DARPA Grand Challenge 2005

Team ENSCO's DEXTER

Gary A. Carr
Team ENSCO Leader
Carr.gary@ENSCO.com

Brian Mee
Co-Team Leader
Mee.brian@ENSCO.com

Abstract

This paper describes the approach that Team ENSCO took to develop a vehicle for the 2005 DARPA Grand Challenge. Our goals were to develop a vehicle that is quick, agile and stable that could handle the very rough desert terrain, develop a sensor array that contains redundancy for accuracy and reliability, develop a software package that was flexible and efficient, and a computer architecture that was rugged and expandable. Team ENSCO incorporated a series of innovative guidance and vision technologies on a lightweight highly flexible all-terrain desert racing vehicle to meet the Grand Challenge requirements.

1 Introduction & Background

Team ENSCO's vehicle is designated as DEXTER; derived from dexterous, meaning having mental skill or adroitness, and dexterity, meaning readiness and grace in physical activity. DEXTER travels at speeds up to 60 mph over rough terrain being guided by a custom navigation system utilizing inertial and DGPS technologies. Obstacle avoidance is achieved using LIDAR, Millimeter Wave Radar, and Stereo Vision Camera systems. The results of this effort are a vehicle fully capable of successfully competing in the DARPA Grand Challenge.

Team ENSCO is a volunteer group of highly qualified ENSCO's engineers that specialize in the development of innovative technologies. They are joined by friends of ENSCO employees and students from Thomas Jefferson High School of Science and Technology. The team is sponsored by ENSCO, Inc., which provides engineering, science and advanced technology solutions for the defense, security, transportation, environment, aerospace, and intelligent automation industries. Founded in 1969, ENSCO is an $85 million, approximately 700-person privately-owned corporation headquartered in Falls Church Virginia.

2 Vehicle Description

2.1 Chassis

The main goal of selecting a vehicle was to choose a vehicle that could handle the rough desert terrain with good handling characteristics, and acceptable acceleration performance while supplying a stable platform for the obstacle detection sensor array. This approach eliminates the need for complex gimbals and/or shock suppression suspensions for the sensor array. The major disadvantage of this approach is that the sensors look in a fixed direction requiring multiple sensors to cover the same zone that a single sensor could handle if it was gimbaled and pointed at the appropriate heading. The team researched several commercial trucks, military vehicles, and desert race vehicles before deciding on a custom-made chassis meeting all of our derived requirements. The vehicle developed is shown in Figure 1.

Figure 1. Custom Chassis selected for Grand Challenge Vehicle

2.2 Suspension, Tires, & Engine

This vehicle utilizes an 18 inch travel suspension in the front and a 22 inch travel in the rear. This is standard desert race technology allowing significant wheel motion under very rough terrain while reducing the motion of the vehicle frame. A concerted effort was put into the selection of the suspension components and tires to minimize unsprung weight and therefore minimize chassis motion during tire impact. The suspension links are lightweight and the wheel and tire combinations are the largest and lightest available on the market today. Bead lock wheels with inner-tubes where selected to minimize the risk of tire failure. Runflat or foam filled technologies were rejected owing to the additional unsprung weight of 60-100 lbs per tire. The tread design with rounded edges was chosen to improve handling and allowing tire slide in a turn instead of catching an edge and possible causing the vehicle to rollover. It has 4-wheel drive with an automatic transmission and a 4 cylinder aluminum supercharged engine. This off-the-shelf engine was chosen to decrease the weight and simplify the vehicle while maintaining a weight to power ratio around 10 lbs per horsepower.

The fuel tank is a 32 gallons Fuel Safe racing cell that has a bladder and is foam filled to prevent spill or an explosion in case of tank punctures. In addition, the tank is guarded with frame supports and skid plates to minimize the risk of tank puncture. The electric fuel pump is directly controlled by the E-Stop Disable relay. Upon activation of the disable relay, the power to the fuel pump is disconnected.

The brake system is designed as a fail-safe system. If power is disconnected from the robot while in motion, due to a wire or connection failure, the spring loaded brake applies full braking to the vehicle. If the ESTOP goes into disable, full braking power is applied to the brake pump stopping the vehicle.

