Sensor Technology and UGV Operations – Lessons Learned from the Urban Challenge

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ABSTRACT

How many sensors are enough to navigate city streets and interact with other vehicles? This was a hotly contested question at the DARPA Urban Challenge where as teams brought everything from LIDAR/GPS combinations to spinning lasers, automotive radar and vision systems to Victorville, CA to compete in the international competition. This paper presents the approaches of the Ben Franklin Racing Team, a consortium led by the University of Pennsylvania with Lehigh University and Lockheed Martin, and the reasoning behind the team's car and sensor selections. The creation of a sensor suite involved a careful analysis of the tradeoffs between perception benefits, computational needs, power consumption and physical footprint on the vehicle. The team followed an approach of analyzing a core group of sensors, then adding additional sensors as perception requirements were discovered.

BACKGROUND

The Urban Challenge is the third in a series of Grand Challenge competitions meant to increase ground robotic system capabilities. This challenge provided for the interactions of ground robotics in city type environments. This included both robot-robot interactions and human-robot interactions.

Previous challenges focused on movement between two points located up to 130 miles apart. This involved perception and behaviors based on that perception while traveling at speeds up to

50-60 mph. The Urban Challenge focused on intelligent behaviors and interaction with other vehicles (manned / unmanned) in the environment. Questions such as “Where should the vehicle be on the road?,” “Who has the right of way?,” and “Is it safe to pass?” were carefully considered. This event challenged the perception and inference abilities of the participants.

The first two Grand Challenges involved traversing off-road or path based routes. The Urban Challenge had the robots traversing a much more well-defined road. This included lanes defined by paint, curbs or large changes in smoothness between the on road areas and the off-road areas. From the original rules, road signs and potential traffic signals were integrated into the Route Network Definition File (RNDF) that would be provided by the event coordinators. This relieved the team from needing to incorporate light signal analysis as part of the configuration.

The challenge was designed to be a six hour driver’s license test for the robotic vehicles. The focus would move away from GPS following and obstacle avoidance and toward perception and analysis of the road/lane position, intersections, static/dynamic traffic right-of-way rules and safety procedures to guide to vehicle (Figure 1). A summary of the milestones and the new capabilities are listed in Table 1. This provides the background for the sensors and approaches the team needed to implement the Urban Challenge’s unique requirements. In Table 2 is a depiction of the process necessary for vehicles to qualify for the final Urban Challenge event.

Vehicle Selection

The team analyzed potential vehicles for the on-road vehicle operation and the Toyota Prius was selected for its power, handling and size. The Prius uses both a 12 volt battery system and a power. This allows the onboard system to charge the battery and run the onboard electronics, assuming that the total vehicle power needed for computation and sensors could be kept under 1 KW. A high voltage DC-DC converter was used to connect the onboard electronics to the car.

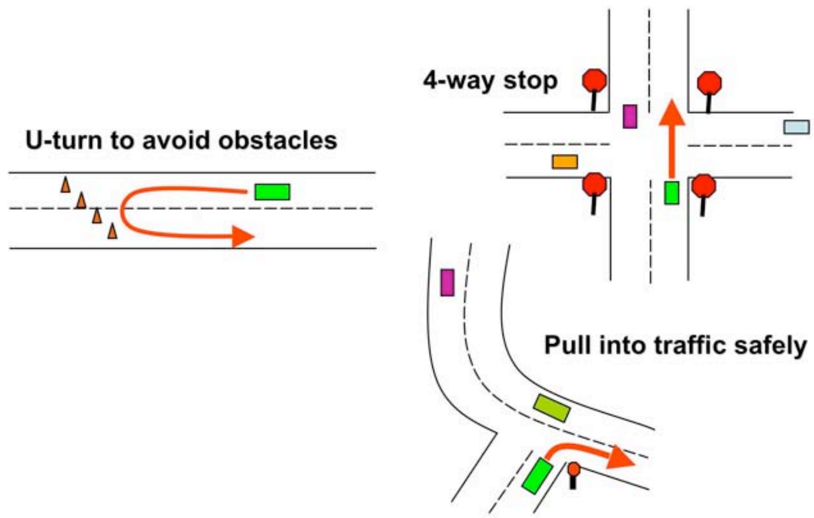

Figure 1. Some of the Urban Challenge "Rules of the Road"

