Technical Paper for Team Tormenta

DARPA Grand Challenge 2005

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Abstract: Team Tormenta's entry into the 2005 DARPA Grand Challenge is a 4 WD, 1993 Jeep Cherokee Sport modified with the addition of sensor, control, processing and power systems required to complete the Grand Challenge. The payload equipment includes: 2 laser rangefinder sensors, stereo vision cameras, GPS and GPS heading sensors, an inertial measurement unit, processors for vehicle control and vision processing, actuators for basic vehicle mechanical functions and an enhanced power system to provide the necessary electrical power. The software is a combination of modified and custom software that performs the sensor processing and vehicle control functions.

Introduction: Team Description and Background Information

Several members of Team Tormenta originated the idea, design and development of one of the 15 vehicles to successfully make it to the starting line for the 2004 event. The experience gained in preparation for the 2004 GC has been invaluable to Team Tormenta.

The team leader for the 2005 Challenge is Ben Raskob, a Ph.D. student in Electrical Engineering at the University of So. California. Ben brings leadership and enthusiasm in addition to his background in robotics and vision. Team members include:

- Dr. Donald J. Bebel, a Systems Engineer at Northrop-Grumman Corp., an expert in systems engineering, integration and test for space-based and ground systems,
- Joseph Bebel, an undergraduate in Computer Science/Computer Engineering at the Univ. of Southern California and former autonomous systems team leader, Palos Verdes Road Warriors,
- Dr. Alice C. Parker, Professor of Electrical Engineering at the University of Southern California and an expert in integrated circuit design, system design and design automation,
- Dr. Petros Ioannou, Professor of Electrical Engineering at the University of Southern California and Director of the Center for Advanced Transportation Technologies,
- Jacob Madden, a Computer Science Masters student at the University of Southern California,
- Kim Tran, an undergraduate in Electrical Engineering at the University of Southern California,
- Tej Patel, a Junior at Palos Verdes High School and former team member of the Palos Verdes Road Warriors,
- Vikram Nair, a Computer Engineering Masters student at the University of Southern California,
- Gabriel Sibley, a Computer Science Ph.D. student in robotics at the University of Southern California,
- Jianlong Zhang, an Electrical Engineering Ph.D. student in controls and intelligent transportation at the University of Southern California,
- Bob Catalano, owner of Island Pacific Jeep and
- Langley Kersenboom, owner of LK Motorsports

1. Vehicle Description

1.1 Team Tormenta's entry into the 2005 DARPA Grand Challenge is a 4 WD, 1993 Jeep Cherokee Sport, the ***Black Pearl*** (shown in Figure 1). The Jeep was chosen based on its reputation and common use as an off-road vehicle. The Cherokee was selected because of the size of the passenger compartment, which was large enough to accommodate all of the equipment as well as maintaining space for developers and testers to ride inside the vehicle during development. The model year, 1993, was selected due to the smaller size profile and less complex electronics than newer models.

Figure 1: The Jeep Cherokee entered into the 2005 DARPA Grand Challenge

The base vehicle itself has not been modified significantly, even for the addition of the mechanical actuators. The vehicle remains street worthy, which we established as a requirement, in order to facilitate testing. The only physical enhancement is the addition of a heavy-duty alternator to provide the additional power required by the payload.

The vehicle functions are actuated with three motors: one each for the gas/brake, steering and gearshift. The gas/brake motor is a commercial unit manufactured by EMC Corporation to allow joystick control of the vehicle brake and accelerator pedals. The steering actuator is a custom design built with a heavy-duty DC gear head motor and a DC motor controller manufactured by Roboteq. The gearshift motor is a linear actuator controlled by a custom-designed control circuit.

A bank of 4 deep-cycle batteries, configured for 12 volts, provides the payload power. An added heavy-duty alternator maintains the batteries' charges. The 70 amps maximum current required by the payload could be fully provided by the alternator, but the batteries are maintained to handle alternator output reduction at low engine speeds and payload operation with the engine off. The payload power is separated from the vehicle main power by installation of an isolator.