3 Autonomous Operations

3.1 Processing

The computational hardware consists of seven computers including a National Instruments PXI, a National Instruments CompactRIO, four MINI ITX Pentium 4 computers, and a single Pentium 4 extreme edition 3.73 GHz computer that uses hyperthread technology for the stereo camera.

Fundamental vehicle controls are managed by the embedded CompactRIO system. This system is a programable FPGA automation controller that combines an open embedded architecture with small size, extreme ruggedness, and hot-swappable industrial I/O modules. This computer controls the throttle position, engine RPM, steering position, shifter position, and variable brake control all utilizing Labview Realtime software. This controller is directly linked to two external systems, the remote control for moving the vehicle when autonomous opertaion is not engaged, and the National Instruments PXI when running autonomously.

The National Instruments PXI (PCI eXtensions for Instrumentation) is a rugged PC-based platform for measurement and automation systems. On this robot, the PXI utilizes a real-time controller with ethernet connection, motion control card for the steering, an analog DAQ card for position feedback, DIO card for system timing, and a relay card for running lights and siren. The PXI is running Labview real-time and operates the fuzzy logic integrated throttle and brake control, pause and run control sequences, DGPS aquisistion and broadcasting, GPS point following algorithims, and internal path overlay indexing.

The MINI ITX computers run the path planning and sensor data aquisisition (DAQ). One Windows based computer is dedicated to RADAR DAQ and preprocessing. Another Windows based computer is dedicated to the path planning. The path planner computer aquires INS information, road centers, and the obstacles from the computers that interface with the sensors, plans the an appropriate path and sends the path to the PXI controller to be followed. This communication to the PXI uses an isolated network to minimize packet loss between the path planner and PXI controller. Two LINUX based computers are used to aquire the LIDAR data and preprocess that data into confident obstacles and road centers which are communicated to the path planning computer. That computer also preprocesses data from the road following LIDAR to send “center of the road” messages to the path planner. An additional process on these computers is the distributed mapping system that collects the obstacles from all the preprocessors and assembles a map that is used by the path planner. A second LINUX based computer reads navigation data from the INS and distributes navigation data to all of the other computers on both networks.

The highspeed Pentium 4 extreme edition 3.73 GHz computer is Windows based and runs the stereo camera system. It collects the data from the cameras, preprocesses the data into defined obstacles and sends the obstacles over the network to the path planner and distributed map.

3.2 System Architecture

The fundamental control system is based on GPS point following. The real-time vehicle controller receives a vehicle location and dynamic state message from the inertial system and the navigation computer. The real-time control determines which message it will use to drive the robot. A “heartbeat” is present with navigation computer. If the heartbeat stops, the real-time controller shifts to the raw inertial system message. This prevents the robot from losing guidance if the network slows down or the navigation computer locks up. The real time computer does the fundamental global position point following with a “best estimated path (BEP)” that is calculated beforehand using HANSEL. This program currently interpolates between the large GPS increments provided in the RDDF file. This algorithm’s purpose is to generate points at increments that the GPS follower could follow even without a path planner active. Other functions of HANSEL to adjust the points based on image processing were planned but not completed. Significant errors existed in the available GIS maps that placed the robot off course even when the points were centered in the roadway. A decision was made to not continue unless improved maps were available. Figure 2 is a functional block diagram of DEXTER’s system architecture.

The path planner also receives this BEP and utilizes it to drive the robot, compute drivable paths, and adjust speeds. The external sensors provide the information to deviate from the BEP. The primary sensor for this adjustment is the road following LIDAR system. Path planner receives “center of the road” messages from the road follower. Based on current position, route boundaries, and operating speed, the path planner decides to follow adjust the path onto the center of the road or use the BEP. This is done using a proprietary real-time path overlaying technique that can adjust the path in the real-time controller while moving at speed. This same technique is used to take evasive action when obstacles are located within the BEP.

