DARPA Grand Challenge

Virginia Tech Team
Vehicle Name: Cliff
Technical Paper

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1. System Description

a. Mobility.

1. Describe the means of ground contact. Include a diagram showing the size and geometry of any wheels, tracks, legs, and/or other suspension components.

The Challenge Vehicle is an off-road, four-wheel-drive utility cart made by Club Car. The vehicle makes ground contact through *four 25x11/12 heavy-duty all-terrain tires*. The front suspension consists of independent A-arms and coil-over shocks. The rear suspension is semi-independent, using both leaf springs and coil-over shocks. Figure 1 shows a photograph of the Challenge vehicle. Figure 2 shows the left front tire, half-shaft and suspension geometry.

Figure 1. Club Car 4x4 Utility Vehicle

Figure 2. Tire and Suspension Geometry.

2. Describe the method of Challenge Vehicle locomotion, including steering and braking.

The Challenge Vehicle has shift-on-the-fly, electronically activated four-wheel drive. Drive power is provided by a 20 horsepower Honda GX620 four-stroke internal combustion gasoline engine. A continuously variable transmission (CVT) provides a neutral (slip) function at low engine speeds. It also provides a range of reduction from 6:1 to approximately 1:1. The vehicle can reach a top speed of approximately 35 miles per hour. The vehicle is equipped with hydraulic disc brakes on all four wheels. A conventional rack and pinion front steering system provides a turning radius of approximately 10 feet. The vehicle has a 1000 lb payload capacity.

3. Describe the means of actuation of all applicable components.

Throttle Actuation. *The throttle is actuated by a 24 volt Japan Servo Company model DME 60B6HF permanent magnet dc gear motor with an integral encoder. The encoder provides throttle position feedback to a National Instruments motor controller. The throttle motor actuates the throttle through a tension cable. This allows a human operator to quickly take control of the throttle. The throttle motor is backdrivable and acts against a return spring. When power is lost to the motor, the throttle returns to idle.*

Brake Actuation. *The vehicle's standard hydraulic braking system is used for reducing speed in autonomous operation and also for situations requiring an emergency stop. A 24-volt DC linear actuator (Motion Systems, Inc. model 85915) is attached to a pivoting lever. The other end of the pivoting lever is attached to the original vehicle brake pedal via a steel cable. A retraction of the linear actuator provides application of the vehicle brake. A linear potentiometer attached to the actuator provides feedback for the braking system. A pneumatic brake activation system has been installed as a secondary fail-safe method of actuating the brakes. Two pneumatic cylinders are attached to the vehicle's parking brake assembly. The cylinders are connected to an air tank separated by a normally open solenoid valve. While the vehicle has power and the E-stop is not activated, the solenoid is held closed. When the vehicle loses power or receives the signal from E-stop, the valve will open. This allows the compressed air to flow into the cylinders, thus applying the vehicle's parking brake.*

Steering Actuation. *Autonomous steering actuation is accomplished using a Bodine 24 volt permanent magnet right-angle gear motor (model 42A-5N) with an integral encoder (model 0941). The gear motor is directly connected to the pinion through a universal joint and spider coupling. As with the throttle and brake actuators, the encoder detects steering angle and feeds this information back to a motor controller.*

b. Power.

1. What is the source of Challenge Vehicle power (e.g., internal combustion engine, batteries, fuel cell, etc.)?

The vehicle is propelled by a 20 horsepower Honda GX620 four-stroke internal combustion engine. In addition, the vehicle carries a Yamaha 1600-watt gasoline powered AC generator that powers the AC computers and fans and indirectly charges two 12-volt lead acid batteries. The batteries act as the primary source for all DC devices, and the generator is used to sustain their charge through a high power battery charger.

2. **Approximately how much maximum peak power (expressed in Watts) does the Challenge Vehicle consume?**

We estimate the peak power consumption of the vehicle and subsystems to be about 2500 watts. We expect the average power consumption top be less than 1200 watts. Table 1 provides a more detailed estimate of maximum power consumption by subsystem.

