Technical Paper
DARPA Grand Challenge 2005

Team UCF

University of Central Florida
4000 Central Florida Blvd.
Orlando, FL 32816
Phone: 407 823-2341

Team Leader: Don Harper
harper@cs.ucf.edu

Team Members:
Dr. Kien Hua, Dr. Hassan Foroosh, Dr. Alexander Leonessa, Dr. Zhihua Qu, Don Harper, Remo Pillat, Dave Norvell, Saul Santiago, Theresa Collins, Gary Stein, Scott Stickler, Geoff Decker, Richard Andres, Yuping Shen, Hao Chen, Fei Xie

Abstract

Team UCF's entry into the DARPA Grand Challenge is based on a standard four wheel drive SUV; the Subaru Legacy Outback. This vehicle has a low center of gravity and is ideally suited for autonomous control where unexpected turns may cause stability problems. A common thread in the design of this vehicle is to allow the system to be easily adapted to other vehicles. To accomplish this goal, minimum modifications were made to the actual vehicle. An overriding design criteria is simplicity combined with redundancy. Redundant systems combined with health monitoring help to ensure that the vehicle will not arrive at unknown states.

1 INTRODUCTION

Our team is comprised of a group of graduate and undergraduate students with dedicated faculty advisors from various departments of the university. Although the team is centered in the College of Engineering and Computer Science at the University of Central Florida, the project has benefited from a high level of interest from the entire university community. As an example, the University Physical Plant has provided support in both automotive shop facilities and heavy machinery used to create test sites. As a multidisciplinary project, exciting new avenues of collaboration between departments have been created.

Figure 1: 2005 Grand Challenge Vehicle

2 VEHICLE DESCRIPTION

Team UCF chose to use a 1996 Subaru Outback Legacy model car as the vehicle of choice. The factors of this choice included price of the car, fuel efficiency, the ability of the car to handle off-road environments as well as to carry extreme loads in or behind the car, and overall reliability.

2.1 Off-Road Ability:

The 1996 Subaru Outback comes equipped with four wheel drive, 26 inch tires, a heavy duty suspension, and a ground clearance of 7.3 inches. To improve upon this design, the car's suspension was upgraded with a three inch lift kit along with heavy duty KYB-GR2 gas struts. The wheel size was also increased to 28 inch tires giving the car a new ground clearance of 10 inches. With the new suspension system, the car can easily cross berms, comfortably handle sand or rocks, and has the ability to pass through standing water. Skid plates were also installed in order to protect the differential and transmission from any loose debris that the car may encounter.

2.2 Fuel Efficiency:

With a fuel efficiency of 26 miles per gallon highway, and 20 miles per gallon city, the Subaru Outback is a logical choice. With a 15.9 gallon gas tank, of which 15 gallons is useable, the Outback is be able to travel a minimum of 300 miles on a single tank of gas with a vehicle weight of 3230 pounds. It should easily be able to complete the 175 mile course on a single tank of gas.

2.3 Performance:

The Subaru outback is equipped with a four cylinder Dual Overhead Cam 2.5 liter engine which can deliver 155 horsepower at 5600 revolutions per minute. This power, combined with the quality of the Subaru frame structure, allows it to easily carry all on-board components which have a weight of less than four adults.

2.4 Overall Reliability:

The Subaru reputation for off-road and commercial vehicles is a selling point on its own with Subaru recently making a name for itself in rally races. Team UCF concluded that Subaru, being one of the top competitors in off-road racing, would be an optimal choice for the DARPA Grand Challenge.

