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From: James Anderson [cobrasauce@hotmail.com]
Sent: Monday, March 01, 2004 10:52 PM
To: Grand Challenge
Subject: Palos Verdes High School Road Warriors- Revised Technical Paper

Here it is!!

DARPA Grand Challenge Technical Paper

Palos Verdes High School Road Warriors

The *Doom Buggy*

Revised 3/1/04

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Introduction

A team of academically advanced and gifted students at Palos Verdes High School, along with students from other schools, is designing and constructing an autonomous vehicle. The project is divided into three groups: an administrative group, an autonomous systems group, and a vehicle/mechanical group. Many student members have extensive computing experience, and include experienced C/C++ programmers. One student placed first in the L.A. County Science Fair Robotics Division for an autonomous vehicle. The team is advised by science teacher Graham Robertson, who has decades of experience teaching gifted youth, and by a collection of advisors, mentors, and parents, many from industry and academia. UCLA, USC, JPL and NASA scientists have all volunteered time to review the work as it progresses. The preliminary design calls for visual input from a digital video camera in conjunction with a laser range finder to provide closed loop steering control. Gyroscopic and attitude sensing provide course correction and dynamical vehicle control input. GPS data is used in course planning and correction routines. Processing, image analysis, sensor fusion, and obstacle avoidance are accomplished by an array of concurrent processing units running Linux. Automation of the vehicle will be accomplished with a subsystem developed by Electronic Mobility Controls LLC, a company that designs and manufactures high quality vehicle controls that make driving accessible to individuals with high level disabilities.

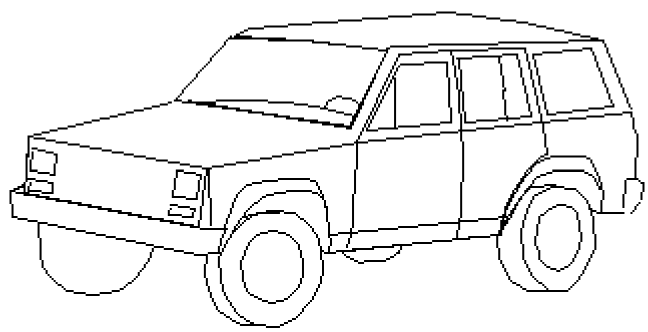
Vehicle

PV Road Warriors "Doom Buggy"

Length: ~15 ft.
Width: ~6.5 ft.
Height: ~6.5 ft.

Characteristics: 4WD, Automatic Transmission

Figure 1 Doom Buggy Configuration



The PV Road Warriors vehicle will be a stock four-wheel drive vehicle, modified for off-road use. The vehicle will ride on 4 tires and the suspension may be modified to increase ground clearance. Optional roll avoidance appliances are currently under consideration. A gasoline powered internal combustion engine will power the vehicle. The control of vehicle functions, such as acceleration, braking, and steering, will be performed by a driving control system based on the Advanced Electronic Vehicle Interface Technology (AEVIT) system from Electronic Mobility Controls (EMC) LLC, which modifies the steering wheel, brake and accelerator pedals with commercially available controls. The AEVIT system also provides updates every 100 msec. of current vehicle status, such as vehicle speed, which should be adequate for vehicle control loops.

Electric power will be obtained with a 12VDC alternator and a pure sine wave 120VAC inverter as needed, for AC powered equipment. The preliminary design utilizes an L-N series high power alternator to accommodate the electric power load presented by the on-board sensors, computers and safety equipment. The payload electric power usage will not exceed 1.2 kW, which includes the 5A/12VDC power requested by DARPA.

The vehicle will run on standard unleaded gasoline. It is anticipated that the vehicle will get between 5 and 10 mpg on the largely off-road course. With an expected range of 300 miles, the fuel capacity will be between 30 and 60 gallons, which may require modification of the fuel tank.