Table 1: Estimated Peak Power Consumption	
Component	Max. Power (W)
Computers	750
Sensors	250
Cooling Fans	100
Vehicle Control:	
Steering	200
Brake	360
Throttle	50
Safety Light	120
Horn	120
DARPA	84
Total:	2034
+ 20% Losses	2441
Adjusted Total with AC Power devices	2441

3. **What type and how much fuel will be carried by the Challenge Vehicle?**

The Challenge Vehicle carries unleaded gasoline onboard in two gasoline tanks. The vehicle's original 7-gallon tank is used to supply gas to the generator. A second 20-gallon tank provides the gas for the vehicle's engine. This fuel capacity provides us with an estimated 10 hours of continuous operation at full throttle.

c. **Processing.**

1. **What kind of computing systems (hardware) does the Challenge Vehicle employ? Describe the number, type, and primary function of each.**

The computing systems for the Challenge Vehicle consist of four sensor interface computers, a global mapping computer, a local mapping/path-planning computer, and a system status/motion control computer. The computation and control system layout is presented in Figure 3.

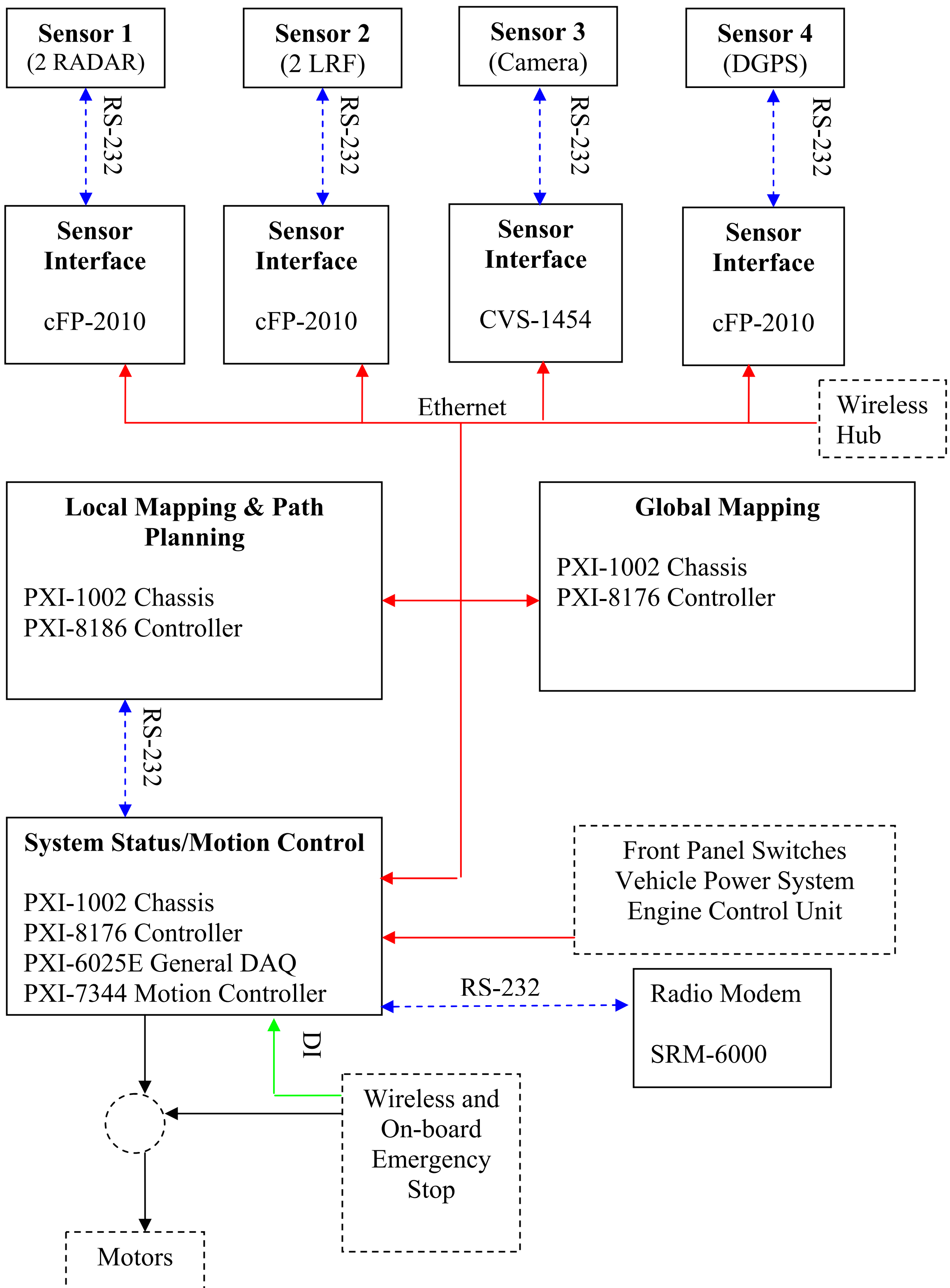

Figure 3. Computational Hardware Layout.