3 SYSTEM DESCRIPTION

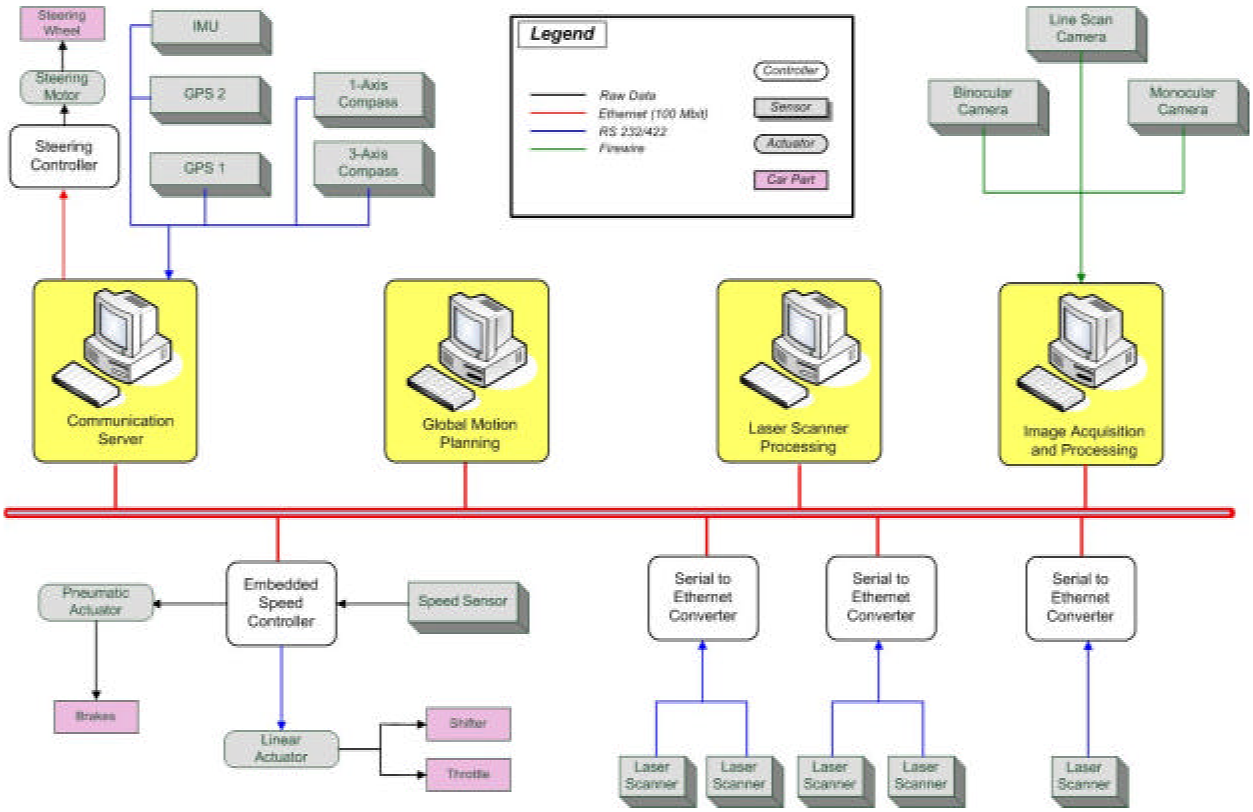

Figure 2: General System Architecture

Figure 2 shows the general system structure in functional blocks to illustrate the sensor-actuator-coupling. The connections between the blocks are colored according to the cable types used. In the next sections the emphasis is put on the most important subsystems.

3.1 Computer Systems:

Autonomous operations of our vehicle are run by four separate computers. Each of these computers consists of a 1.7 gigahertz Pentium M processor with one gigabyte of DDR memory supported by an AOpen motherboard. The Pentium M processors use dramatically less power than common desktop CPUs while maintaining the necessary processing power and are ideally suited for mobile applications. Each computer is running the GNU/Linux operating system Debian Sarge, which allows for full customization and easy interfacing to custom hardware. The choice of Linux also allows the use of a number of open source software packages that are targeted towards robotics. For ease of service, each system was made identical in both hardware and software to reduce complexity.

3.2 Sensors:

The platform's sensors consist of five laser scanners, one stereo vision camera, two GPS receivers, and two compasses.

