JOURNAL OF AEROSPACE COMPUTING, INFORMATION, AND COMMUNICATION
Vol. 4, December 2007

Route Navigation in the Urban Grand Challenge with Compromised GPS

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DOI: 10.2514/1.33309

The DARPA Urban Challenge is providing an opportunity for interested scientists to compete in designing and proving an unmanned vehicle. The autonomous vehicle must avoid collisions, operate in compromised conditions and be robust and independent of human operators. Navigation may be achieved by a varied number of methods. Most will rely on Global Positioning System (GPS) for waypoints, checkpoints and general travel. A route file will be provided for the test site that contains information related to GPS coordinates throughout the course. Vehicles must safely navigate to checkpoints while maintaining road rules with safety. In the event that GPS is lost or compromised, the vehicles must still navigate to the checkpoints while determining traversable pathways. Optional techniques have been developed in order to navigate without GPS. We build a map of all of the waypoints along with other route information. Whenever we need to navigate to a checkpoint or gate in the absence of GPS, we identify the location we want to head to and use that as a directional bias compared to our current location. We then follow road rules to get through correct gates to the checkpoint using modified orienteering techniques.

I. Introduction

THE Global Positioning System (GPS) allows us to interpret signals from a group of satellites to determine our location on earth. When you first start connecting to these satellites, you can determine your location with three of the signals and that usually occurs in less than three minutes. The more satellites you connect to, the better your position determination becomes;[1] you can interpret positions in three dimensions to include height as well as longitude and latitude. Whether GPS is handheld or mounted equipment, users tend to rely on the availability and accuracy of these signals.

GPS can be compromised or denied such as when the user may be in a tunnel or an urban canyon. The GPS signal is weak and can be easily jammed[2] creating serious problems for military and civilian alike. Some techniques for overcoming the loss of GPS include orienteering where the user has a compass and a gyroscope or an inertial measurement unit (IMU).[3] This type of orienteering, sometimes called ‘dead reckoning’ is performed using a map of the area to plot locations. Other techniques include using TV radio waves as discussed in ‘GPS World Forum’, Sept 4, 2007, or as in the military, implementing techniques with high resolution radar.[4] ENSCO’s Ranger system is a patented system which can augment or replace GPS capabilities in compromised areas. Full descriptions of this system can be found at their website at http://www.ensco.com/technologysolutions/geolocation/overview.

The downside of the direct orienteering approach is that multiple accesses to a region of pathways provide confusing choices over which pathways are optimal and that local maps must be developed and remain accurate.

Received 6 July 2007; revision received 15 October 2007; accepted for publication 14 November 2007.

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Interpreting radio waves requires that the environment has local broadcasts and sophisticated electronics. When high resolution radar is used it requires wave-shaping and optimizing software and equipment.

We introduce techniques which overcome the loss of GPS by creating a directional bias. This bias is the general direction we need to navigate to using a compass or IMU. In addition, all waypoints have been mapped and augmented with arrays which contain waypoint groups which are all accessed by specific gates or entryways to lanes. The lanes are evaluated to determine if they are traversable pathways using the arrays to chain together the waypoints that lead from an entry gate.

II. Urban Challenge Background

Defense Advanced Research Projects Agency (DARPA) has continued the search for autonomous vehicles by providing the Urban Grand Challenge for 2007. This challenge asks scientists and engineers to solve a number of problems related to vehicle movement in a robust environment. The vehicle computer will have to find traversable pathways in an urban environment with numerous other vehicles performing similar tasks at the same time. They will be asked to go to designated segments and GPS-defined lanes and waypoints throughout the course, pass over some designated as checkpoints and do this safely (Fig. 1).

The course will be defined by roadways, most painted with center and boundary lines. Stop signs will be replaced by GPS points and vehicles will have to stop within one meter of a stop line. Some curves within the course are marked, however, intersections are not and will have to be managed in the same way humans do by following general rules of precedence.

Data for the course is managed in an route network definition file (RNDF) which contains information about road segments, lanes and waypoints (Fig. 2). Some of the waypoints are identified as checkpoints, exit, stop or entry locations. When preparing for a site visit, the entrant supplies data for the RNDF gathering all of these points from their own test site. This data is then submitted to a DARPA-provided parser which checks to determine if the data are within reasonable parameters and will ‘pass’ the user when all data fits for a segment map. This map shows the locations of points on the route and the distances between them. Data for the RNDF is supplied by DARPA for the semi-finals and finals.