The power distribution system provides 120v AC and +5v, +12v and +24v DC. The AC power is generated with a 600-watt inverter, providing a pure sine wave output through an Uninterruptible Power Supply (UPS) to the two computers.

The basic vehicle has been designed so as to remain drivable by a human driver and quickly convertible between autonomous and non-autonomous modes. For safety purposes, a human driver has been in the vehicle for all testing. Power to the gas/brake and steering actuators can be disconnected by two driver-accessible switches that allow the driver unimpeded control of these vehicle functions through the stock steering wheel and gas and brake pedals. Furthermore, the accelerator and brake pedals are fully accessible and usable to a human driver even while the vehicle is in autonomous mode.

The Jeep Cherokee gets approximately 16 miles per gallon in expected DGC conditions, and has a gas tank size of approximately 20.2 gallons for a driving range of over 300 miles, providing some margin for an anticipated 175 mile Challenge course and for unknown driving conditions. The vehicle operates on standard unleaded gasoline, and the fuel tank is unmodified from the stock Jeep fuel tank.

The Jeep has 4 wheel drive and automatic transmission. The gearshift lever is computer controllable via a linear actuator that will offer Park, Reverse, Neutral and Drive gears. The gearshift linear actuator is controlled by electro-optical sensors and a Xilinx FPGA (field programmable gate array).

The dimensions and specifications of the 1993 Jeep Cherokee are as follows:

Wheelbase, in.	101.4
Overall Length, in.	166.9
Overall Width, in.	67.7
Overall Height, in.	63.8
Curb Weight, lbs.	2955
Fuel Capacity, gals.	20.2
Range, mi (at 16 mpg)	323

2. Autonomous Operations

2.1 Processing

2.1.1 Processing in the Black Pearl is performed by two AMD Opteron 244 processors running Gentoo and Debian Linux operating systems. These processors communicate via gigabit Ethernet. Stereo image processing is performed using SRI's Small Vision System (SVS) software, provided by Videre Design. The remaining software is custom or open source C99 code with GNU extensions. One processor performs basic control, sensor processing, sensor fusion and planning functions, while the second processor is dedicated to stereovision processing. This dual-processor system is designed to provide adequate system performance, while simplifying communication between the processors. The computer rack is shock mounted to minimize damage due to vibrations and shock, and the hard drives are equipped with an internal shock protection system. The software is tolerant to a number of failure modes of the processing hardware. The processing subsystems are equipped with ECC RAM.

2.1.2 A functional block diagram is shown in Figure 2. The approach to the system architecture was to keep the architecture and system software as uncomplicated as possible. The sheer number of RS-232 connections as well as the range of types of data being communicated required a methodical programming discipline.