The vehicle utilizes multiple laser scanners to provide obstacle detection and terrain mapping. Currently, there are four forward looking scanners that provide seamless coverage in front of the vehicle. The four forward scanners are mounted at key locations to best provide sensing for the different scenarios that will be encountered. The first scanner is mounted on the front bumper of the vehicle. The purpose of this scanner is to detect and avoid low immediate obstacles of sufficient height in front of the vehicle. Because obstacles need to be detected further away based on speed, the second, top-mounted scanner can be tilted under computer control. One disadvantage of this location is that hills or bumps may be seen as large obstacles. To overcome this issue, in a departure from the normal horizontal mounting, two of the scanners are mounted in the vertical direction on the sides of the vehicle. This orientation allows for instantaneous detection of the profile of the upcoming terrain and road following. Therefore any slopes or ditches can be characterized without using multiple scans. In addition, this orientation allows for detection of overhead objects for purposes of clearance and avoidance. In an information fusion step the data gained from the two side scanners is combined with that of the two forward looking horizontal scanners.

An additional scanner is mounted in the rear for use during reverse operations. It is mounted horizontally in the rear of the vehicle to scan for obstacles at low speed while reversing.

LOCATION	TYPE	SPEED	SCANNING RANGE	RESOLUTION
Vertical Right	SICK LMS291	25 Hz	90 Degrees	0.5 Degrees
Vertical Left	SICK LMS291	25 Hz	90 Degrees	0.5 Degrees
Horizontal Front	SICK LMS200	20 Hz	180 Degrees	0.5 Degrees
Horizontal Back	SICK LMS200	20 Hz	180 Degrees	0.5 Degrees
Tilted Top	SICK LMS221	20 Hz	180 Degrees	0.5 Degrees

Table 1: SICK Laser Range Finders

To provide an additional form of obstacle sensing and terrain mapping, a stereo vision camera is employed. The Videre STH-MDCS-VAR-C uses two Firewire cameras mounted on a fixed baseline. Because the custom cameras are synchronized, they supply two disparate images. When these images are correlated, they provide depth information. The system is mounted on the center top of the vehicle looking forward. Figure 3 shows the two cameras along with the water and dust shield.

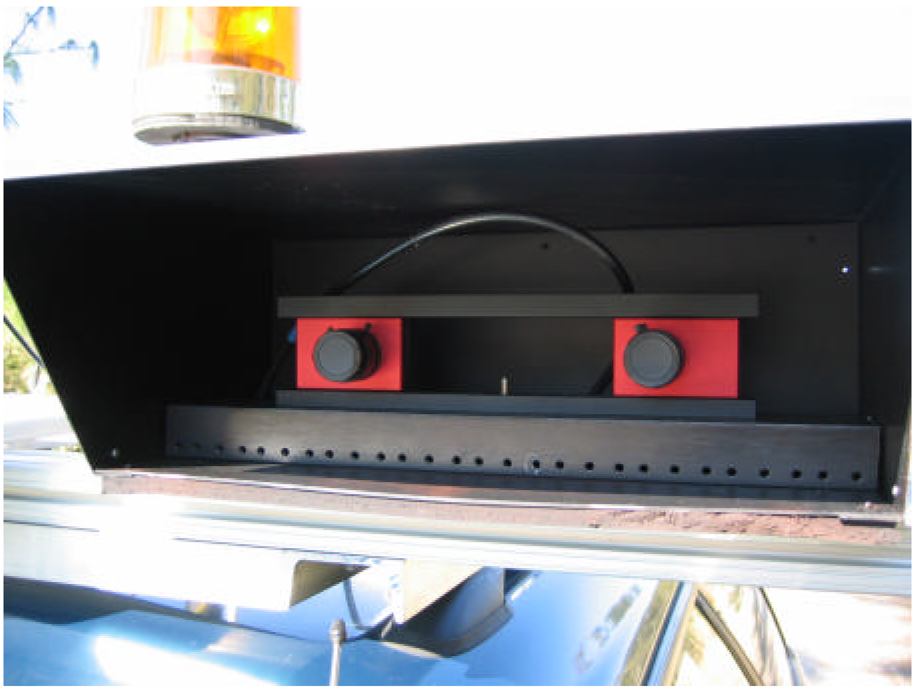

Figure 3: Stereo Camera

To complement the forward looking tilted laser scanner, which provides only depth, a line scan camera is used. The Baseler L104k provides a 2048 pixel line scan at 29.2 kHz. to provide the corresponding visual information for the terrain surface. When the visual information from the camera is combined with the distance information from the laser, a robust interpretation of the terrain can be derived. This single line technique, when combined with a moving vehicle, has greatly reduced the vision system's image processing requirement by reducing redundant data.