An mission data file (MDF) (Table 1) is issued to each team which contains the checkpoints that must be encountered and the order they are in. In addition, speeds for route segments are included. The vehicles must independently find these checkpoints adhering to the types of waypoints in the course and do this safely, without collision in a dynamic environment.

III. TeamNOVA Vehicle

The Urban Grand Challenge requires safety-proven vehicles to be modified so that they can find traversable pathways in an urban environment and avoid collisions. There are numerous choices of vehicles and options for building one from personal designs. The hardware to use depends on the type of vehicle whether it can be controlled

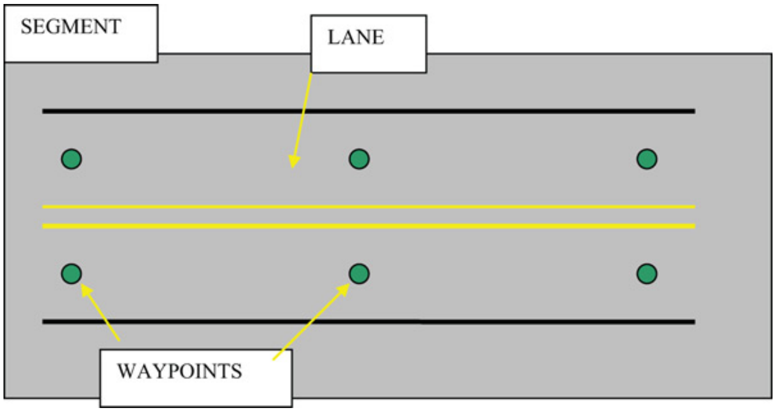
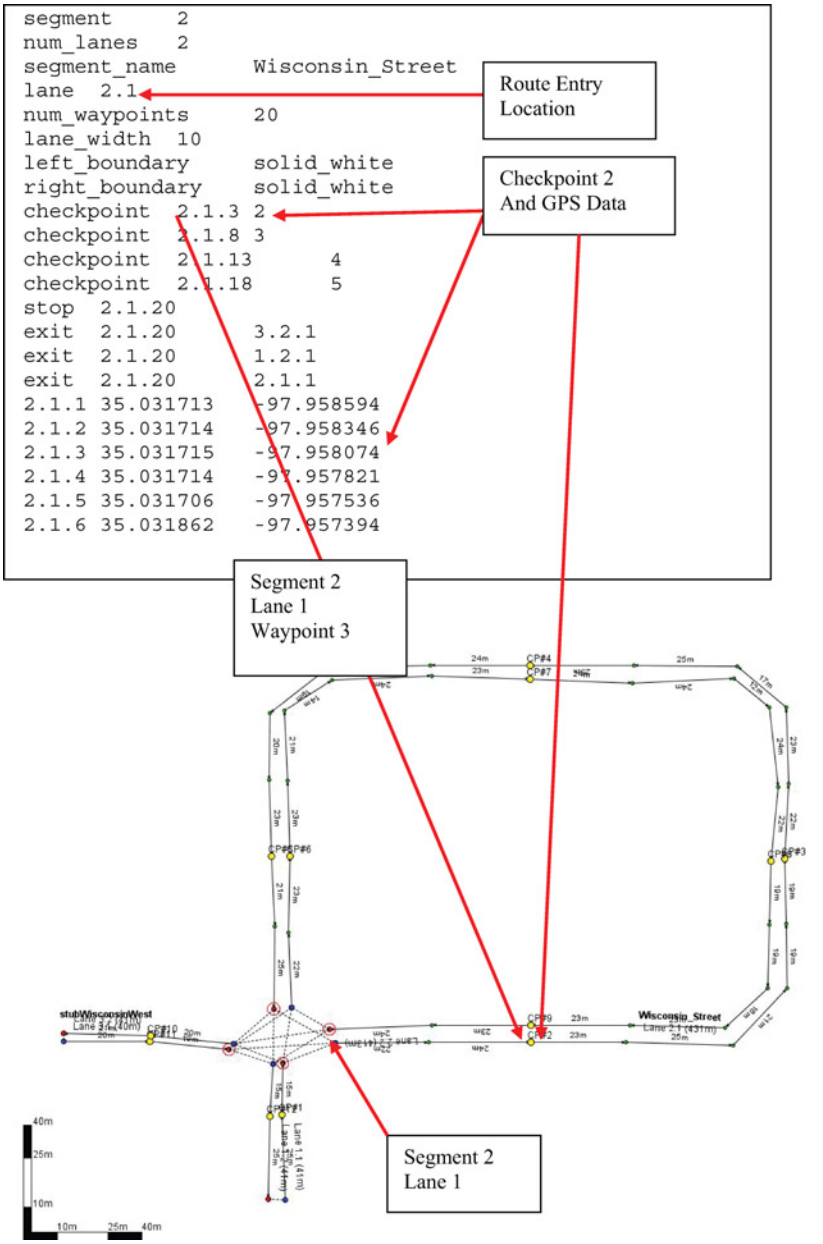