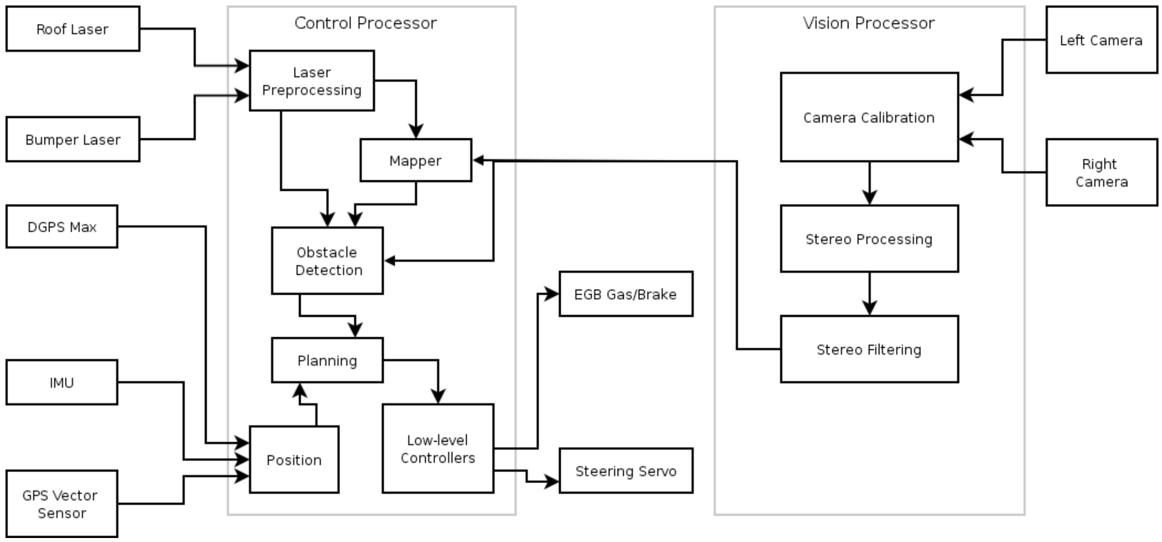

Figure 2: Functional block diagram of the processing architecture

2.1.3 The system was designed top-down, but construction proceeded bottom-up. Prior to construction, the system was modeled with Task-Flow Graphs. Each sensor was enabled individually and tested before being integrated into the system. The system evolved from a single GPS sensor system to the full system, with one additional sensor incorporated at a time. An extreme programming approach insured that key members of the team understood all the code, and caught potential errors early.

2.2 Localization

2.2.1 The primary source of localization is a DGPS Max (Differential GPS) unit provided by CSI Wireless, Inc. that receives publicly available satellite-based differential GPS corrections. This unit has a CEP (circle error probability) accuracy of approximately 30 centimeters 50% of the time and has less than one-meter accuracy 95% of the time, with Position, Velocity, and Time (PVT) provided at a 5 Hz rate. Accurate heading information is computed by the Vector Sensor subsystem from CSI Wireless, Inc, a Real Time Kinematic (RTK) based GPS system that utilizes two GPS antennas placed 0.8 meters apart on the roof of the vehicle. By determining the relative location of the antennas, true vehicle heading, accurate to 0.15 degrees, is determined at 10 Hz. The Vector Sensor provides true geographical heading, the actual direction the vehicle faces, as opposed to Course Over Ground (COG). PVT can be provided by the GPS units on the Vector Sensor, but these GPS units use Wide Area Augmentation System (WAAS) signals, at three-meter accuracy, rather than the more accurate Omnistar DGPS correction signals.

The system contains an Inertial Measurement Unit (IMU), with three angular rate gyros, three orthogonal DC accelerometers, and three orthogonal magnetometers, which provides filtered, IMU-stabilized orientation.

In case of primary GPS failure, PVT will be read from the GPS units on the Vector Sensor at 5Hz, or from a backup Garmin GPS18 unit, which receives WAAS corrections for three-meter accuracy at 1Hz.

In case of complete GPS outage, the IMU orientation and acceleration data provide position and velocity estimates over a short period of time. The GPS Vector Sensor includes a specialized gyro-aiding system to filter heading data when GPS is active and to compute new heading solutions during GPS outages for up to 60 seconds.

2.2.2 Our vehicle is not dependent on preloaded mapping data of any kind, except in the form of RDDF waypoints provided by DARPA.

2.3 Sensing

2.3.1 A SICK LMS 220 unit is mounted on the front bumper of the vehicle, oriented level to the ground. It scans +/- 90 degrees from the vehicle heading, has a resolution of 0.5 degrees and a maximum range of 80 m.

A SICK LMS 291-S14 unit is mounted on the roof rack of the vehicle, angled down approximately 10 degrees from horizontal. The laser field of view, which is +/- 45 degrees, intersects the ground plane 10 meters forward from the vehicle. This second laser is used to detect changes in terrain across the path of the vehicle, for example, to detect a berm or a trench along the edge of the road.

The stereo cameras are Videre Design DCAM-Ls, with 12mm focal lengths, capable of 30 Frames per Second (FPS) at 640x480 pixels in grayscale. The Field of View (FOV) of the lenses used is 18 degrees horizontal by 13 degrees vertical. The stereo rig is configured with a baseline of 148 mm, which allows a useful range of 10 meters to 80 meters.

