

# Ohio State University Experiences at the DARPA Challenges

**Keith A. Redmill, Umit Ozguner, Scott Biddlestone,  
Alex Hsieh, and John Martin**  
The Ohio State University

Copyright © 2008 SAE International

## ABSTRACT

The Ohio State University has fielded teams at all three of the DARPA Grand Challenge and DARPA Urban Challenge autonomous vehicle competitions, using three very different vehicle platforms. In this paper we present our experiences in these competitions, comparing and contrasting the different requirements, strategies, tasks, and vehicles developed for each challenge. We will discuss vehicle control and actuation, sensors, sensor interpretation, planning, behavior, and control generation. We will also discuss lessons learned from the engineering and implementation process for these three vehicles.

## INTRODUCTION

In July 2002, the Defense Advanced Research Projects Agency (DARPA) announced a Grand Challenge [1] for unmanned and autonomous off-road ground vehicle development. Vehicles and development teams were to be entirely self-funded. The vehicles should be able to navigate a course consisting of several hundred miles of off-road terrain in the desert southwest region of the United States, following a path defined by a series of waypoints unknown to the teams until immediately before the race and negotiating natural and manmade obstacles and terrain features without outside intervention. Once the race began, no contact or communication with the vehicle or its systems was allowed.

DARPA conducted the first Grand Challenge event in March 2004. The course, defined by over 2000 waypoints, would take the vehicle across approximately 150 miles, beginning at Barstow, California, and ending at Primm, Nevada. A prize of \$1 million (US) would be awarded to the fastest vehicle that completed the course in less than ten hours. Nobody won. In fact, the furthest distance traveled was 7.2 miles.

The second Grand Challenge event was held in October 2005. A 132-mile course, defined by almost 3000 waypoints beginning and ending at Primm, Nevada, traversed rocky trails, dry lakebeds, and mountain passes. This time, 5 teams finished the course (4 within

the allowed 10 hours) and the vehicle Stanley, developed by the Stanford Racing Team, took the \$2 million (US) prize by completing the course in 6 hours and 53 minutes with an average speed of 19.1 mph.

Unlike the Grand Challenges, the 2007 DARPA Urban Challenge was a race competition to design and implement a completely unmanned, autonomous automobile that can deal with a wide variety of mostly urban conditions and scenarios. Autonomous behavior generation occurred at much higher and more sophisticated levels than in the off-road Grand Challenges and required sensing and control that could detect and evaluate moving obstacles, understand road situations, plan and replan routes, obey California traffic laws and driving procedures, and deal with stop signs, vehicular traffic, and other obstructions. The DARPA Urban Challenge, although quite complex, did have fairly low speed limits, careful drivers and no traffic lights. Visual lane markings were unreliable, and thus true to life, and the terrain was fairly flat, although some areas were unpaved, generating an unusual amount of dust and creating problems for some sensors.

Successful implementation of a Grand Challenge autonomous vehicle involved a number of daunting requirements:

- Very accurate position and orientation localization, even with GPS blackouts
- Sensing of vehicle environment and state in a complicated, semi-structured environment
- Long term autonomy and vehicle control over an unknown course and terrain
- Long-term robustness of both hardware and software in a bumpy, dusty, hot, and occasionally wet environment
- Safe behavior and performance of the vehicle in the absence of an onboard human driver

- Completion of significant testing and validation efforts

For the 2004 Grand Challenge our team, a partnership with the Oshkosh Truck Corporation, developed Terramax'04 [2,3,4,5], an Oshkosh Truck Corporation Medium Tactical Vehicle Replacement (MTVR) 6-wheeled heavy duty vehicle, as our autonomous off-road vehicle entry. This vehicle is shown in Figure 1. Of 106 applicants, it traveled 6th furthest.



Figure 1: Team Terramax 2004 Challenge Vehicle

In 2005, our "Desert Buckeyes" team outfitted ION: the Intelligent Off-road Navigator [6], based on the much smaller but very robust and capable 6x6 Polaris Ranger utility vehicle shown in Figure 2. Of the 196 applicants, ION traveled 29 miles and 10<sup>th</sup> furthest.