Fig. 1 Example of road segment with lanes and waypoints.



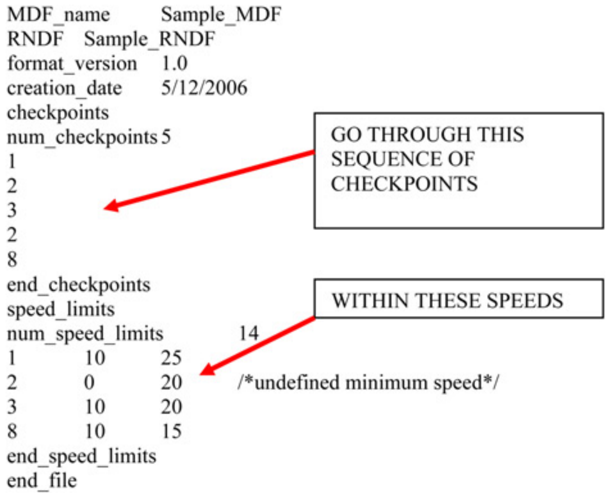
```
segment     2
num_lanes   2
segment_name      Wisconsin_Street
lane  2.1
num_waypoints     20
lane_width  10
left_boundary     solid_white
right_boundary    solid_white
checkpoint  2.1.3 2
checkpoint  2.1.8 3
checkpoint  2.1.13      4
checkpoint  2.1.18      5
stop  2.1.20
exit  2.1.20      3.2.1
exit  2.1.20      1.2.1
exit  2.1.20      2.1.1
2.1.1 35.031713   -97.958594
2.1.2 35.031714   -97.958346
2.1.3 35.031715   -97.958074
2.1.4 35.031714   -97.957821
2.1.5 35.031706   -97.957536
2.1.6 35.031862   -97.957394
```

Fig. 2 Route network data file (RNDF) at top and segment map below.

through wires in drive-by-wire systems or the older conventional methods found in most cars. The latter requires controllers which can actuate the gas, brake, transmission and steering. The hardware installation requires some insights into motion control and mechanics.

We have designed software to be used with computer controllers, amplifiers and other special equipment for responding to decisions to move the vehicle in certain ways. Our system is Linux-based using C++ with a graphical user interface (GUI) toolkit. The top layer in our software responds to images from cameras with laser range-finder data complementing it. We can see the vehicle domain to about 140 feet and overlay the range distances to aid in finding good roadway, obstacles, pot holes and other impediments to travel. Our artificial intelligence is used to manage the reasoning about elements in the immediate environment, making decisions and learning.

Table 1 Checkpoints and speeds within a sample MDF.



```
MDF_name        Sample_MDF
RNDF   Sample_RNDF
format_version   1.0
creation_date    5/12/2006
checkpoints
num_checkpoints 5
1
2
3
2
8
end_checkpoints
speed_limits
num_speed_limits          14
1          10        25
2          0         20        /*undefined minimum speed*/
3          10        20
8          10        15
end_speed_limits
end_file
```

GO THROUGH THIS SEQUENCE OF CHECKPOINTS

WITHIN THESE SPEEDS

There are many problems associated with this type of project. The vehicle must navigate around a course partially marked with center and boundary lines and stop lines where you must stop and queue with other vehicles in your lane or intersecting lanes. Many waypoints will be marked with GPS data so that the vehicle can discriminate between different parts of the routes. Knowing your location can be found using a GPS system and keeping close track of your route can be done with an IMU. At times, the lanes may be blocked forcing the vehicle to make a safe U-turn and go back on the route to find a different path to a particular checkpoint. The following sections contain information about our hardware, software and our previous background research including our non-proprietary artificial intelligence designs.