The Challenge Vehicle uses three National Instruments Compact Field Point (cFP) 2010 units and a CVS-1454 Compact Vision System to capture and preprocess local sensor data. These are used to interface with the four main navigation sensors (*radar, laser rangefinders, differential GPS/INS sensor and visible light camera*). As shown in Figure 3, these units communicate through Ethernet interfaces to provide distributed input/output and distributed computing. Figure 4 is a photograph of a typical cFP unit. The cFP is designed for use in harsh in-vehicle environments and can withstand 50g shock loads for 3ms. Each device communicates with its respective sensor and sends data to the local mapping/path-planning computer using an Ethernet connection. Each Compact Field Point unit includes a separate processor. This will allow preprocessing of sensor data before routing to the local mapping computer. In addition to the obvious speed advantage of distributed processing, this system will facilitate error rejection and allow better temporal coordination of data.

Figure 4. cFP-2010 Compact Field Point Unit.

The National Instruments PXI – 8176 Controller, shown in Figure 5, is used as the global mapping computer. The global mapping computer is used to store Geographic Information System (GIS) data, develop a global passibility map, and plot "best path" waypoints. It is housed in a PXI – 1018 Chassis that has three additional PXI slots for expansion. This computer uses a Pentium III 1.26 GHz processor with 512 MB SDRAM and runs the Microsoft Windows 2000 operating system.

Figure 5. PXI-8176 Controller.

The local mapping/path-planning computer is a PXI 8186 Controller housed in a PXI-1002 Chassis. The controller runs LabView Real-Time. The local mapping/planning computer receives data from the global mapping computer, Compact Field Point units, and the Compact Vision System. This computer creates a local map in order to find the desired path, and then transfers this information to the system status/motion control computer.

The system status/motion control computer uses a PXI-1002 Chassis, PXI-8174 Controller, PXI-6025E General DAQ card, and a PXI-7344 Motion Controller. These are shown in Figures 6, 7 and 8. The PXI-6025E Controller is a Celeron based embedded controller that sends information to the motion controller. The motion controller is capable of controlling 4 axes; we use three of these to control the throttle, brake, and steering motors. The DAQ card is used to monitor the status of the vehicle and to control the lights and siren. We also monitor the temperature of the electronic enclosure and battery voltage.

Figure 6. PXI-8174 Controller.

Figure 7. PXI-6025E General DAQ.

Figure 8. PXI-7344 Motion Controller.

2. **Describe the methodology for the interpretation of sensor data, route planning, and vehicle control. How does the system classify objects? How are macro route planning and reactive obstacle avoidance accomplished? How are these functions translated into vehicle control?**

Navigation is based on a combination of stored map data, global position information from a Honeywell TALIN DGPS/INS system, and local terrain data from Sick laser rangefinders, an Eaton VORAD radar system, and a visible light camera.

Based on the approximate starting and ending locations and the approximate 250-mile maximum course distance, we believe the course will lie within ellipse shown in Figure 9. Although more specific route information has been published, we will not rely on this information for navigation.

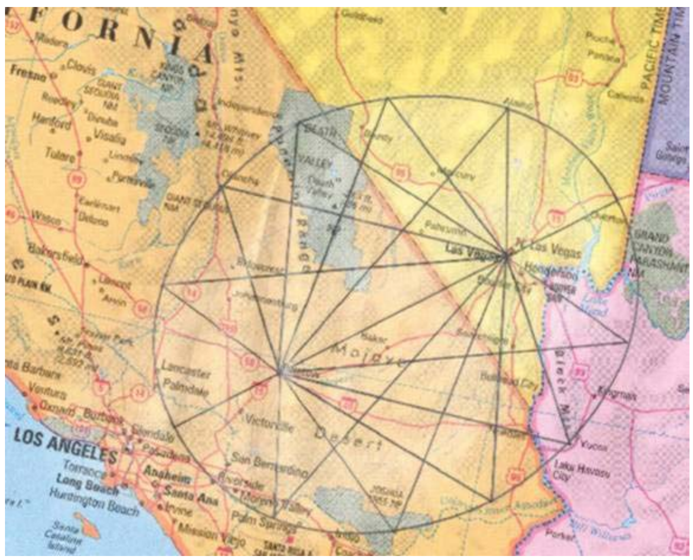

Figure 9. Elliptical Course Boundary

We currently have 30m GIS data for the entire course area and we are working to get higher resolution data. When we are given waypoints and widths two hours before the race, we will discard data for all areas outside the course boundaries. This will significantly reduce the data set to be review during mapping. Macro route planning is conducted using stored map data to determine which routes are passable. Impassable routes such as lakes, cliffs, and areas outside the allowable boundaries will also be removed from the database of possible solutions.