Table 1. Urban Challenge Milestones

Urban Challenge Metric	Urban Challenge Milestones	How was it done?	What makes it challenging?
60 Mile City-like Environment	Large scale UGV urban environment testing	Setup a mock environment at the old George AFB living area	Dynamic environment, vehicle must respond and behave to changes while executing original plan
Multi-robot Interactions	Driving in traffic	Up to 11 robotic vehicles on course at the same time	Robotic vehicles must follow "human" rules of road to interact with other robots. No direct communication allowed.
Human-robot Interactions	Driving in traffic	Fifty human test drivers navigated throughout the challenge	Robotic vehicles must interact with each other and human drivers, increasing the difficulty of navigation and increasing the needed perception of the environment
Complex Maneuvers	Merging, Passing, Parking and Negotiating Intersections	On road / off-road / parking lot and intersections setup	Robotic vehicle must incorporate these techniques into their toolkits to change modes and still reach their overall goals
Driver License for Robots	Following Rules and Guidelines	Rules and Guidelines	First Challenge that moves past just safety into defined rules of the road.

Table 2. Urban Challenge events necessary to reach final event from

http://www.darpa.mil/grandchallenge/rules.asp

	Safety	Basic Navigation	Advanced Navigation	Basic Traffic	Advanced Traffic
Video Demonstration	• Wireless E-stop • Manual E-stop • Audible and visible warning systems	• Autonomous Navigation • Waypoint following • Lane keeping			

	Safety	Basic Navigation	Advanced Navigation	Basic Traffic	Advanced Traffic
	• Five second pause before entering autonomous mode • Vehicle utilizes brake lights	• Obstacle avoidance			
Site Visit	• Everything above • E-stop works from 20 mph to 0 in less than 20m	• In autonomous mode five minutes after receiving DARPA MDF • Remain in travel lane at all times • Conform to min and max speed limits • Act to avoid collisions and near collisions • Stop with front bumper within one meter of line • One vehicle separation when leaving a lane to pass and one to four when returning to a lane • U-turn		• Respect precedence order at intersections • One vehicle length per 10 mph is maintained • Exhibits correct stop-and-go behavior in a line of stopped vehicles	
National Qualification Event	• RUN, PAUSE, DISABLE and Manual E-stop will be tested and verified. • Full test of the government E-stop system. E-stop brings the vehicle traveling at 20 mph to a smooth, controlled and complete rolling stop in less than 20 meters.		• Obstacle Field • Parking Lot • Dynamic replanning when roads are blocked • Road following when sparse waypoints are present • Vehicle can tolerate intermittent GPS outage		• Merge into traffic • Left turn across traffic • Zone navigation • Emergency braking • Defensive driving • Traffic jam
Urban Challenge Final Event	All of the above	All of the above	All of the above	All of the above	All of the above

240 volt DC battery system to create the hybrid drive system. The higher voltage battery pack is charged from the engine during operation and has approximately 1.8KW of available While the Prius is not known for its high performance handling, its low center of gravity and sloping lines provides a good stable platform for sensor operation and city based driving. The moderate size of the Prius creates an efficient and agile platform for urban operations.

Sensor Selection

The team's approach to sensor selection was to invest in a small number of key sensors and then make choices about secondary sensors and their placement to provide specific perception abilities. For control, the team chose to have a drive-by-wire system installed by Electronic Mobility Controls allowing the team to focus their efforts on development and testing.

Unlike the first two Grand Challenges, GPS could not be used as the primary sensor for position because urban "canyons" and interference from trees and buildings caused GPS degradation. A more complete positioning system was needed to ensure continuity should the GPS signal drop out. The team combined an inertial navigation unit with the odometry from the car to supplement the GPS signal. This would provide "enough" coverage without requiring too much power.