IV. Hardware

One of the first problems we addressed was to identify a street legal vehicle that could be controlled with actuators. A ‘drive-by-wire’ would be convenient and allow us to bypass the installation of actuators and the special computers, amplifiers and accessory hardware needed with more conventional drives. In addition, the mandate from Congress declares that there will be around 400,000 vehicles to fit for autonomy. Very few of these are drive by wire and it will require conversions similar to the ones we are making. Our choices will give us experience in adapting a conventional vehicle for autonomy. In time, we may have an opportunity to apply those conversion skills to military vehicles.

We purchased a 2001 Ford Escape, an SUV (Fig. 3) with enough room for our equipment. The interior was stripped so that we could weld with safety. A frame was designed to hold a generator, power supplies and electrical accessories. The design included a ‘hot box’ to hold the base of the generator so that we could channel the heat out of the vehicle. It was fitted with an extended exhaust which was welded through a hole we made in the bottom of the chassis (Fig. 4).

An electronics box was constructed to hold a controller and the amplifiers. The controller receives instructions from the onboard computer and then sends signals to the amplifiers. These control the actuators which in turn control gas, brakes, shifting and with a servo motor, the steering. We welded a frame to hold the actuators (Fig. 5) and allow us to quickly convert the vehicle from autonomous to manual. Metal boxes were designed to hold the actuators and pins are used to secure them to the frame. These can be secured further with cotter pins removed easily. This is important whenever we need to move the vehicle manually.

We removed the steering column in order to weld a gear to the shaft. A servo motor was mounted to a frame welded between the floor and inside the lower dashboard area. It engages the steering column and moves to turn the steering wheel whenever it receives instructions to do so. For times when the vehicle is steered manually, the servo freewheels and doesn’t need to be disengaged. The relationships of the position of the actuators can also be seen in the figure.

Fig. 3 TeamNOVA vehicle with sensors.

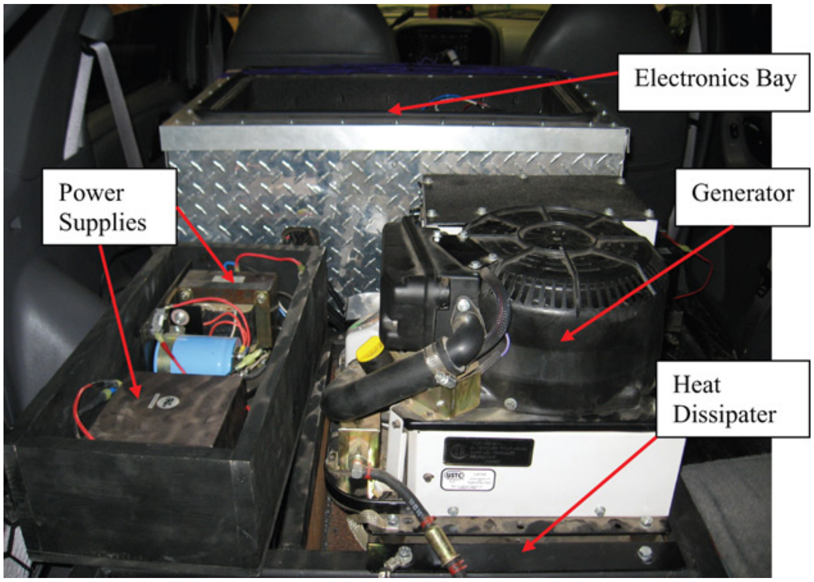


Fig. 4 Electronics bay and generator with heat dissipation box.

V. Sensors

A prime objective with the vehicles is to find traversable pathways and still follow the RNDF and MDF. One technique for finding these pathways is with image processing. The TeamNOVA vehicle is fitted with five cameras. One is located in the center of the vehicle above the windshield with a second and third located to the sides of the cab. The side cameras look for traffic on both sides of the vehicle and white stop lines. Two in the rear on both sides do similar work and watch for traffic in conditions where the vehicle may safely depart the lane for passing.