The Challenge Vehicle generates an initial best global path using GIS data and an approach similar to the well-know A* algorithm. Costs are assigned based on terrain slope, ground cover, deviation from the straight-line path and other factors. In the two hours prior to the race, we will develop an optimal global path for the entire route. This will create a curved path within the course boundaries. Since data from the global mapping computer will not provide the resolution needed to see obstacles, the Challenge Vehicle uses radar, laser rangefinders, and a *visible light camera* to sense local obstacles and discontinuities. Information from the local sensors (via their dedicated processors), the DGPS/inertial guidance unit, and global mapping computer is sent to the local mapping/path-planning computer.

As long as the local sensors see no impassible obstacles or discontinuities, the vehicle tracks along the planned global path. Speed is kept within the specified course limits and may be further limited by the current turning radius of the vehicle. Data from the three local sensors *(laser rangefinders, radar and camera)* are fused to create an occupancy grid in front of the vehicle. A bias is included so that the vehicle continually attempts to return to the original global path. The mapping/path-planning computer selects an optimal path based on one of several localized navigation strategies, such as Vector Field Histograms, to determine optimal local paths. If the deviation from the planned global path becomes large, the vehicle may slow or stop and plan a new global path. If global path calculation are too time consuming, we may elect to look only a few segments ahead and dynamically re-plan the global path.

Despite the complex challenges of sensing and navigation, vehicle control ultimately translates to controlling velocity and steering angle. Low-level control of both of these functions is handled in the System Status/Motion Control computer shown in Figure 3. The National Instruments PXI-7344 Motion Controller controls the steering, throttle and brake actuators using standard PID control loops with encoder feedback. PID control loops are used to determine high-level speed and steering commands. Actual speed, as determined from the DGPS/INS unit and a wheel encoder, is compared to the desired speed. In typical operation, we expect to actuate only the throttle. The brakes are applied only at zero throttle, so the brake and throttle should never act in contention. Steering angle is adjusted based on the actual heading of the vehicle, determined from the DGPS/INS unit, as compared to the desired heading.

d. Internal Databases.

1. What types of map data will be pre-stored on the vehicle for representing the terrain, the road network, and other mobility or sensing information? What is the anticipated source of this data?

The Challenge Vehicle has stored on-board map containing the best GIS information we can obtain. The team is currently using 30 by 30 meter grid data that is readily available to the public from the GSPS. This database includes digital elevation maps and land cover information.

e. Environment Sensing.

1. What sensors does the challenge vehicle use for sensing the environment, including the terrain, obstacles, roads, other vehicles, etc.? For each sensor, give its type, whether it is active or passive, its sensing horizon, and its primary purpose.

The Challenge Vehicle uses radar, laser rangefinders and a visible light camera for sensing the environment. Three Sick optic laser rangefinders, shown in Figures 10 and 11, actively scan the surroundings for obstacles. These units have a horizontal field of view of 90 degrees. Two laser rangefinders are mounted vertically from the roll cage of the vehicle. These laser rangefinders are used to detect obstacles in front of the vehicle. The third laser rangefinder is mounted on the *brush guard in front of the vehicle. The positions of the laser rangefinders allow measurements from the laser rangefinders at different levels. The absolute difference between the two measurements determines whether the object seen by the sensor is an abrupt discontinuity or a gradual change in elevation. Small differences in distance might indicate a vertical obstacle, while a large difference in distance might indicate a slope of a hill.*

Figure 10. SICK Laser Rangefinder.

Figure 11. SICK Laser Rangefinder.

A radar system is also used to complement the laser rangefinder. Two Eaton VORAD radar units are mounted to the front of the Challenge Vehicle, each with a horizontal field of view of approximately 14 degrees. The radar system actively distinguishes obstacles moving relative to the vehicle from the surroundings. The radar system and laser rangefinders are used to determine the direction, size, and speed of obstacles.