In addition to position knowledge, the robot needed the ability to perceive the environment around it. A single scanning laser can provide some amount of situational awareness for the robot. However, the data is only a single line analysis of the environment. A better option proved to be the Velodyne HDL-64E (Figure 2). This laser scanner performs a 3-D scan and provides vehicles with a 360 degree view of the environment. This sensor became the backbone of the sensor analysis and provided medium/long range sensing capabilities for the Prius.

Figure 2. Velodyne Scanning Laser (from www.velodyne.com)

The team successfully demonstrated site visit capabilities with a GPS and Velodyne configuration. As more advanced maneuvering and lane positioning techniques were incorporated, additional SICK lasers were placed around the vehicle to supplement medium/short range sensing. The Stereo Bumblebee system was installed for additional lane tracking information. Table 2 highlights the final list of sensors used on the vehicle. The final system configuration (Table 3) shows the set of sensors and their function in the final system. Figure 4 shows the footprint of the various sensors.

Table 3. Table of Sensors Used on the Prius

Sensor	Image	Reason
Velodyne		360 medium and long range sensing of obstacles in the environment
SICK Scanning Laser		2-D scan of environment both horizontal and vertical for both short and longer range scanning of environment
Bumblebee Camera		Forward long range stereo vision for lane tracking

Sensor	Image	Reason
Hokuyo Scanning Laser		2-D scanning for close quarter operations
SICK LDRS		2-D Scanning in front of vehicle for close quarter operations

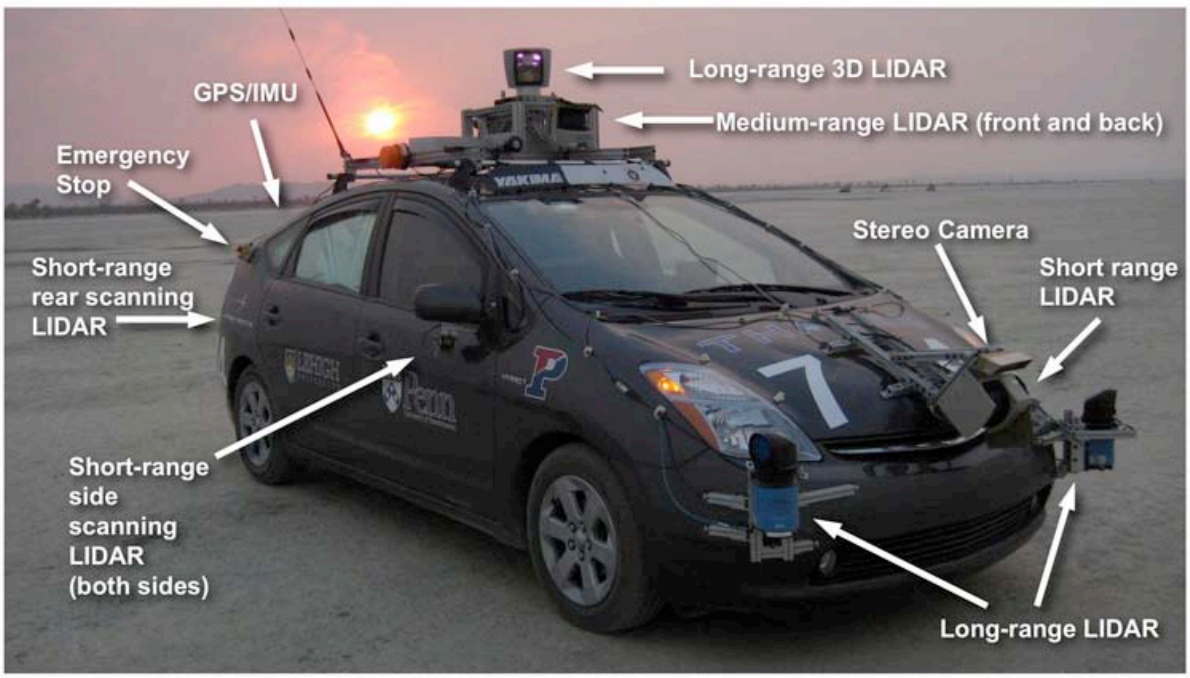

Figure 3. Ben Franklin Final Robotic Configuration

System Architecture

The basic system architecture is shown in Figure 5. This straightforward approach outlines components for the vehicle drive system, sensor inputs and interaction for effective command/control. The system was run completely within MATLAB which allowed for rapid development and debugging.