Collision avoidance can be achieved with image processing and can be augmented with a laser scanning system such as a SICK laser range finder. This instrument is used to find obstacles such as K-rails or trees on the roadway and for holes or ditches in the surface. Together, these instruments paint a fairly accurate picture of the roadway

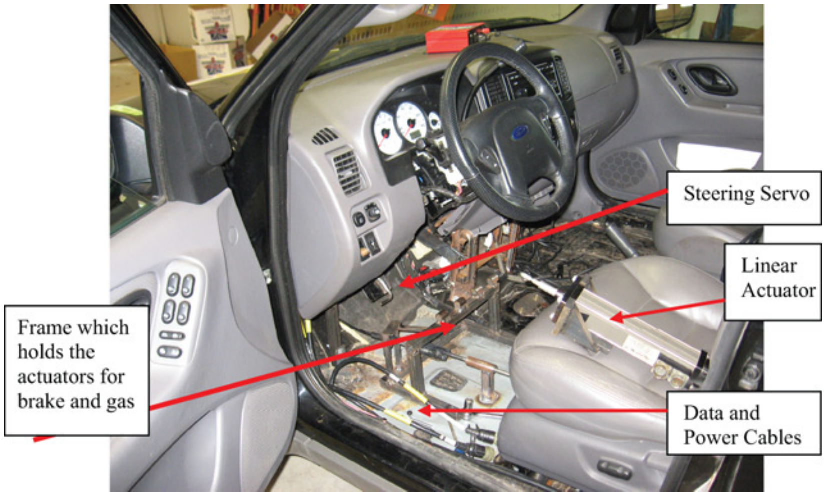


Fig. 5 Actuator frame and steering servo.

and help determine if it's traversable. Other sensors such as an inertial measurement unit (IMU) can be used to determine location and to aid in making maps. The GPS unit also supplies compass headings to other positions noted by longitude and latitude. Mapping can be a great aid in determining location and plotting routes.

GPS units can provide fairly accurate longitude and latitude for a vehicle. Whenever they are wide area augmentation system (WAAS-enabled), they can achieve a location accuracy of approximately 3 m. These location accuracies are based on satellite data only; other ground-based GPS-enhancing tools are not allowed. The RNDF files contain GPS data for waypoints and their variations such as entry or exit points. The RNDF files are critical in providing location information for the onboard computers to use in navigating different parts of each segment. There are times when GPS data can be compromised such as the vehicle going through a tunnel or under an underpass. The signals can be interfered with by some electronics in close proximity. If GPS is lost, the data from the units is lost. Alternative methods must be designed in order to complete a mission whenever this failure occurs.

Figure 6 shows the hardware interfaces for our autonomous vehicle. A Garmin GPS receiver is mounted on the top of the vehicle and the IMU is mounted on an equipment frame inside the vehicle. The five cameras are mounted: main

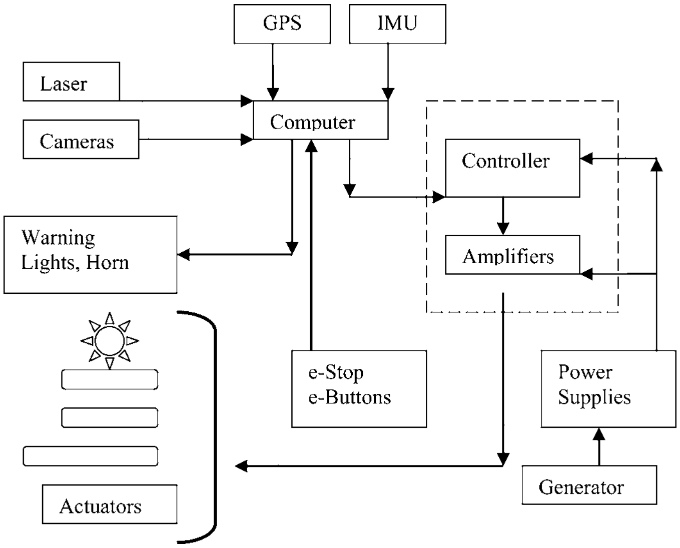


Fig. 6 Hardware interfaces.

camera above the windshield center position, two on front of vehicle roof pointed to the sides where they can see traffic both left and right and two at the rear which also look left and right as well as to the rear to determine if any traffic is passing the vehicle. The cameras are situated so that they can keep a meter clearance on all sides of the vehicle and in addition, the front ones can see the stop lines when approaching a designated stop.

An emergency stop (e-Stop) is achieved through a wireless connection to a laptop computer external to the vehicle. A controller is attached to it that allows us to move the vehicle for routines such as going to a starting chute. It also has an ‘all stop’ control for safety. The vehicle is equipped with three additional manual red stop buttons on the sides and rear of vehicle. Safety personnel can push any one of these buttons which disables the vehicle according to guidelines furnished by DARPA.