Two GPS receiver units are being used in tandem for greater accuracy and to provide instantaneous vehicle heading information. Each Navcom Starfire SF-2050Ms GPS receiver, when combined with the Starfire satellite differential service, provides 15 cm accuracy. The GPS antennas are strategically positioned over both the front and rear axles to provide optimum feedback for both the steering system and localization system. With the GPSs positioned at these locations, an instantaneous heading can be derived for the vehicle even while the vehicle is stationary.

Speed and distance sensing is accomplished by using the vehicle's built in anti-lock sensors present on each wheel. Each sensor produces a sinusoidal signal with a period proportional to the speed of each wheel. Using an embedded computer, both the timing and total pulse count are provided to the navigation computer. A redundant Hall Effect sensor is also mounted on the drive shaft as another measure of speed.

Finally, there are two magnetic compasses that help augment the heading information provided by the GPS. Both the KVH Azimuth 1000 digital compass and the Honeywell HMR 300 3-axis digital compass are accurate within half a degree in all axes. The pitch and roll of the 3-axis compass is used in vehicle sensing to help detect dangerous operations. Each compass is mounted at locations far from the main body of the vehicle to reduce magnetic disturbances.

3.3 Actuators:

The steering system is designed to allow full and accurate computer control of the vehicle steering wheel. Special attention was paid during design to allow a human driver to take control of the vehicle and override the actuator. Another design consideration was to make the steering actuator mechanically compliant to allow the wheel to move in response to the large loads transmitted from the ground during off-road conditions. The image in Figure 4 shows the large v-belt pulley attached to a brushless servo motor. An *Elmo Harmonica 12/60* digital servo drive is used to program the servo position.

Figure 4: Steering and Gear Shift Actuators

The vehicle's gear select mechanism is controlled using a linear motor. Both electrical and mechanical fail-safe systems are employed to prevent accidental shifting while the vehicle is in motion. Figure 4 shows a side view of the shifter from the driver's seat.

The main vehicle brake system is designed to allow both fail-safe autonomous operation along with the ability of a human driver to override the controller and apply the brakes while testing. A flexible cable is attached to the brake pedal and is used by the actuator to pull the brake in from the rear. Since the cable is flexible, a human driver is able to override and apply the brakes in any situation. To provide the fail-safe component, a large spring constantly pulls the brake in using the attached cable. A pneumatic cylinder, controlled by an electronic valve, is used to compress the spring and release the brakes. A loss of electrical power or a loss of air pressure will cause the pneumatic cylinder to release and apply the brakes. Figure 5 depicts the spring and the pneumatic cylinder, along with the control cable entering from the right.