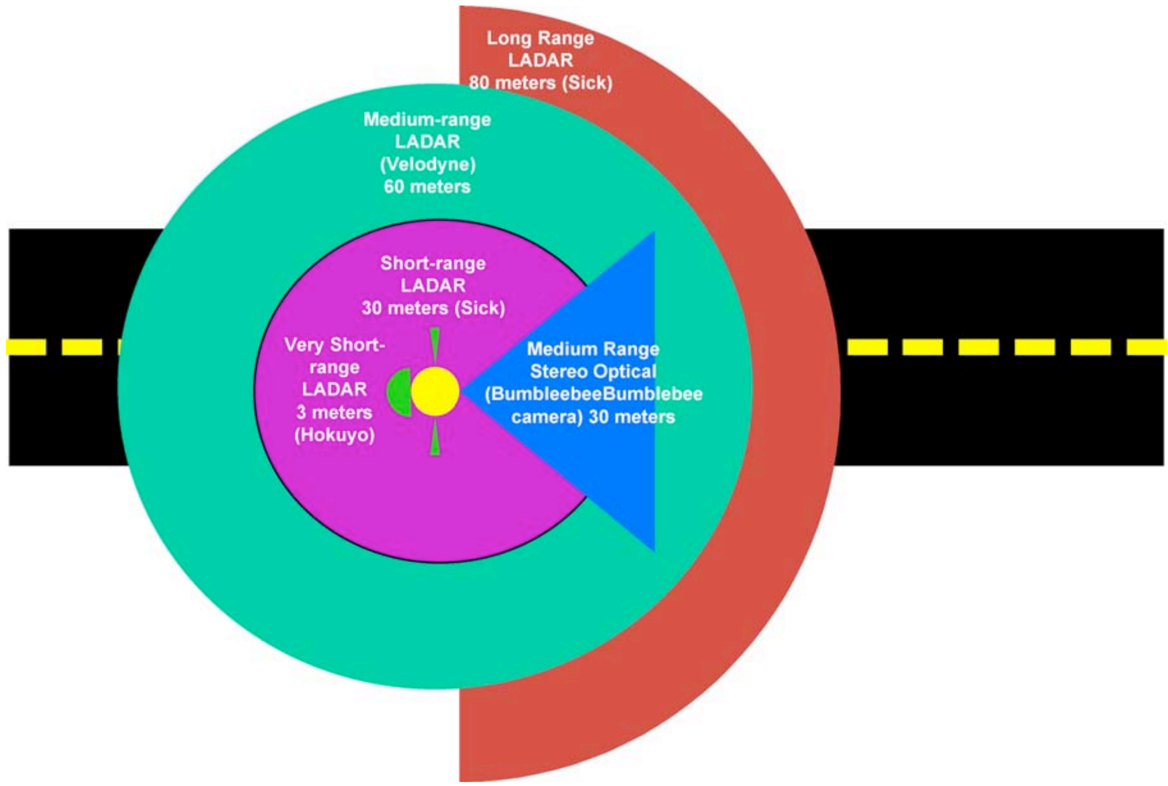

Figure 4. Prius Sensor Overlap

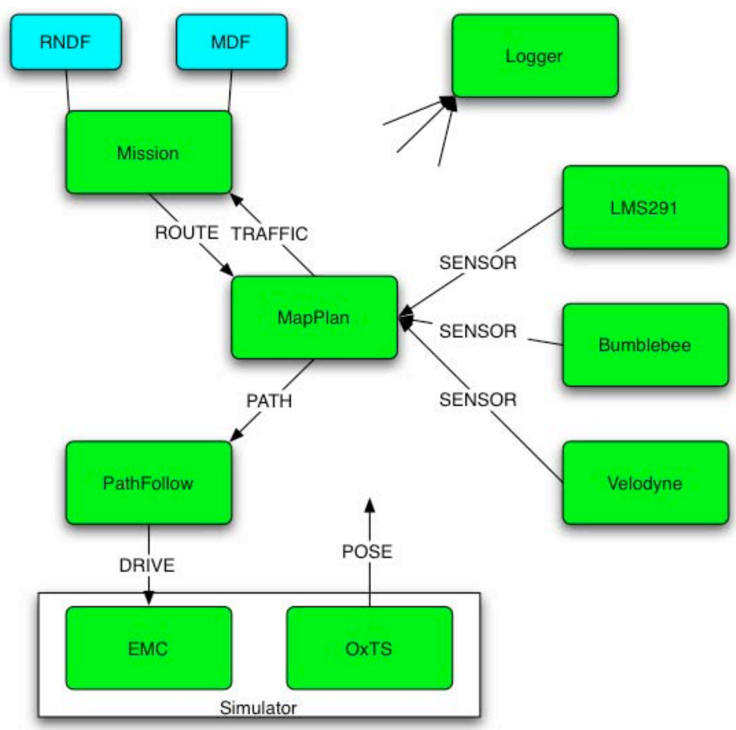

Figure 5. Prius Onboard Architecture

DARPA provided mission and course information in the form of two text files to be loaded by the system from an external USB key. Information about the course was defined in the Route Network Definition File (RNDF), specifically listing the GPS points with course, intersections and lane boundaries. The RNDF also contained information about the traffic lines for each road segment and indications regarding permission to pass. The Mission Definition File (MDF) provided information about the specific mission that the vehicle will execute on the course. It consists of GPS checkpoints and the order the vehicle should visit those points. Both of these files where processed by our Mission module and high level route information was calculated and passed to the central software component we called the Map Plan module. The Map Plan module was responsible for incorporating all sensor information into a cohesive model of the environment, generating the path plan necessary to achieve the goals set by the Mission module. Finally, the Path Follow module converted the specific requested path into low level actuator commands that are sent to the EMC system for execution.

Although this architecture appears overly simple in design, its simplicity allowed us to easily partition capabilities and maintains standard interfaces between the major components. This provided an environment where software integration between developers was quick and without major issues.

TEAM TESTING

The difference between success and failure in any fielded system is testing. This is especially true of unmanned systems when a human is not onboard to anticipate or recover from failure modes. The Urban Challenge required that each vehicle perform without human intervention for the six-hour final event. To ensure that our system could demonstrate all the required capabilities and operate without human intervention we adapted a standard practice used when reviewing proposals before submission called “Red Team.” The Red Team concept uses individuals who are not involved in the creation process to serve as impartial reviewers. Members of a Red Team adhere to a given set of requirements for evaluation and provide constructive feedback so those involved in the creation process can perform improvements before submission. Adapting this basic process to field testing, Red Team was made up of engineers from Lockheed Martin who were not involved in the design and development of the system and could serve as objective reviewers. These tests were in addition to the daily unit and system testing that the team performed and were designed to provide system-level performance validation by an external reviewer.

In the three months between the semi-finalist notification and the national qualifying event (NQE), eight Red Team tests were performed. As Table 4 illustrates, the tests focused on incremental capabilities.

Table 4. The Red Team test plan was a highly-compressed schedule that tested progressively complex behaviors.

Week of	Requirements Focus	General Requirements
2-Sep	Site Visit + Parking lot	Site visit + Parking lot
9-Sep	Everything previous + Zones	Site visit + Parking lot
14-Sep	Everything previous + Merge	Site visit + Merging
16-Sep	Everything previous + Merge	Site visit + Merging
23-Sep	Everything previous + Left into traffic +Traffic circle	Site visit + Merging
30-Sep	Everything previous + GPS outage + Road following	UFE
7-Oct	Everything previous + Traffic jam + Obstacle field + Dynamic re-planning	UFE
14-Oct	Everything previous + Emergency braking +Defensive driving	UFE

For each test, the Red Team would perform the following actions:

1. Identify and secure test locations with the necessary environmental features
2. Generate an RNDF of the site (sent to the development team 48 hours pre-test)

3. Create test missions in Mission Definition File (MDF) format based on the published DARPA requirements
4. Hire township police or make arrangements to handle safety concerns
5. Physically construct the course using cones, barrels, and obstacles
6. Perform the test and document the system performance.