VI. GPS Solution with Linked Lists

The map in Fig. 2 shows the course design as segment, lane and waypoint numbers. Some of these are checkpoints, exits or entries. To navigate the course, the points can be mapped in a linked list where each point is attached to the previous one and the next one in the map. This can be developed by associating every point with the one in front of it and the one in back of it. Each point has a pair of points associated with it.

To get to a particular location, the program looks at this list and determines where it is now and where the target location is. Then it can follow points one-by-one by going from one set of longitude and latitude locations to the next. Measurements based on the relative position of upcoming waypoints can be used to determine when to turn at an intersection or side road. Some waypoints track to the end of the stub segments (the lower left short roadway segments) where a U-turn is required in order to get to the next point.

In Fig. 2, the example points to waypoint/checkpoint 2.1.3. Our parser takes the RNDF data and creates these links as shown below in Table 2. The point name is followed by longitude and latitude. The descriptors that show ‘next1’ or ‘last1’ refer to the number of entry or exit points associated with the waypoint. This is important at side roads and intersections so that the programs see the opportunity to chose the correct entry point in the lane.

Whenever the vehicle gets within about 4 m of a point, it then looks for the next point to determine if a curve, intersection or side road is to be expected with the next point in the lane (Fig. 7). The last data in Table 2 refers to the next point in each sequence and if a checkpoint is associated with it and if it is a stopping point.

Table 2 The parsed RNDF files in a linked list.

```
Point Name: 2.1.3
35.031705
–97.958074
next1: 2.1.4
next2: Not Connected
next3: Not Connected
prev1: 2.1.2
prev2: Not Connected
prev3: Not Connected
Sequence: 2.1.4
CheckPointNumber: 2
Not a Stop Point
```

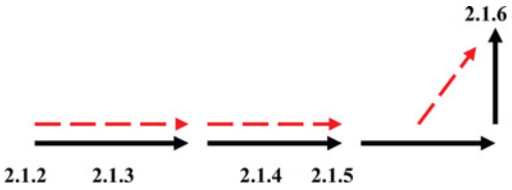


Fig. 7 GPS directing travel in dashed red line with waypoints in black.

When approaching an intersection, the directional travel will point to the next numbered point in the sequence that it needs to move to. The pointing is actually accomplished by calculating the angle of turn needed. At the intersection, travel is pointed to one of the three possible entry points in a sequence for either a right or left turn or to continue straight ahead. At the end of a stub section, the directional arrow will point back to the left lane for a U-turn. The onboard computer then can direct the vehicle to the checkpoints it needs to pass while using image analysis with laser range finding to travel within the roadway.

VII. Compromised GPS with an Alternate Navigation Solution

The RNDF file is provided to all teams at the start of a mission. This RNDF file contains all of the GPS-located points needed to traverse the route and properly identify places to enter and exit lanes. These points represent locations on a route and can be used to create a simple map of all the points using the GPS data as distances from an identified single location at the start of a segment. Then all of the points can be referenced by numerical coordinates on the map. The distances between the points and the compass direction between any points can be determined. We call this a directional bias which will always provide the direction we need to go to get to any waypoint. When the directional bias points to two checkpoints in opposite lanes, the proper lane to enter into a segment can be determined with a simple route map in a one-dimensional array (Fig. 8). The array contains all waypoints within a route. Whenever a lane choice is needed, the system looks at the current checkpoint and traces back through the array to find the proper entry gate. This can be very useful in determining a simple way to navigate the course without pointers. The directional bias holds true for every checkpoint within the course.

For example, if we use the data shown in Fig. 8, we may be somewhere near an entry gate. There may be multiple gates nearby and we need to determine the correct one to use. If the waypoint or checkpoint that we need to travel to is known, it will have identifiers associated with it. This example shows that the checkpoint we are looking for is 2.1.7. This is interpreted as section 2, lane 1 and waypoint (which is a checkpoint in this case) number 7. Our directional bias will point from wherever we are located to that checkpoint and give us a compass heading towards it. If we had no additional data, we would at least know the general direction we need to go. A problem might be that once we arrive close to a segment entry gate, there may be multiple gates nearby. This problem might occur if the vehicle is in a tunnel, GPS is denied and multiple gates or openings for travel are fairly close to each other.