Vehicle air conditioning will provide the required cooling to ensure that the ambient conditions of the processing equipment are within published tolerance.

A passive platform will be designed utilizing materials developed to minimize mechanical shock to the processors and sensor mounts.

Processing

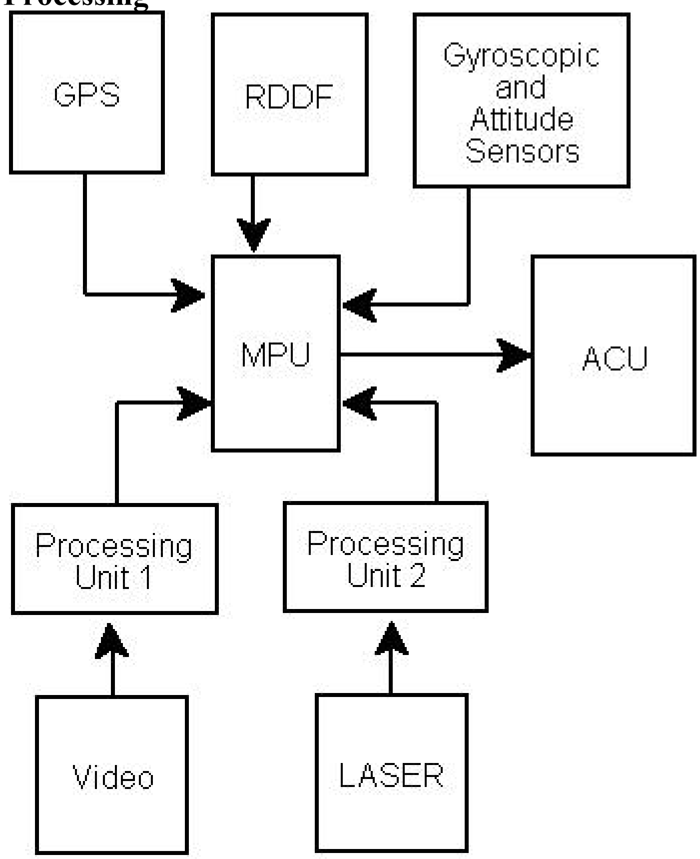


Figure 2: Basic Processing Structure

The PV Road Warriors Challenge vehicle, named "The Doom Buggy", employs a custom, hybrid computing system. A distributed network of units connected by a gigabit Ethernet switch performs the required processing. Figure 2 is a block diagram of the processing scheme.

The choice of storage media for onboard data is dependent on its importance to the function of the vehicle. For example, the mission-critical operating system, software, and parameters may be stored on highly reliable solid-state media that is relatively immune to high temperatures or other shock conditions. Secondary data, such as mapping, may be stored on regular magnetic media that, although are less reliable in extreme conditions, store many times more data than other storage components. Shock mounts and an isolation platform will be used to enhance the survivability of these components.

Except as noted, all units are general-purpose processor boards, running Linux, in an air-cooled shock-mounted rack. These units perform primary sensor processing, secondary sensor processing, sensor fusion, planning, and actuator control. Primary sensor processing units are devoted to processing laser data, video data, GPS data, and vehicle gyroscopic, attitude and health data. Primary video processing units perform color, texture and gray scale filtering and coarse image segmentation, primarily using DSP units. Secondary sensor processing units continue processing video data at a higher level, including motion sensing, roadbed/path location and horizon location. Sensor fusion units combine laser and video data to provide range, size and location of potential obstacles. Sensor fusion also involves a combination of gyroscopic and horizon data to determine vehicle attitude. Sensor fusion also sets up the data the planning units require to determine the type of path – e.g. dry lake bed, rocky path, sandy path, or paved road. Finally, GPS data is fused with image information in the planning units to assist in determining path selection and desired vehicle direction. Road roughness is determined through the detection of high amplitude Fourier components in the gyroscopic data, a primary determinant of vehicle speed. The Parallel Planning Units use stored topographic information along with several competing approaches to determine whether to brake, turn, accelerate, or hold the course. The Master Planning Unit (MPU) inputs plan information from the competing planning units, along with a confidence factor for each plan proposed, and makes a final decision based on the confidence each planning unit places on its decision, when there are multiple recommendations. The actuator control unit (ACU) translates the MPU's plan into specific commands to brake, accelerate and turn the steering wheel.