The results of the Red Team test were sent to the development team to make improvements to the vehicle and software. Examples of the test procedure and the test report summary are included in Figure 6.

Type: Basic Navigation ☐ Basic Traffic ☐ Advanced Navigation ☐ Advanced Traffic ☒

Description: Vehicle merges with oncoming traffic

Requirements:

	Vehicle always merges into moving traffic when there is a delay of 10 seconds or more before the arrival of the next traffic-vehicle. Vehicle may pull into a gap of less than 10 seconds when conditions permit.

Pre-Conditions

Vehicle is running with MDF file loaded	☒

Test Procedures

The vehicle is set to begin/resume a mission	☒
The vehicle approaches a merge and stops	☒
The vehicle observes oncoming traffic and waits to go	☒
Once traffic is sufficiently spaced, it merges	☒

Success Criteria	**Pass**	**Fail**
The vehicle merges into oncoming traffic	☒	☐

Test	***P***	***F***	***Summary***
Preparation	☐	☒	Warning horn died. Power steering failed. Computers occasionally lose network for unknown reason.
Mission Start	☒	☐	
E-Stop	☒	☐	Not tested explicitly, but demonstratively working
Checkpoints	☒	☐	Followed checkpoints even when that meant driving into the grass
Stay in Lane	☐	☒	Sensors not detecting road, so if the GPS drifts it will drive right off the road without pause. Also has issues around turns with sparse waypoints
Speed Limit	☒	☐	
Excess Delay	☒	☐	
Right Turns	☒	☐	
Left Turns	☒	☐	Turn signal sometimes goes off before turning.
Collisions	☐	☒	Fails to avoid cones and a-frames when parking
Stop Line	☒	☐	Observably correct
Vehicle Separation	☒	☐	Got a little too close on some occasions

Figure 6. Sample Sections of the Red Team Test Procedure and Report

This process was perfect for the type of testing we required because the NQE and UFE were to be performed without any foreknowledge of the mission details and without the advantage of testing on the course. The Red Team used four locations to construct the courses for each evaluation so that the system would be exposed to various obstacles, road surfaces, GPS coverage, terrain elevation, etc. The Red Team function was a valuable component of the team's strategy for performing well in the Urban Challenge competition and allowed the team to confidently perform in an unknown environment.

Before the final event, the team continued its testing near the Urban Challenge environment. Figure 7 show a test setup on a lake bed near Victorville, CA. The test process used sample vehicles and obstacles in open desert areas. This allowed the algorithms to be tuned for the different environments that the Prius might encounter. This included updating small sensors used when backing up and sensors under the side mirrors that allowed the vehicle to perceive close obstacles during parking lot operations.

Figure 7. Desert Testing Environment

The Prius entered the final Urban Challenge event fourth after the NQE. Other than a few minor "close calls," the vehicle performed very well throughout the entire six hour 60 mile course, one of only six teams to complete the competition. The Prius was able to maneuver through interesting situations demonstrating an understanding of the rules of the road.

The most interesting part of each of the Urban Challenges was watching vehicle personalities. Little Ben was described as a cautious little bot. The vehicle was programmed with conservative algorithms. After the initial excitement of starting the challenge, the different vehicles settled into an almost boring drive through a neighborhood. After many pauses for other robots, the Prius came back to finish the challenge in just over six hours. Figure 8 shows the Prius finishing the event in fourth place. This was an exciting finish to a long road of development and testing.