Data from all three sensors is fused together to create a local terrain map. The navigation computer uses this data to select an optimal path.

2. **How are the sensors located and controlled? Include any masts, arms, or tethers that extend from the vehicle.**

The sensors are mounted directly to the frame of the vehicle and will not be articulated. Figure 12 shows these sensor locations. A pair of laser rangefinders are mounted vertically to the roll cage, at a height of approximately 7 feet above the ground. A third laser range finder is mounted to the brush guard on the front of the vehicle. The radar units are also mounted by the brush guard on the front of the vehicle. A GPS antenna is mounted from the top of the roll cage, at a maximum height of approximately 8 feet. The camera is also attached to the roll cage, at a height of approximately 6-7 feet above the ground.

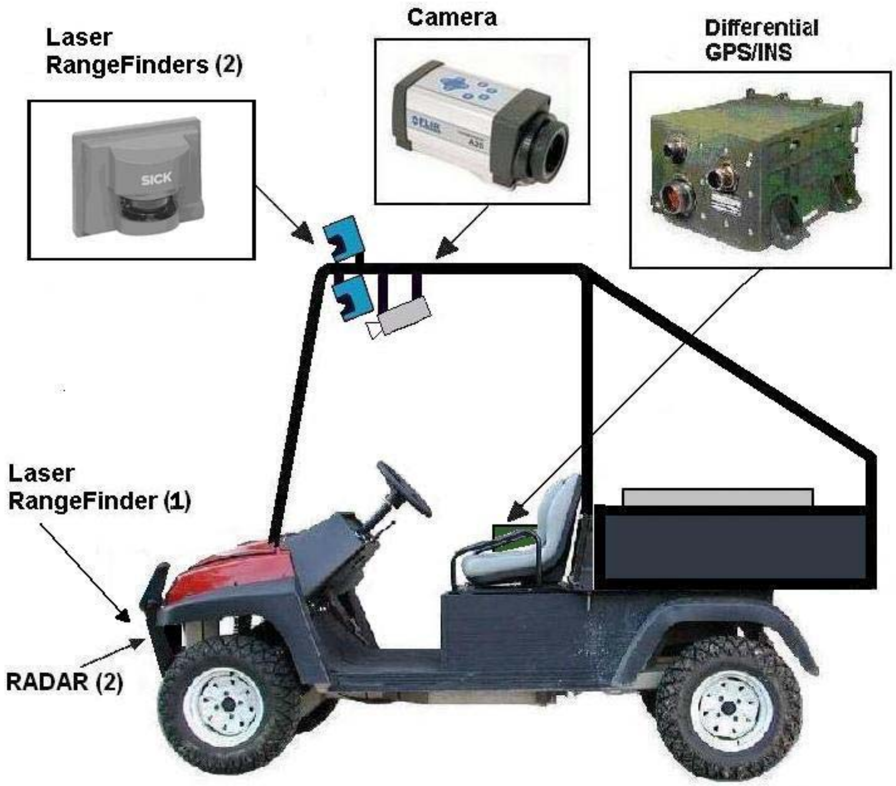

Figure 12. Challenge Vehicle showing sensor locations.

f. State Sensing.

1. What sensors does the Challenge Vehicle use for sensing vehicle state?

The Challenge Vehicle uses optical encoders to determine the position and velocity of the brake, steering and throttle motors. A fourth encoder provides wheel velocity, which is used in the integrated TALIN DGPS/INS system.

Status sensors are used to monitor the health of the overall vehicle and its subsystems. As a minimum, we expect to monitor battery voltage for each on-board battery and the temperature inside all electronic enclosures.

2. How does the vehicle monitor performance and use such data to inform decision-making?

The vehicle has both local and global (DGPS/INS) sensors on board. Since our goal is to navigate between predefined GPS waypoints, the DGPS/INS unit serves as the primary sensor. Its output is monitored at 25 to 50 Hertz to check position and heading of the vehicle. If no obstacles are encountered, navigation is conceptually straightforward. We simply correct our heading to maintain the precalculated path described above. The local sensor data is fused into an array using one of several local navigation techniques.

g. **Localization.**

1. **How does the system determine its geolocation with respect to the Challenge Route?**

The Challenge Vehicle uses a TALIN integrated DGPS/INS system from Honeywell for positioning. This system is shown in Figure 13. The integrated system uses Kalman filtering to provide precise position and velocity information at speeds up to 50 Hz.