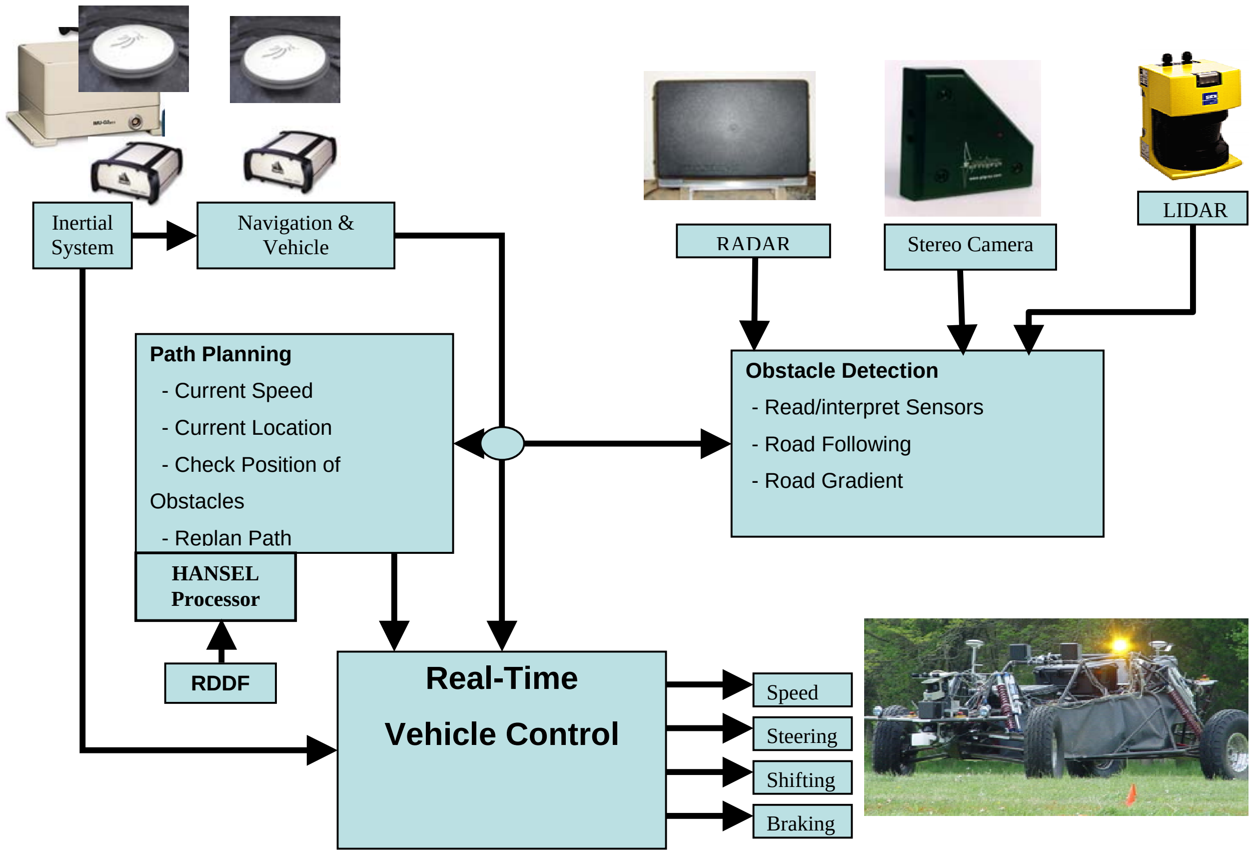

Figure 2. Functional Block Diagram of DEXTER

Each obstacle detection component is an independent system. The RADAR system, for example, preprocesses the data to locate obstacles in the vehicle path. It receives broadcast messages from the vehicle location navigation computer to determine a global position of the obstacle. Based on a confidence of the obstacle, the RADAR computer broadcasts the obstacle parameters including position in both local and global coordinates along with obstacle size to the path planner map. Each obstacle detection sensor follows the same process. A failure of any individual sensor results in no information being broadcast from that specific sensor. Each sensor computer filters the data by comparing the data from other sensors of the same type which provides true positive obstacles to the path planner. Plans are in place to compare obstacles from all sensors as another means of distinguishing false obstacles from true obstacles, but might not be completed in time. Determining the most effective criteria for distinguishing between real obstacles and false reports has proven to be very difficult. Additionally, small variations in the car’s pose can result in very large errors in the positions of distant obstacles, even if inertial data is considered. Terrain features also complicate the analysis of detection.