Figure 2: 2005 Intelligent Offroad Navigator (ION)

In 2007, a 2006 Toyota Highlander Hybrid SUV, shown in Figure 3, was selected for automation as the Autonomous City Transporter (OSU-ACT) for the DARPA Urban Challenge [7]. The interior space available in the vehicle provides significant flexibility for

the mounting of processing, power, and control hardware, at the cost of only two additional feet of curb-to-curb turning circle diameter and 4 inches of additional width relative to an ordinary passenger sedan. The exterior has convenient hard points for mounting sensors or attaching mounting brackets. The hybrid vehicle technology provides a number of advantages for automated vehicle purposes. DC power for computers, electronics, and sensors can be derived directly from the vehicle's 280-volt battery pack using DC-DC converters and DC-AC inverters. The task of actuation is also significantly simplified since the vehicle employs electric actuators for its stock systems. The vehicle is inherently throttle-by-wire, as the division of electric motor vs. ICE power is dynamically controlled. Under normal operating conditions the vehicle is essentially brake-by-wire as well: the hydraulic master cylinder is isolated from the actual hydraulic brake system and driver requested braking torque, which is sensed using brake pedal position sensors and pressure sensors in the master cylinder-stroke simulator hydraulic circuit, is measured and then generated automatically through ECU control of regenerative braking and the electrically-operated hydraulic brake system. The transmission is controlled electronically as well, with the exception of the parking gear.



Figure 3: 2007 Autonomous City Transporter (OSU-ACT)

For each of these vehicles, we implemented drive-by-wire capability to control steering, throttle, brakes, and transmission. Various sensors, including GPS, inertial measurement units, multiple digital cameras and image processing systems, lidars, radars, and other sensors, were integrated. Additional electrical power generation, equipment enclosures and cooling, and safety systems were also implemented as needed for each vehicle.

## SYSTEM ARCHITECTURE

A generic functional architecture for an autonomous vehicle is given in Figure 4. Each block is, of course, tailored to the required functionality and degree of autonomy of the vehicle application. For even the simplest autonomous vehicle scenario, for example a

vehicle capable of driving autonomously in the highly controlled environment of an interstate highway, each of these subsystems would be required. The detailed architecture of our 2007 OSU-ACT vehicle is shown in Figure 5.