The sensors are protected from environmental elements. The SICK LMS units are outdoor models, and have a custom sun shield to protect from sun glare and rain. The roof-mounted SICK provides reflectivity values as well as range values that can be used to filter erroneous range data. The cameras will be encased in a protective enclosure to guard against water, dust, and sun glare. In the case of sun glare in the cameras, the data will be filtered by the stereo processing algorithm to prevent false matches.

2.3.2 Sensor data is processed different ways with multiple goals. Range data from the lasers and stereo cameras are used for obstacle detection, and combined together into a map around the vehicle. Given the positions of the sensors relative to a central origin point in the vehicle, all range data is converted from separate sensor coordinate systems to a standard right-handed three-dimensional vehicle coordinate system. Current sensor readings are then converted from vehicle coordinates to world coordinates using the current vehicle position and orientation, which allows the data to be combined over time with previous sensor readings. Laser and stereo range data is then processed to find obstacles in the environment, which are stored internally and marked on a map maintained for the space around the vehicle. Data from the angled laser on the roof is also used to detect the edges of the road, storing these edge regions as obstacles.

2.3.3 The primary sources of vehicle state data are the primary GPS sensor, the GPS Vector Sensor, and the IMU. The GPS devices provide feedback about the vehicle's current velocity and current change in heading, while the IMU provides more sophisticated roll, pitch, and yaw of the vehicle as well as measurement of the shock and sudden accelerations of the vehicle that may cause sensor errors.

2.3.4 The vehicle attempts to steer towards a path defined by the lines between consecutive waypoints, including the current waypoint, several previous waypoints, and several future waypoints. A Roboteq DC motor controller containing an internal PID controller controls the steering servo directly, while a PD controller generates steering commands that are sent to the motor controller. This PD controller operates by attempting to minimize the distance between a point 6 meters directly in front of the vehicle and the desired path. Computing the distance from a point in front of the vehicle, rather than from the vehicle’s current location, allows for mechanical delays in the system as well as preventing over-steer, under-steer, or oscillating steering conditions. A PID controller is used for speed control, providing acceleration and braking as needed to maintain the desired velocity. Obstacles are detected by the two laser rangefinders and the stereo vision system. Laser rangefinder data is processed and filtered to locate specific laser data points that are flagged as obstacles and added to an obstacle array. Obstacles are also flagged in the stereo image data. The obstacle array is checked to see if there are obstacles in the desired path the vehicle is tracking, or the path the vehicle is currently tracing, passing through any known obstacles. If there are no obstacles, the vehicle proceeds normally. If there are obstacles, the obstacle avoidance procedure begins execution. This procedure places temporary waypoints slightly away from the current desired path and checks to see if any obstacles intersect that path. This process is repeated until no obstacles intersect the temporary path. If a temporary waypoint happens to be placed within the Lateral Boundary Offset (LBO) of an RDDF-specified waypoint, the RDDF specified waypoint is replaced with the temporary waypoint. Then, a new path is drawn from the vehicle to the temporary waypoints and then to the next desired RDDF waypoint. The PD controller then attempts to steer the vehicle on to the new desired path. If there are still obstacles in future cycles, new waypoints are selected further from the obstacle and the procedure repeats. The placement of temporary waypoints is performed using a simple heuristic to bridge the obstacle by placing temporary points to the side before and after the obstacle, to generate enough control effort to ensure the vehicle will steer fully around the obstacle. A more complex path-planning algorithm is also under investigation.

2.4 Vehicle Control

2.4.1 Because of the nature of the PD steering controller, the vehicle will not turn around to aim towards a missed waypoint. Rather than processing data at the waypoint level, the low-level controllers operate given a desired path which may have arbitrary or practically infinite resolution, so the missed waypoint scenario is irrelevant at the low level, where the vehicle follows the desired path which may spread over many waypoints. However, since it is undesirable to calculate complete path data for long distances, path data is computed for a limited subset of points surrounding the current waypoint (defined as the most advanced waypoint which has not yet been passed or skipped). Therefore, in the unlikely case that the vehicle will not enter the LBO of any waypoint in the examined set, when the path the PD steering controller tracks reaches the end, additional waypoints will be added.