3.3 Development Process

A variation of Extreme Programming was utilized to develop the majority of the software. A rough architecture was initially sketched out, but the details of the various implementations were left somewhat vague. A core set of classes were developed and ported to all operating systems. Hardware and software architectures were enumerated, as many of the sensors have very specific hardware requirements. A communications layer was developed, and then the individual applications were developed in parallel with simulators and other proprietary testing tools. Code reviews were performed, and large discussions were held before refactoring certain experimental algorithms. A very large emphasis was placed on using well-known design patterns and STL libraries.

A primary development process for the software was to develop a simulator using the actual real-time PXI controller software. Since the real-time modules are the same ones that run the robot, any conflicts or errors would be immediately evident in the simulation. The simulator estimates where the vehicle position would be based on the commands sent instead of reading its position from a GPS device, but is otherwise identical to the software on the robot. This facilitates testing and optimization of the complex interaction between the path planner and PXI without the need to operate the vehicle.

In addition, a software program called HANSEL was developed for viewing the GPS data on satellite image maps. This program has evolved into a very significant part of the system diagnostics program. All the time stamped obstacle data, planned path data, and actual traveled path are plotted on the map. This map shows when the vehicle saw the obstacle, when the new path was sent to the controller, and the final result of the vehicle motion all represented in global position and time. Each obstacle is color coded to indicate which sensor saw which obstacle and where it was located relative to the vehicle.

3.4 Localization

Team ENSCO has developed a system that combines two Novatel Pro-Pack LB dual frequency (L1/L2) GPS receivers and NovAtel’s SPAN™ (Synchronized Position Attitude

Navigation) Technology. This system combines GPS and inertial functionality to provide uninterrupted operation with highly accurate position and attitude measurements. It is augmented with Differential Global Positioning System (DGPS) receivers to provide corrections when in coverage. The system can provide high accuracy position (10cm) and heading at operating speeds of 20 Hz

The primary source of position and attitude data is the INS portion of the NovAtel SPAN™ system. In motion, the SPAN system provides location information at a 20-Hz rate by combining DGPS and inertial data from an internal Honeywell HG-1700 tactical-grade IMU. The DGPS source used is the Omnistar HP™ proprietary broadcast. The Pro-Pack LB automatically provides for degraded DGPS capabilities from HP to regular Omnistar DGPS, to WAAS, and finally to non-augmented dual-frequency GPS if no geostationary satellites are in view with sufficient SNR. The INS portion of the Pro-Pack LB allows for smoothing of GPS data and dead reckoning with inertial data for short periods of time such as in tunnels or areas of GPS blockage.

When stopped for long periods of time the INS heading will drift. The SPAN system automatically conducts periodic zero velocity updates when at rest, but it cannot constrain heading. At the same time the GPS position will dither and GPS heading will experience large variations. To avoid problems with navigation, steering commands, and map functions, a means of constraining the heading when stopped was needed. The team developed a system using the additional NovaTel Pro-Pack LB dual frequency GPS receiver to help constrain heading when stationary. An algorithm calculates the vector between the two GPS antennas located on the vehicle. At the same time it calculates the distance between them. If the distance is within close tolerances of the actual distance tests have shown that the resulting calculated heading of the vector between the GPS antennas remains within a few degrees of the correct value. This eliminates the effects of multipath as well as the basic GPS uncertainties. The second GPS unit also provides redundancy in case of failure of the primary GPS or at times when the primary GPS antenna is experiencing high levels of blockage.

Team ENSCO's vehicle can navigate within the 10 ft boundary with DGPS alone if the signal is available and with multi sensor fusion in the INS without DGPS. Where there are true hard boundaries such as tunnels, the road following LIDAR system is capable of centering the vehicle within the boundary.