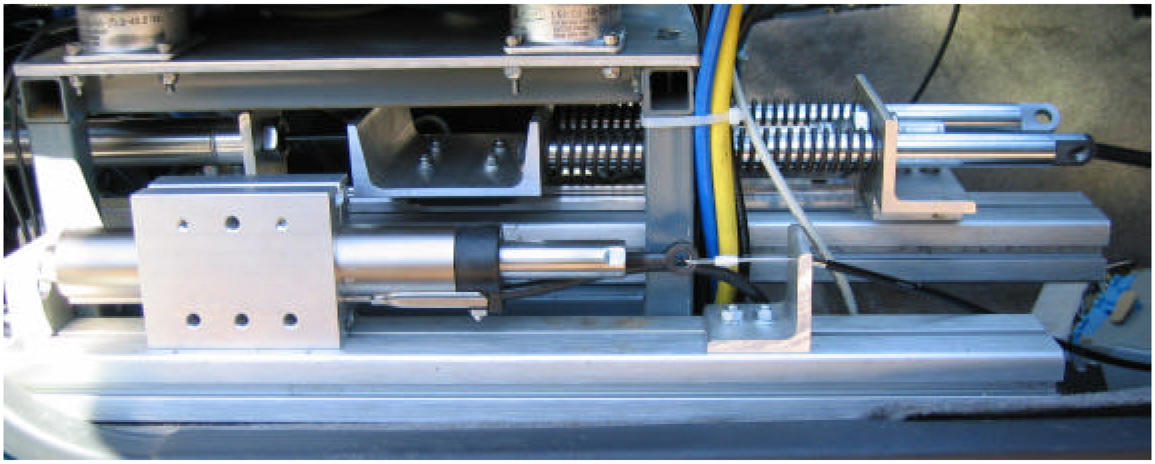

Figure 5: Brake and Throttle Actuators

The design of the throttle actuator also follows a similar fail-safe conscious approach. A steel control cable is attached at one end to a linear motor and at the other end to the vehicle's throttle control arm. This linear motor has the property that if power is lost, it will fully release all pressure on the throttle and allow a safe return to the idle state. The LinMot P01-37x120 is an electromagnetic direct linear motor with integrated position sensing, containing no physical gears.

3.4 Health Monitoring:

In an autonomously operating vehicle, monitoring of the internal health is important to ensure the safety of the vehicle. The Subaru Outback is equipped with a standard ODB-II sensor network which provides a wealth of information such as: engine RPM, coolant temperature, oil pressure, and other important information on the state of the vehicle.

In addition, a completely separate sensor system was developed to oversee the vehicle operations. This low level system operates independently and provides checks to ensure the safety of the vehicle and override possible errors in the more complicated high level system. As an example, this system will physically prevent improper shifting while the vehicle is in motion to protect the transmission. Another example is that the system will also independently monitor the forward laser scanner and will avoid a potential collision with obstacles.

3.5 Power System:

There are two separate power systems employed in order to meet the various power requirement of the different systems in the vehicle. The main DC voltage system must supply clean DC voltage at 5, 12, 24, 36, and 48 volts as needed by the many sensors and actuators. This system consists of four deep cycle marine gel cell batteries that are combined in series and are charged automatically using a 48 volt alternator.

To provide the AC 120 volt power required by the computer systems, a 2000 watt true sine wave inverter from BLANK provides clean noise free power at high efficiency. This inverter is powered off of the vehicles stock alternator during operation. A transfer switch is used to change the computer system to wall power after testing without requiring the restarting of machines.

DEVICE	**POWER CONSUMPTION IN WATTS**
Sick Laser Range Finder (5)	5
Steering Servo	200
Throttle Linear Actuator	90
Servers (4)	500
Compass (2)	2
Cameras (3)	10
GPS (2)	4
Safety Light	10
Total Consumption (Watts)	821

Table 2: Power Consumption

4 AUTONOMOUS OPERATIONS

The overall software and processing structure is depicted in Figure 6.