The methodology for sensor data interpretation involves preprocessing to determine answers to several simple questions: Should the vehicle go faster, slower, or maintain speed? Should the vehicle turn right, left or maintain direction? Should the vehicle brake? In order to answer these questions, the processing determines the answers to these secondary questions: Where are the sides of the road? Are there any turns to the right or left? Are there any obstacles, and if so how far away are they and how big are they? The video processing segments the image into chunks using color, gray scale intensity, texture and edge information. These chunks are correlated with a trapezoidal region of the image that is the vehicle's direct path. The highest correlation chunk is either the path/road or is an obstacle. Assuming the chunk is not an obstacle, the secondary image-processing unit determines the difference between the chunk's horizontal center and the trapezoid's center. This difference is used to control the vehicle steering. Because the vehicle steering must anticipate turns before the bulk of the chunk appears to shift, individual attention is paid to the shift of the upper half of the chunk. Depending on the vehicle's speed, the planning software may suggest changes to the vehicle's current steering settings. For paths like the sandy path, the correct vehicle direction may only be determined by examining spatial frequency information in the image.

Road markings will be handled in the following manner: Any white or yellow markings in the trapezoid will be segmented. Shape detection (using directional filters) will be used to determine markings that are long and thin (lane markings) versus embedded letters and horizontal lines. Lane markings will be labeled and used in higher-level steering decisions while other markings will be ignored and smoothed.

The vehicle will attempt to evade any obstacle taller than the ground clearance of the vehicle. Objects below a threshold size and shorter than ground clearance of the vehicle will be ignored. Objects that are taller than vehicle clearance need to be avoided completely. These objects require an adequate detection range so that, at the vehicle velocity, there is sufficient turn radius for the vehicle to safely steer at an angle that combines the vehicle size with the half width of the vehicle. Such steering will involve significant turning radii, which will need to be compared to limits that depend on vehicle attitude and speed. This feature will prevent unintentionally rolling the vehicle. Objects that are lower than vehicle clearance but above a certain threshold size will initiate a turning routine meant to avoid collision with the vehicle's tires. The turning dynamics for such an event requires less steering and less detection time and the vehicle can tolerate higher velocities. These algorithms take into account vehicle attitude, which imposes a speed-dependent lower bound on the turn radius.

Figure 3 is a chart of the effect of attitude and speed on allowable turn radius for a sample vehicle. The chart shows the minimum allowable uphill turn radius for the given speed and roll angle (the angle of the terrain across the vehicle path) to prevent vehicle rollover. A safety factor is built into the algorithm, which provides an additional 15% margin in radius.