The route boundaries are considered hard obstacles boundaries that must be avoided. They are input to the reactive route route-planning algorithm as described in the processing section. If the robot is started outside the established route, it limits the speed to 7mph or lower and proceeds directly toward the closest point within the route boundary. Routes can overlap, they are followed in order except during a restart of the planning software.

3.5 Use of Map Data

The RDDF and the BEP are the only map inputs used. The sensor conditioning software and the path planner have internal map structures, but they are not prepopulated or in global coordinates. Satellite images are used in HANSEL for triaging problems after a run, but they are neither necessary for pre-planning. Elevation data was considered, but not used.

3.6 ESTOP Control Function

The ESTOP system is completely integrated into the central system. The E-stop triggers an electrical relay that cuts the power to the brake deactivator. The spring-loaded brake applies automatically. The estimated stopping distance under disable emergency stop at a the top speed of 60 mph is less than 175 ft from signal to final stop.

The manual DISABLE buttons cut the power to the brake deactivator. The spring-loaded brake will apply automatically. The main engine power is disconnected and the engine control module is grounded causing the engine to stop completely. This will prevent any unexpected movements.

To move the vehicle, an emergency brake manual deactivation knob on the outside of the vehicle can be turned which will release the brakes. A manual brake lever is available if the vehicle starts to roll. In addition, the gear shift switch is available to put the vehicle in PARK if necessary.

3.7 Sensors and Mounting

There are three fundamental zones of interest in front of our vehicle, long range (400ft), mid range (200ft), and instantaneous (40ft). A simplified schematic of the sensor array is shown in Figure 3. Each of these zones is covered by the set of sensors shown in Table 1.

Sensor	Region			Field of View
	Instantaneous	Mid Range	Long Range	
	X < 40 ft	40 ft< X <200 ft	200 ft > X	
Stereo Camera	X	X		43 Deg
LIDAR	X	X		180 Deg
Millimeter Wave Radar		X	X	12 Deg
DGPS/INS	X	X	X	N/A

Table 1. Sensor Allocations

The sensors were chosen to enhance both high speed and low speed navigation. The RADAR is not susceptible to dust/mud interference or lighting conditions and has the longest range. Since its error in location of the obstacle is large, it is only used to slow the vehicle if an obstacle is present in the planned path. Obstacle data from all three sensor types is sent to the path planner both geolocated and in local coordinates. The path planner will react to obstacles within the instantaneous zone regardless of their global position. It does this by adjusting the currently computed plan (in global coordinates) by some amount calculated from the local coordinate of the obstacle and sending the adjustment to the PXI, who follows the points. If there is an obstacle in the instantaneous zone that is sufficiently close, the path planner will direct the car to stop. The actual global positioning and sizing of the obstacle is done with the LIDAR and Stereo Cameras.