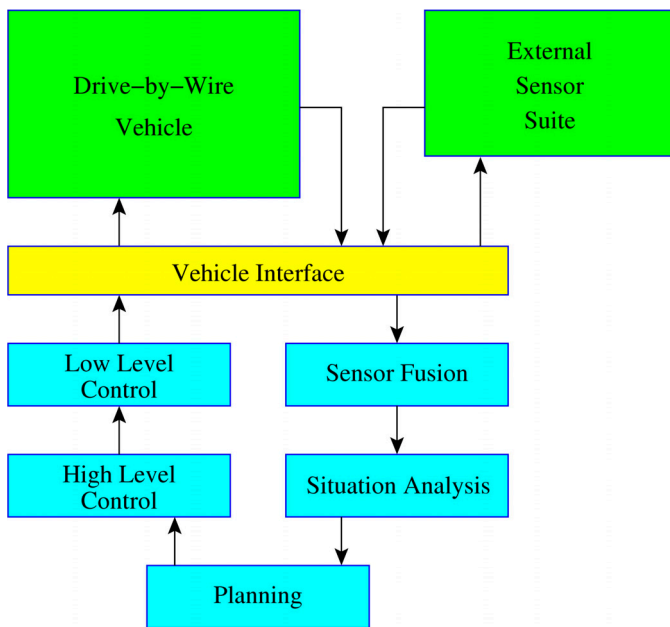


Figure 4: Generalized Autonomous Vehicle Architecture

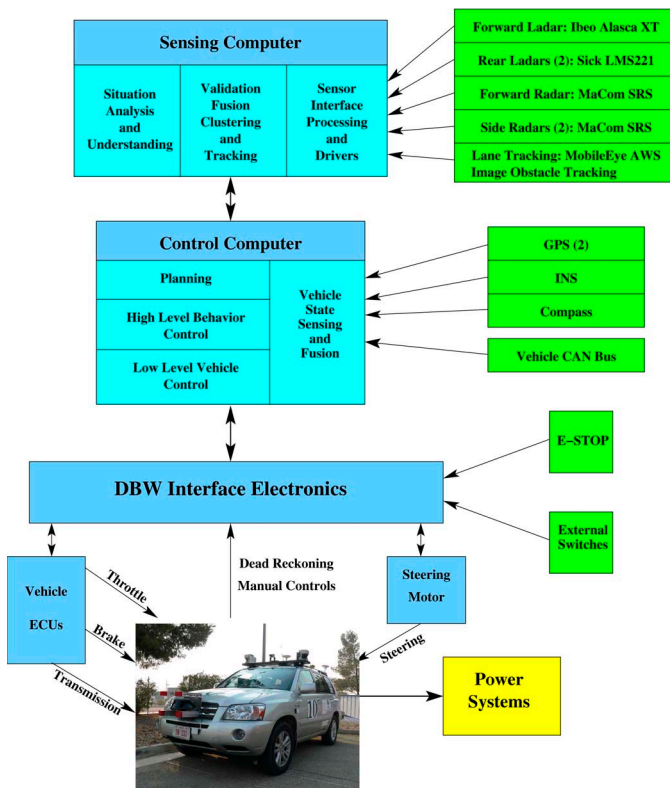


Figure 5: OSU-ACT Architecture

## PLANNING

Planning and path generation can take a number of forms depending on the required application. In the

Grand Challenges, a starting point, an ending point, and a single route between them were defined by a series of waypoints, latitude and longitude coordinates, along with a corridor width between each waypoint. The vehicle was free to travel anywhere in the corridor. There were no high-level decisions to be made. The desired path could be defined by fitting smooth spline functions through the waypoints, and deviations from this desired path were generated as a reaction to local sensing information.

For the Urban Challenge, however, the behavior was defined as an ordered series of goal locations the vehicle has to attain. The vehicle might start from any location, and the route had to be planned in real time over a map database defining the road network as well as parking lots (zones) and parking spaces. For this task, there were often multiple possible routes, and an optimal route had to be identified based on estimates of travel time. The planning software also required the capability to remember blocked or impassable roads so that, if an initial plan failed, a new path could be identified.

## HIGH LEVEL CONTROL

High-level control can be thought of as behavior generation and in our autonomous vehicles is expressed as a hierarchy of finite state machines. At the top level, overall families of behavior appear as independent state machines, which we designate as meta-states. The DARPA Grand Challenges of 2004 and 2005 were both off road races. As such, the only behavior and thus the only meta-state required would be path following with obstacle avoidance from point A to point B [8]. However, since there was no path or lane that could be discerned from a roadway, the only method of navigation is to rely on GPS and INS based vehicle localization [9] and a series of predefined waypoints. Obstacle avoidance techniques were needed, although in the less structured off-road scenario greater freedom of movement and deviations from the defined path were allowed. The Grand Challenge race rules ensured that there were no moving obstacles and different vehicles would not encounter each other in motion. General off-road driving would of course not have this constraint.

Fully autonomous urban driving introduces a significant number of new meta-states, situations where different behavior and different classes of decision need to be made [10]. Figure 6 shows the highest-level meta-state machine that defined the urban driving behavior of OSU-ACT. Each meta-state represents a sub-state machine. These state machines are too complicated to be legibly shown here.

In contrast to the off-road challenges, obstacle avoidance in urban situation presents a much more complicated array of options, including dodging maneuvers within the current lane, lane changes when there are multiple lanes traveling in the same direction, passing an obstacle in an oncoming traffic lane, or even