulink ROS Node

Each model is associated with a unique ROS node. At the start of each simulation, Simulink creates the node and deletes it when the simulation is terminated. If multiple models are open and being simulated, each model will get its own dedicated node, but all the nodes will connect to the same ROS master. This is because all the models use the same ROS network address settings.

In simulation, the Simulink ROS node name is `<modelName>_<random#>`. This takes the model name and adds a random number to the end to avoid node name conflicts.

In generated code, the node name is `<modelName>` (casing preserved). The model name is also used in the archive used for generated code. Do **not** rename the tgz file from code generation (e.g. ModelName.tgz). The file name is used to get the ROS package name and initiate the build.

Differences Between Simulation and Generated Code

In simulation, the model execution does not match real elapsed time. The blocks in the model are evaluated in a loop that only simulates the progression of time, and whose speed depends on complexity of the model and computer speed. It is not intended to track actual clock time.

In generated code, the model execution attempts to match actual elapsed time (the Fixed-step size defines the actual time step, in seconds, that is used for the model update loop). However, this does not guarantee real-time performance, as it is dependent on other processes running on the Linux system and the complexity of the model. For more information, see the *Tasking Mode* section in the "Generating a standalone ROS node from Simulink®" example.

Publishers and Subscribers in Simulink

All publishers and subscribers created using Publish and Subscribe blocks will connect with the ROS node for that model. They are created during the model initialization and topic names are resolved at the same time. The publishers and subscribers are deleted when the simulation is terminated.

NOTE: If a custom topic name is specified for a Subscribe block, the topic is not required to exist when the model is initialized. The Subscribe block will output blank messages until it receives a message on the topic name you specify. This allows you to setup and test models before the rest of the network has been setup.

Simulink Support and Limitations

Robotics System Toolbox does not support the following ROS features in Simulink:

- ROS Services
- ROS Parameter Server
- Transformation trees
- Messages containing cell arrays of strings

If your application requires these features, consider using MATLAB ROS functionality. You can write a ROS node using MATLAB that can publish services, parameters, and transformation trees to a topic as ROS messages. Simulink can then subscribe to that topic to work with those messages. The following functions are used in MATLAB to work with these features:

- ROS Services: `rosservice`, `rossvcserver`, `rossvcclient`, `call`
- ROS Parameter Servers: `rosparam`
- Transformation trees: `rostf`, `transform`, `getTransform`
- Messages containing cell arrays of strings: `rosmessage`