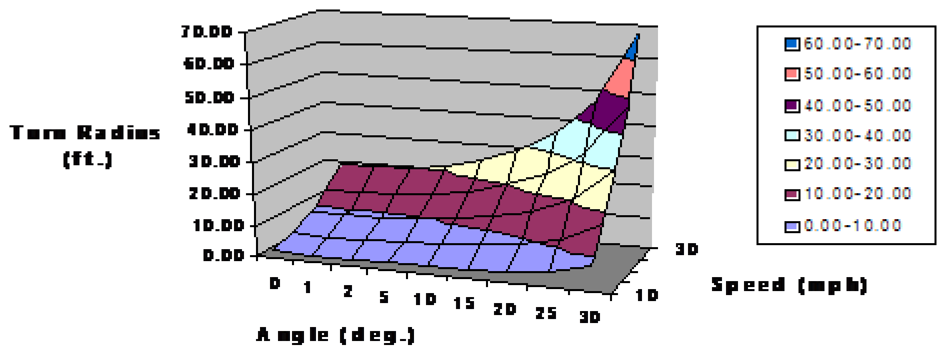


Figure 3- Minimum Turn Radius

The laser sensor processing determines obstacles in a plane immediately in front of and in a 180-degree radius around the vehicle. These obstacles are located in the image data during sensor fusion, and a check is performed to see if the obstacles fall in a trapezoidal region of the image that is the vehicle's direct path. Obstacles in the vehicle's direct path greater than a threshold size cause the Remote Obstacle Avoidance Processing (ROAP) to initiate. The threshold size is determined by examining the laser data, and correlating obstacles with the number of associated pixels (pre-segmented) in the visual image. ROAP uses the obstacle location, along with image sensor data about the path location, GPS data about the corridor, and path branches to the left and right, to determine whether to turn or brake or both. If there is a choice of direction, the ROAP processing tries to continue in the path that most closely fits the direct path to the next GPS *waypoint*. ROAP processing dominates (supercedes) other planning activities when obstacles are detected.

The system does not classify objects in the traditional sense (rock, tree, tumbleweed, SUV). Rather it determines the size of the object, the distance the object is from the vehicle, whether it is in the vehicle's direct path, and whether the object is moving or still. Thus, the vehicle might avoid tumbleweeds if they are dense enough to produce a confusing laser pattern.

On a macro level, the vehicle maintains a direction that would take it directly from its current position to the next GPS *waypoint*. For locations like a dry lakebed, where there is no obvious path, this information will have the highest confidence factor and be used directly in determining steering. However, for other locations, the direction the road is taking is of primary importance and dominates the choice of direction. If there is a choice of paths (path branches to the left or right or both) the path with direction closest to a straight line to the next *way point* is chosen, checking current location against corridor location to be sure that that path does not take the vehicle out of the corridor

Once the master planning unit (MPU) has determined the plan to take (e.g. turn 20 degrees to the left, increase vehicle speed), the Actuator Control Unit (ACU) translates the plan into specific signals to the actuators to brake, accelerate and turn the vehicle. The Actuator Control Unit interfaces to the AEVIT system Driver Module that translates the received signals into servo actuator control signals to implement the plan.