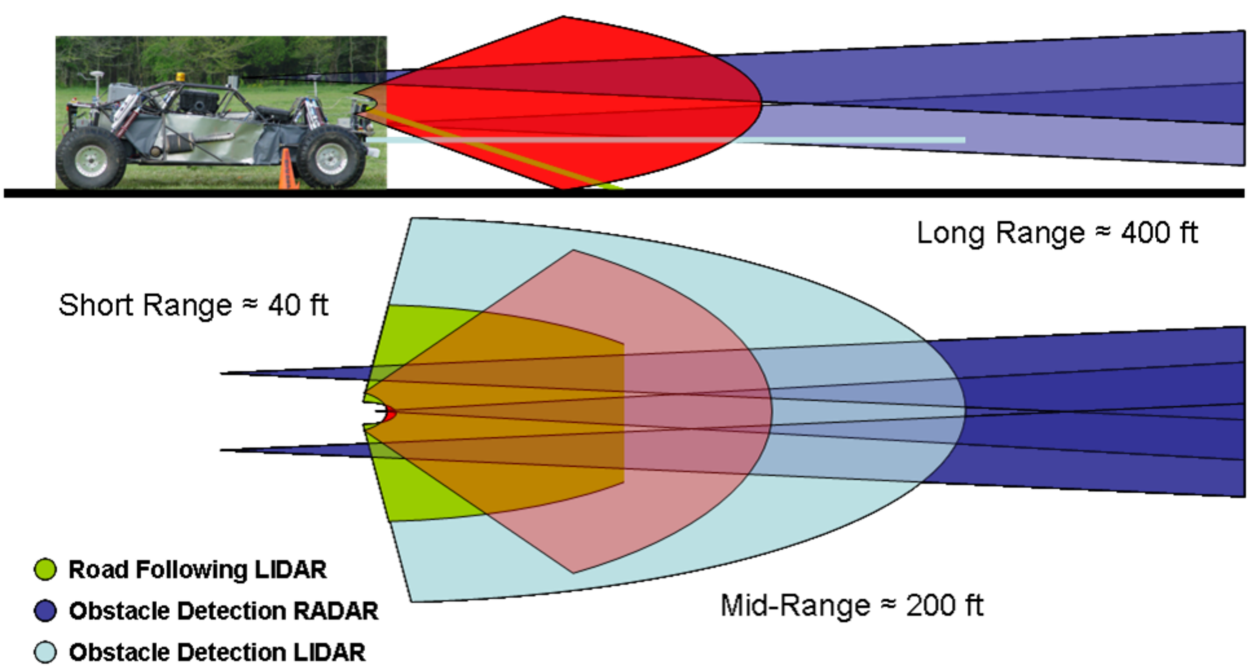

Figure 3. Sensor Arrangement and Range

3.7.1 Sensing Architecture

Data from each of the sensors is filtered first by comparing it to data from other sensors of the same type. A second level of filtering compares the obstacle data from all three types of sensors. Obstacle data that is confirmed by multiple sensors is sent to the path planner's decimeter grid map for obstacle avoidance planning.

3.7.2 Internal Sensing System

The SPAN system is the primary sensor for the vehicle state. The speed, location, attitudes, accelerations, and rates from this system are used by the processes in the PXI real time controller and the other computers. There are additional sensors for steering position, wheel tachometer, throttle position, engine RPM and other parameters.

3.7.3 Sensors and Vehicle Control

The speed throughout the course is computed by the path planner. Braking zones, curvature of the path, density of obstacles, and other considerations are used. The speed is part of the path communicated to the PXI controller. The actual speed of the vehicle is managed by a real-time fuzzy logic controller. This ENSCO developed controller manages both the brake and the throttle position. The vehicle state message tells the controller what speed the vehicle is running. The path planner commands what speed is needed to conduct a maneuver. The controller meets the required speed. In the case of going down hill, the controller will apply the brakes to maintain the required speed. During testing of the system on the JOUSTER offroad race course, where there are significant continuous down grades with curves, the vehicle maintained control of the speed within 1 mph of the requested speed, even at speeds as slow as 5 MPH and up to 45 MPH. Since the path planner has advance knowledge of the curves that are approaching, it incorporates enough braking distance to assure correct corner entrance speed.

The required braking distance is defined by the path planner which utilizes the known performance of the braking system assuming a minimum tire friction available. The curving speed is also defined by the path planner. It assumes a maximum lateral acceleration allowed and defines the speed required to meet that acceleration. This is to minimize the rollover risk. Both the curving and braking parameters are very conservative. The vehicle can successfully navigate nearly twice the acceleration that is defined by the estimate. The path planner sends segments of intermediate GPS points between the RDDF points. If there is no viable path, the path planner can send a message for the car to stop. Otherwise, the intermediate points are adjusted around obstacles or toward the road center. Once adjusted, the relevant segments are resent to the PXI. The path planning and obstacle avoidance systems have no direct control over any aspect of the hardware.

3.8 Vehicle Control

3.8.1 Autonomous Operation

The path planner controls the motion of the vehicle by sending interpolated GPS waypoints between the points defined by the RDDF to the real-time controller. If the planner determines the vehicle is outside the defined lateral boundaries, the vehicle stops and replans a course back on path close to the point where it left the course boundary and redefines the speed profile not to exceed 7 MPH until back on path. The real-time controller is keeping track of the current position and the interpolated points it is trying to meet. If it misses an interpolated waypoint it will continue to the next interpolated waypoint. If the vehicle becomes stuck against an obstruction, the path planner will direct the real-time controller to back up away from the obstacle. When an obstacle is detected in the upcoming path, the path planner plans an avoidance maneuver and sends the revised path to the real-time controller.