The vehicle's PID speed controller will adapt to differing terrain types and slopes by minimizing the difference between the desired speed and current speed. In the case of the vehicle being stuck on a rock or other large object, or going up a particularly steep hill, the integral term of the PID controller will slowly accumulate built-up velocity error and apply more gas accordingly. For safety reasons, the PID controller can only apply a maximum amount of gas continually. In the case where current velocity is below a certain threshold, despite the PID controller applying maximum gas, a special-case function will apply bursts of additional acceleration as needed until the vehicle frees itself. If this does not succeed, the vehicle will attempt to back up and then continue forward progress.

When the vehicle is outside the RDDF-defined LBO corridor, the vehicle will attempt to return to corridor as quickly as possible. Since the PD steering controller attempts to navigate the vehicle to the center path, rather than the next waypoint, the vehicle will return to the corridor at the same turning rate regardless of whether the next waypoint is close or far away. This avoids the undesirable case (see Figure 3) where the vehicle may spend an extended period of time outside the corridor where there may be rough terrain and more obstacles, just to navigate the shortest path. When temporary obstacle-avoiding waypoints must be placed, they will be placed as far inside the corridor as possible.

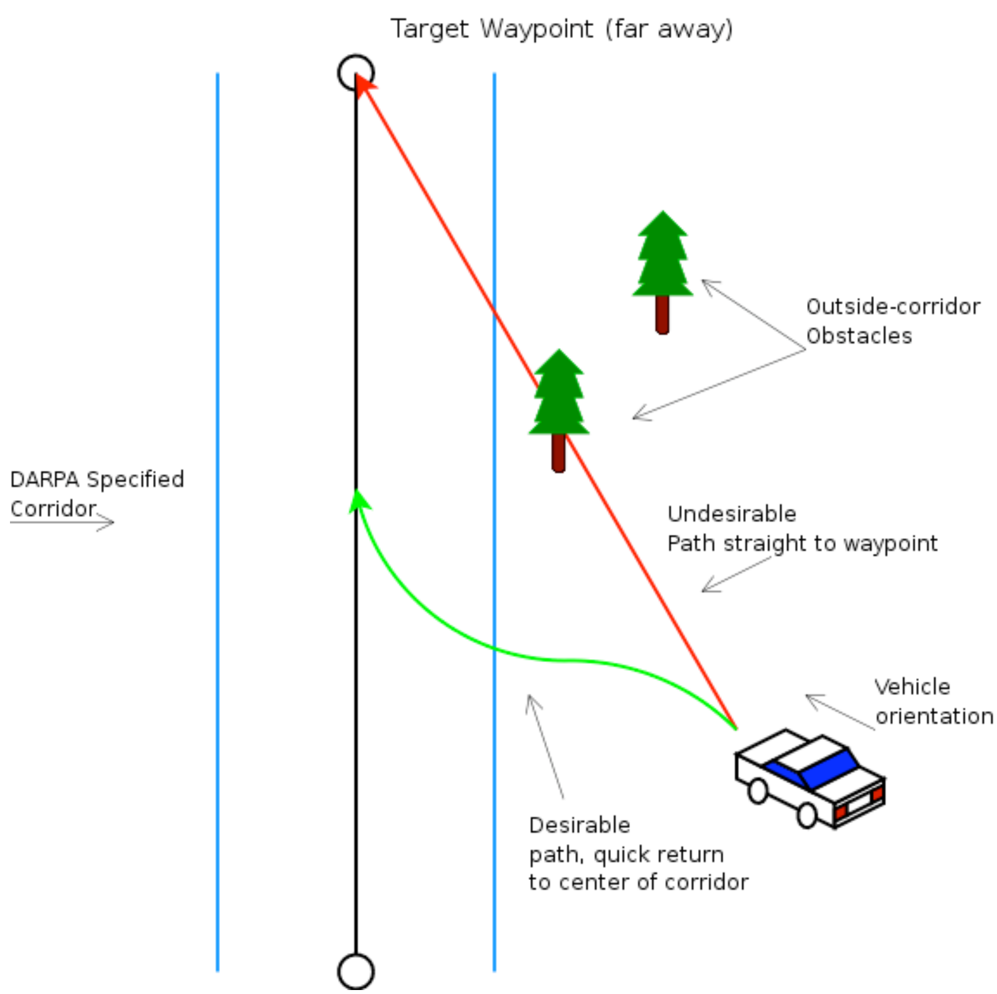

Figure 3: Obstacle avoidance