Figure 13. TALIN Navigation System from Honeywell.

2. **If GPS is used, how does the system handle GPS outages?**

Our Honeywell TALIN integrated GPS/INS system is designed to handle exactly this situation. The relatively noisy and infrequent GPS data is interpolated and smoothed using inertial data. In cases where the GPS signal is blocked, the integrated INS system automatically produces position information. Angular error of the inertial system is 0.125 degrees/hr, which should be more than sufficient for reasonable GPS outages.

3. **How does the system process and respond to Challenge Route boundaries?**

The boundaries are treated as impassible obstacles. When the course data is received two hours before the Challenge, data from areas outside the course boundaries will be deleted from memory. The global mapping computer will store only the mapping data that is within the Challenge Route boundaries.

h. Communications.

1. **Will any information (or any wireless signals) be broadcast from the Challenge Vehicle? This should include information sent to any autonomous refueling/servicing equipment.**

No signals will be broadcast from the vehicle during the Challenge.

2. **What wireless signals will the Challenge Vehicle receive?**

The Challenge Vehicle receives differential GPS signals from the Omnistar subscription service. Information on the Omnistar service is available at www.omnistar.com.

i. Autonomous Servicing

Does the system refuel during the race? If so, describe the refueling procedure and equipment.

The Challenge Vehicle will not refuel during the race.

1. **Are any additional servicing activities planned for the checkpoint? If so, describe function and equipment.**

No checkpoint servicing activities are planned.

j. Non-autonomous control. How will the vehicle be controlled before the start of the challenge and after its completion? If it is to be remotely controlled by a human, describe how these controls will be disabled during the competition.

A human operator will control the vehicle before and after the race. An operator can control the vehicle via a joystick installed inside the vehicle's cab, which controls the vehicle's actuators. In case of an emergency, the operator has full manual control over the standard brake pedal to stop the vehicle. A kill switch has been installed inside the vehicle, so that the operator can easily shut down the vehicle's engine, if needed.

2. System Performance

a. Previous Tests. What tests have already been conducted with the Challenge Vehicle or key components? What were the results?

The Virginia Tech Team is using this Challenge as a senior design experience for undergraduate Mechanical Engineering students. Hence, our team only began to focus on the Challenge Vehicle at the start of the academic year about 7 weeks ago. As a result, we do not yet have an operational challenge vehicle, although we do have a base vehicle and most of the major components. We do have experience with similar projects and the related subsystems. For example, the Virginia Tech team won 1st and 2nd place in the Autonomous Challenge at the 2003 Intelligent Ground Vehicle Competition. Although the speeds are slower (limited to 5 mph), these vehicles operate using cameras, laser rangefinders, digital compasses and Differential GPS.

The photographs in Figures 14 and 15 show one of theses vehicles, which we are using to develop software and test sensors until our Challenge vehicle is automated.

Figures 14 and 15. Test Vehicle from the Intelligent Ground Vehicle Competition

b. Planned Tests. What tests will be conducted in the process of preparing for the Challenge?

The team plans to conduct extensive tests on the challenge vehicle. The planned test site is the Virginia International Raceway in Danville, Virginia. GPS points have been taken at the VIR site and will be sent to DARPA to obtain a sample RDDF. The initial tests are scheduled to begin at the end of October. These will be low-speed tests using only the DGPS sensor and a simple path-following navigation algorithm (no obstacles). This will also help us test the converted base vehicle system. Low speed testing using the vehicle’s local sensors is scheduled to begin in early December. These tests will help us refine and integrate the laser rangefinder, thermal camera and radar systems. In mid-January, high-speed tests will commence. These tests will verify the vehicle’s sensors and positioning systems function at the speeds necessary to complete the challenge course. At this point, the vehicle will be tested on a cross-country course to simulate the competition course.

3. Safety and Environmental Impact

a. What is the top speed of the vehicle?

The top speed of the vehicle is approximately 35 miles per hour.

b. What is the maximum range of the vehicle?

The maximum range of the Challenge Vehicle is slightly over 300 miles, limited only by fuel capacity.

c. **List all safety equipment on-board the Challenge Vehicle, including:**

1. Fuel containment. *Two gasoline tanks are used. The vehicle's original 7-gallon tank is used to supply gas to the generator. A second 20-gallon tank provides the gas for the vehicle's engine.*

2. Fire suppression. The Challenge Team requires a person to stand by with a fire extinguisher in hand when the vehicle is being refueled. Since this is a mostly open vehicle, we do not have a fire suppression system on-board.