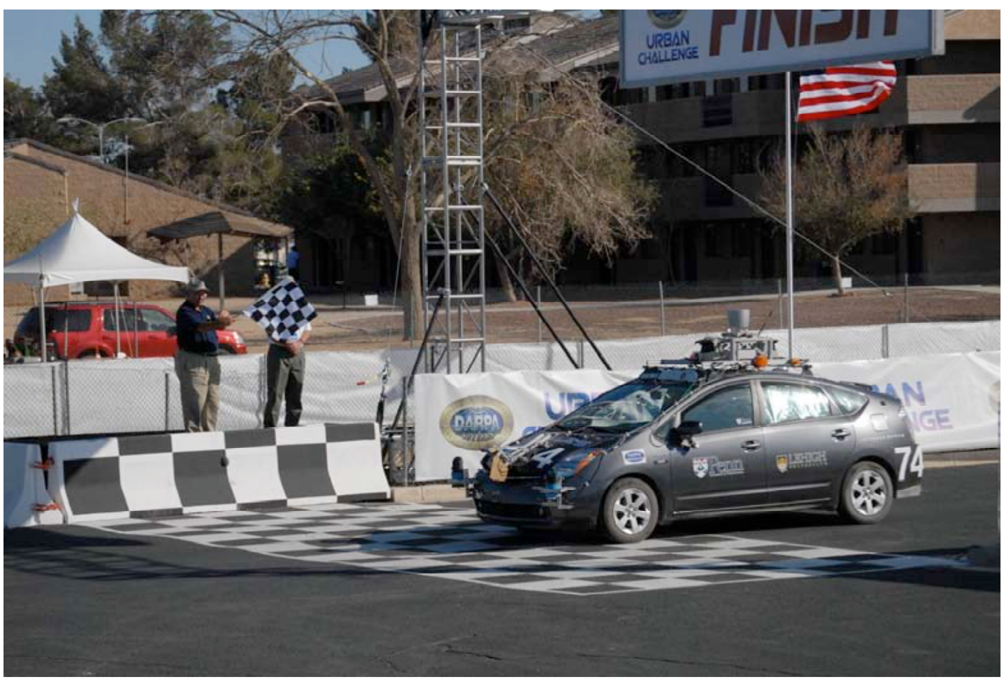

Figure 8. Vehicle Crossing the Finish Line Fourth

Post race analysis indicated that the sensors did well in perceiving the environment. There were several situations where the SICK lasers provided information outside the range of the

Velodyne. The rest of the sensors provided additional situational awareness in specific situations. Some of the tuned algorithms had the vehicle returning to lanes at slightly high angles causing some unexpected behavior. This created a few scary moments when the vehicle appeared to head towards a wall until the vehicle moved into a lane.

After the Urban Challenge event, the Prius ran additional tests in various environments such as unimproved roads, off-road and additional on road testing. As part of the follow-up testing, the Lockheed Martin team ran an autonomous “victory lap” along with the Carnegie Mellon and Stanford teams at the Long Beach Grand Prix. The only tweaking was the GPS denied areas that were much larger at the Grand Prix than the Urban Challenge. The Urban Challenge was run at an average 10-12 mph, the Grand Prix increased the average speeds over 18 mph with top speeds of 30 mph.

LESSONS LEARNED

One of the most interesting side aspects of the system was that the analysis and control algorithms fit onto a single computer. For redundancy and low CPU loading for the challenge, the processes were split onto four CPUs. For the follow on events, various configurations were used, resulting in a single laptop controlling the entire system. The Velodyne and GPS/IMU systems are needed for smooth operations and specialty sensors for different conditions. This configuration is different from previous models for the onboard processing needed for UGV operations.

We credit the success of the vehicle with our sensor and system wide testing. Setting up independent testing teams away from the development and support team provided defined metrics to keep the development on schedule. The test teams provided testing areas based both on the Urban Challenge rules, and interesting cases that required more diverse operations.

The final onboard sensor configuration was able to perceive and react to the different stimuli within the event environment. It was effective in assisting the vehicle maneuvering throughout the challenge. Future enhancements should include the ability to read and react to road signs, stop lights and finer road markings. Additional testing environments along with redundancy and more robust fail-over capabilities will bring this technology closer to mainstream vehicle mobility environments.

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