When an obstacle is detected that intersects the current desired path of the vehicle, or the current trajectory of the vehicle if the vehicle is off the center path, a set of temporary waypoints which avoids the obstacle are inserted in a bridge formation. This ensures complete avoidance of the detected obstacles, and recomputation of the desired path of lines between waypoints. Placing temporary waypoints in a bridge formation means that, rather than placing a waypoint directly to the side of an obstacle, two waypoints are inserted to the side of an obstacle, one before the obstacle and one after. This is seen in Figure 4, where an obstacle is placed in the desired path (a), and the steering controller is experiencing over-steering (b) and under-steering (c) conditions. By placing the waypoints in a bridge formation, rather than simply placing a waypoint to the side, the controller ensures that if an over-steering or under-steering condition occurs, there is sufficient margin to avoid the obstacle.

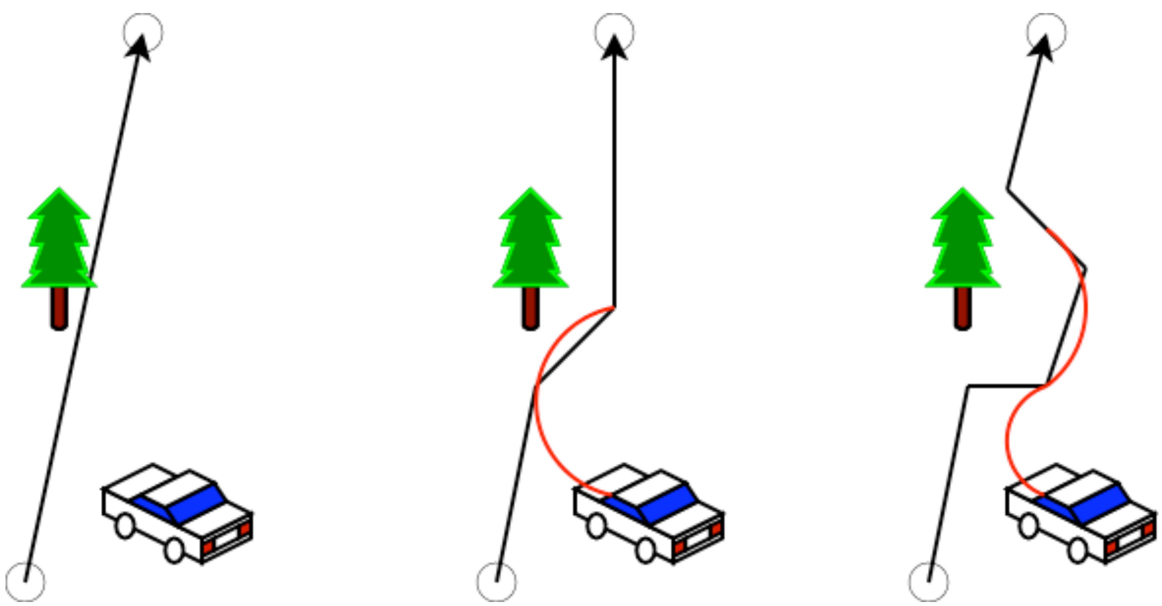

Figure 4: Bridging waypoint insertion to avoid an obstacle

2.4.2 The decision to brake the vehicle is made by the PID speed controller, which will attempt to apply the brake in a smooth fashion to slow the vehicle when higher level vehicle intelligence deems it necessary. If an obstacle is detected close in front of the vehicle, higher gain values would be used in the PID controller to enable quicker stopping. Starting on a hill will not be a problem for the speed controller unless the hill is sufficiently steep that the car would be caused to roll backwards before enough gas is applied to enable forward motion. In this case, the IMU would be used to recognize such a steep gradient.