3.8.2 Autonomous Maneuvers

Braking is controlled as part of the overall speed control loop. Combinations of throttle and braking force are used as necessary to maintain a commanded speed. This system compensates for variations in slope or other terrain features such as surface friction, water drag, etc. If the vehicle is put into pause mode on a hill, the emergency brake is set and the vehicle remains in drive at idle. When the ESTOP commands to run, a startup sequence is initiated which require full application of the service brakes, removal of the emergency brake, and the path planner speed is defined. This prevents the vehicle from rolling backwards upon startup. In a tight turn, that is beyond the limit of the turning radius or if an obstacle prevents continued motion, the vehicle has a reverse reset function. It can reverse straight, reverse left, and reverse right. The path planner defines based on the obstacle position which way to reverse.

3.8.3 Integration of Navigation and sensing information.

All navigation and obstacle avoidance is planned in geo-referenced coordinates, except for reflexive stopping for close obstacles, which is performed in local coordinates. Refer to 3.1.2 for details.

3.8.4 Non-autonomous Operation

The vehicle is operated by a FUTABA DIGITAL T3PKM remote control system. This is used only for start-up of the engine and moving the vehicle around when not in autonomous mode. The system runs the throttle, steering, and brake. The ESTOP disable function is fully operating when in remote control mode. The ESTOP must be turned on and remain in override/Run mode for the R/C to function. A manual switch on the vehicle is used to shift the gears from neutral to forward or reverse. The receiver on the vehicle is removable by undoing a single connector and removing the receiver box with antenna. Standard procedure is to remove this receiver box prior to autonomous operation. Its removal can be visually confirmed by DARPA observers during NQE and Grand Challenge events.

3.9 System Tests

3.9.1 Testing Strategy

Team ENSCO's vehicle has been thoroughly tested in many different environments. A mockup of last years QID was constructed on a farm (site visit location) to test path following, high speed navigation, and obstacle avoidance. During the development of this system we have endured many failures. Countless hours have been used investigating computer failures/corruptions, network failures, electrical issues, and a few mechanical failures. This experience has led to redesign of some components of the vehicle, improved cooling for computers, and knowledge of critical spare parts to have on hand.

Team ENSCO took advantage of the opportunity provided by DARPA to utilize the JOUSTER site at the Virginia International Raceway (VIR). The test allowed for continuous operation of the vehicle at many speeds and configurations. A tremendous amount of water was present at the test site which showed us that the waterproofing techniques we using were insufficient to protect the computers. A motion control card failure stopped testing for nearly an entire day. The JOUSTER site provided additional terrain features not found on ENSCO's normal test site. Additional testing is planned on hard surface pavement such as that found at the NQE site.

3.10 Key Challenges and Insights

3.10.1 False Obstacles

Determining the most effective criteria for distinguishing between real obstacles and false reports has proven to be very difficult. Additionally, small variations in the car's pose can result in very large errors in the positions of distant obstacles, even if inertial data is considered. Terrain features also complicate the analysis of detection.

3.10.2 Open source Simulation Environment

Team ENSCO attempted to implement an open source robotic simulation environment to assist in the evaluation of the code prior to running on the robot. This proved to be ineffective since the overhead of the open source package swamped the limited computational resources available for real-time operation. Therefore, the real-time code had to be redone outside the open source environment. The final solution was to develop a simulator utilizing the Team ENSCO developed real-time code. The simulator estimates where the vehicle position would be based on the commands sent instead of reading its position from a GPS device, but is otherwise identical to the software on the robot.

3.10.3 Chassis Selection

The time spent in chassis specification and selection has paid off in safe reliable operation of DEXTER on a variety of surfaces and at speeds and turning radiuses not achievable by either our previous Grand Challenge vehicle DAVID, or by conventional SUV or pickup trucks. The suspension response is benign enough to eliminate the need for active control of sensors, saving development time and considerable cost.