The bias shows us the direction we need to go and usually does not point directly at a gate, however, it certainly is convenient whenever it does. To solve this problem, we find all GPS waypoints at the beginning of each mission while we have GPS and note their locations relative to each segment, lane and direction of travel. This example would be segment 2 and lane one where our checkpoint is. We record each waypoint in a lane in a two-dimensional array so that the start of the data may show an entry gate (2.1.1) and an exit gate which in this figure may be 2.2.12. This data is kept in an array so that whatever checkpoint we are looking for, we can find it and associate it with the entry point or gate by simply moving from the current location in the array to the start of the array data for this segment and lane. We locate the entry gate and proceed to the checkpoint. The bias will change depending where we are and the relative location of the checkpoint.

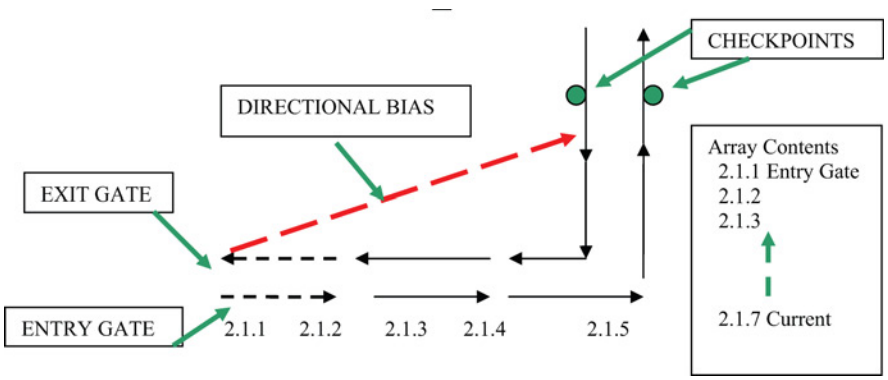


Fig. 8 The directional bias and the corresponding array used to find an entry gate.

With the bias, the vehicle always knows the direction to the next checkpoint. Looking at the entry arrays, the vehicle software can always find the entry gate and the proper lane to enter. Because the image processing has to find traversable pathways, the vehicle will stay on the road and look for the turns, blocked roads and other obstructions. The linked-list approach will provide a direction to go to the next point in the route, however, the directional-bias points to the next checkpoint. It is because of this feature which contains associated arrays of gates and waypoints, that routes and checkpoints can be navigated in missing or compromised GPS.

The GPS points in the RNDF can be used to plot distances between points and the direction the vehicle has to travel. The distance between adjacent points can also be easily calculated. This data can be saved separately as a backup to the GPS programs and if the GPS is lost, it can be used to navigate to any checkpoint. Using orienteering techniques with the above technique, the direction and distance between features in a route can provide a route the vehicle must take. However, the waypoint arrays are necessary to directly find gates and waypoints of interest or checkpoints. A compass or IMU can provide the direction between points while the distance is provided in the original longitude and latitude values. The onboard computer then directs the vehicle along traversable pathways from point to point along the course providing distance and direction at each point in the lane.

With any course there can be additional problems. For example, the roadway may be blocked forcing the vehicle to turn around and find an alternate route. Without GPS, the directional bias continues to point to where the next checkpoint is. Turning around, the vehicle searches for different pathways in an attempt to head toward the bias direction. This also works for bypassing side roads and whenever the roadway has deteriorated. With the directional bias, the vehicle can navigate to any point in the route.

VIII. Conclusion

The Urban Challenge provides a stimulus for developing autonomous robotic vehicles. The military will make conversions to autonomous systems for vehicles during the next few years in an attempt to automate and save lives. Commercial vehicle will benefit from spin-offs of this program through intelligent driving assistants. These assistants will provide driving help such as damping lane-wandering, slowing the vehicle when following too closely, adjusting safety restraints and supporting the driver in dangerous or hazardous conditions.

We have developed techniques for navigating routes with and without GPS. One method we've shown is a simple and yet robust technique which uses a type of orienteering with saved data of route points. We use a 'route bias' in order to guide the vehicle in a particular direction and simple arrays to hold data referencing lane entry and exit gates. When GPS fails, this technique provides a means to still navigate all points in a route even when the route may have obstructions or is not well defined.

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doi: 10.1109/ICU.2006.281556

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