When the vehicle is approaching a sharp turn, defined as a large angle made by the formation of the previous, current, and next waypoint, the vehicle will be attempt to slow down enough to make the turn so as not to leave course boundaries.

2.4.4 Autonomous mode of the vehicle can be disabled from the two switches accessible to the driver, for the steering motor and gas/brake motor. When these are switched off, the vehicle can be driven with the steering wheel and gas/brake pedals as any other normal car.

2.5 System Tests

2.5.1 Testing of the Black Pearl has been performed in conjunction with a staged integration. Integration stages coincided roughly with the major milestones in the schedule leading to the National Qualification Event, i.e., the video demonstration, the site visit and the NQE. The basic strategy was to develop and integrate key subsystems (navigation, obstacle avoidance) in stages, with the supporting infrastructure (vehicle control and power). As components were integrated, thorough testing was performed to shake out problems and demonstrate capability. At the conclusion of each stage, results were evaluated, problems were identified and enhancements were made. The sequence progressed as follows:

Event	*Demonstrated Capability*
Video Demonstration	• Basic vehicle control • Waypoint navigation • Power generation • Sensor suite definition
Site Visit	• Complex navigation • Basic sensor operation • Obstacle avoidance • Upgraded power system
NQE	• Full sensor operation • Sensor integration • Path planning through complex obstacles • Full vehicle actuation (added gear shift control)

To ensure reliability, care was taken in the design of components and selection of materials and equipment to ensure reliability. To the greatest extent possible, commercial equipment was used to minimize the number of custom designed components and the shakeout testing associated with new design. With this approach, custom designs were required for only three components, the steering actuator, the gearshift actuator and the on-board processors. In these cases, cost as well as performance drove the design approach.

We made the decision to use a stock vehicle, the Jeep Cherokee, that was designed for off-road use to take advantage of the reliability associated with an established design, allowing us to focus our attention and resources to the design of the vehicle's intelligence. The only vehicle modification was the upgrade to the alternator to provide the additional power needed for the control system. Based on experience from the 2004 Challenge and published reports from some 2005 teams, the steering actuator was designed with significant margin to minimize likelihood of failure. The computers have been designed with only the components required for this application, have been assembled in rugged, rack mounted cases and have been integrated into the vehicle in a shock mounted rack. The custom designed gearshift actuator is perhaps the most detailed component design undertaken. This design includes a motor, sensor circuit and Xilinx FPGA-based controller. Special consideration has been given to testing this component to ensure reliability.

In some sense, all testing of the Black Pearl since the preparation of the demonstration videotape has been performed off-road. The primary test area has been an open field that has provided rugged terrain for testing the reliability of our design. In the months since filming the videotape we have not experienced a reliability-related failure in well over 100 hours of field testing. Furthermore, to prepare for the NQE and the DGC, we have augmented the test area with an assortment of obstacles that we expect to be present, in order to test the vehicle sensors and the Black Pearl's response.

2.5.2 The testing experience has been rich with successes and challenges. Thanks to CSI GPS units and the Omnistar DGPS service, the ground track of the vehicle is very repeatable, often rolling over the exact same point on multiple loops of the test course. Watching the Black Pearl complete a successful maneuver is always a thrill. However, there are many challenges. Overgrown grasses challenge the laser systems, as do clouds of dust, rain and fog. Uneven terrain, both short duration (rough) and long duration (rolling) cause problems with obstacle localization.