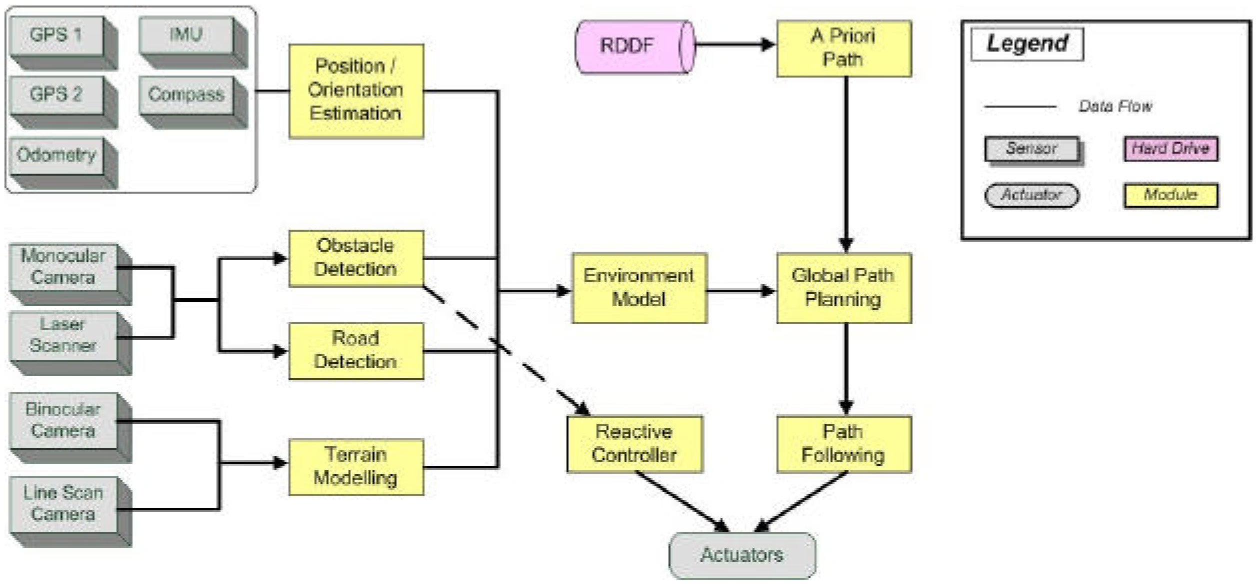

Figure 6: Software Architecture

These software modules allow for an autonomous operation of the car. In the following sections, the most important aspects are generally covered.

4.1 Localization:

To perform localization of the vehicle, the GPS information is augmented by additional readings from the compass, IMU, and odometry sensors. Sensor fusion is accomplished through the use of an Extended Kalman Filter. The GPS is used as the main source of position information, however, during outages the Kalman Filter will continue to provide a stable estimation by using the remaining sensors and the vehicle dynamics. No specific a priori map knowledge was introduced into the navigation system other than the automatic preprocessing of the RDDF file.

4.2 Obstacle Detection

The main sensors used for obstacle detection are the laser scanners and the cameras. After the initial filtering of the raw laser measurements, geometric primitives are fitted to the data. These shapes are tracked over successive readings via scan matching and the determined obstacles are introduced into the environment model. Furthermore, the color cameras are used to perform detection of anomalous objects in the environment. This includes man-made obstacles, water hazards, and negative terrain.

4.3 Lane Detection

The lane detection is performed through a combination of the readings of the forward tilted laser scanner and the line scanning camera. The laser scanner is able to detect the edges of the road, whether they appear as curbs or drop offs. The line scanning camera is able to detect color gradient differences in front of the vehicle. These differences include man-made painted lines and the difference between a dirt road and the surrounding terrain. Through the means of a line finding algorithm, the road can be robustly detected and projected into the environment grid.

4.4 Path Planning

By gathering all the information collected from the other processing modules, the path planner generates a continuous curvature path that considers the physical constraints of the vehicle. In case of obstacles detected in the proximity of the path, a re-planning module ensures safe passage through the environment. When a route cannot be detected in the forward direction based on the car's kinematics, the path planner is able to retrace the previous taken path in the backward direction in order to make a reevaluation at decision points. A decision point is created when several possible paths around an obstacle are equally weighted, but only one can be chosen based on the current information.

4.5 Path Following

The path following incorporates the current state of the vehicle versus the preplanned path. A dynamic "follow the carrot" control algorithm based on PID controller and the current speed of the vehicle is used. This dynamic mode is able to deal with different path curvatures and vehicle speeds to guarantee path convergence.

5 SYSTEM TESTS

5.1 Testing Strategy

To reflect the difficulties of the National Qualification Event and the Grand Challenge route, a test site was created on a remote location of the university. Different subsections were developed to model various conditions encountered in the desert. This includes hills, water hazards, natural and man-made obstacles, S-turns, switchbacks and several road surfaces.

The algorithms of the vehicle were developed and tested based on this course.

5.2 Testing Results

Due to the frequent daily rains and thunderstorms in Florida, it was difficult to simulate the dry desert conditions. Sensors became obscured with mud and the wet terrain posed a problem to the car control. One key challenge encountered is the concern of lightning during testing possibly damaging the top-mounted sensor rack or injuring team members.

The testing site provided a wealth of testing opportunities for both the vehicle's as well as the software systems. Extended testing runs were performed to ensure the reliability and robustness of the subsystems. During the tests, numerous faults were identified and corrected.

Testing continues to be one of the biggest hurdles due to the given timing constraints and the varying weather conditions.