3. Audio and visual warning devices. *The audio safety device consists of a weatherproof back-up alarm. The horn produces intermittent sound with pressure greater than 85 dB at 10 feet. The visual warning device consists of a 24 V rotating warning light with an amber lens. The light has two Par 36 sealed beams (35,000 candle power each) rotating at 90 FPM and meets all SAE requirements.*

d. **E-Stops.**

1. **How does the Challenge Vehicle execute emergency stop commands? Describe in detail the entire process from the time the on-board E-Stop receiver outputs a stop signal to the time the signal is cleared and the vehicle may proceed. Include descriptions of both the software controlled stop and the hard stop.**

Software-Controlled Stop. *A soft stop input to the computer cuts the throttle actuation, putting the engine at idle. The computer stops sending control signals and actuates the brake. The safety horn and light continue to operate in this e-stop mode. When the signal is cleared, the vehicle resumes normal operation. The braking and throttle will continue to be controlled by the autonomous vehicle actuators*.

Hard Stop. *The hardware stop immediately cuts vehicle engine power and applies an air-powered fail-safe brake. Power to all auxiliary systems such as the vehicle motion controllers, on-board computers, and safety light and horn is cut off and grounded.*

2. **Describe the manual E-Stop switch(es). Provide details demonstrating that this device will prevent unexpected movement of the vehicle once engaged.**

The manual E-stop is a two-part system. When the switch is flipped into emergency stop mode the spark plugs are then grounded out, thus the engine will no longer be able to fire. Flipping this switch also activates the fail-safe brake. A solenoid requires power to hold the fail-safe brake, thus when it is grounded out the brake will engage. These simultaneous systems will be sufficient in bring the vehicle to a quick stop.

3. **Describe in detail the procedure for placing the vehicle in "neutral", how the "neutral" function operates, and any additional requirements for safely manually moving the vehicle. Is the vehicle towable by a conventional automobile tow truck?**

A lever inside the cab of the vehicle controls the transmission. The lever's upward position puts the vehicle in drive. The downward position is reverse, and the middle position is neutral. The vehicle has a continuously variable transmission (CVT) which defaults to a fail-safe neutral position whenever the engine speed drops below approximately 1500 RPM. This allows all four wheels to rotate freely. The vehicle can easily be pushed by one or two people. A traditional tow truck with a tow strap would have no difficulty in towing the vehicle.

e. Radiators.

1. **Itemize all devices on the Challenge Vehicle that actively radiate EM energy, and state their operating frequencies and power output. (E.g., lasers, radar apertures, etc.)**

Table 1. EM Radiators.

	Laser Rangefinder	Radar
Output Power	7.21 mW	3 mW
Operating Freq	905 nm wavelength	24.7 GHz

2. **Itemize all devices on the Challenge Vehicle that may be considered a hazard to eye or ear safety, and their OSHA classification level.**

Both the laser rangefinder and radar systems are eye-safe. No system poses a threat to eye or ear safety.

3. **Describe any safety measures and/or procedures related to all radiators.**

Only team members that have been instructed on the proper safety instructions are allowed to handle each sensor.

f. Environmental Impact.

1. **Describe any Challenge Vehicle properties that may conceivably cause environmental damage, including damage to roadways and off-road surfaces.**

The vehicle has an unloaded weight of 1150 pounds, an overall wheelbase of 81 inches, and a track width of 45.75 inches at the rear tires. This is significantly smaller and lighter than standard trucks. The vehicle's small size and relatively slow speed will result in less damage to the environment then a standard truck.

2. **What are the maximum physical dimensions (length, width, and height) and weight of the vehicle?**

The vehicle has an unloaded weight of approximately 1150 pounds, an overall length of approximately 126 inches, and an overall width of approximately 56 inches. The overall height of the vehicle including roll cage and GPS antennae is roughly 8 feet.

3. **What is the area of the vehicle footprint? What is the maximum ground pressure?**

Each tire has a contact area of 39 square inches while the vehicle is at rest on concrete. This means that the Challenge Vehicle has a total contact area of 156 square inches. The total unloaded pressure of the vehicle is approximately 7.75 psi.