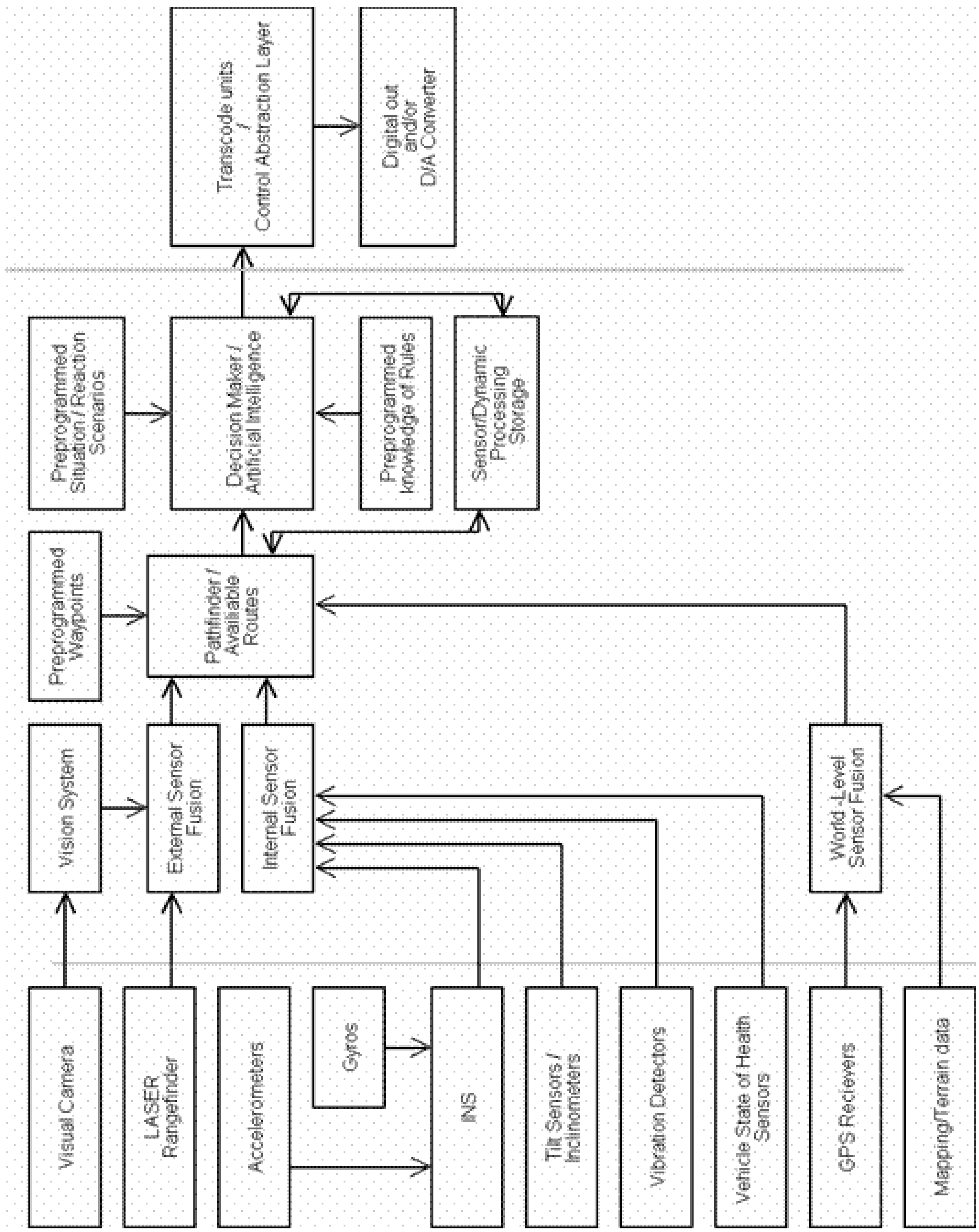


Figure 4- Detailed System Components

With a few exceptions, most of the programming will be in C/C++. Higher-level scripting languages may be used for sections where speed is not a primary concern or where it would be required that the code be easily read or modified.

Mapping

USGS topological maps will be used to provide terrain and road information. However, due to the off-road nature of the competition, the vehicle will not rely on this data as the sole source of information about possible routes. The RDDF Data will be parsed as it is loaded onto the vehicle and stored in onboard main memory.

External Sensors

The Doom Buggy will be using a laser range finding system, a video camera, a gyroscope, GPS, and a vibration sensor to determine the location of the path being taken, location of the vehicle, obstacles in the path, and the condition of the road/path surface.

The video camera and laser will be shock-mounted on the dashboard of the vehicle. The GPS receiver, gyroscope and vibration sensor are located in the interior of the vehicle. Except for sensor locations that require visual access, all vehicle windows will be sealed with R2 insulation to minimize heat gain.

The video camera is a generic, high-resolution color digital camera capable of approximately 30 frames per second. The video stream from the camera is transmitted digitally into the computer in real-time. The resolution of the video camera will be at a minimum of 680 kilopixels, in the interest of detecting obstacles with a visible surface area of greater than 9 square inches at a reasonable distance. The stream must have sufficiently low detail as to allow processing to be completed with minimum latency so the vehicle does not move too far away from the position where the data was recorded by the time it reacts. We are assuming a field of view of approximately 50º, which is customary for commercial video camera lenses. That field of view will give us a resolution of at least ¼ inch at 10 feet, and 1 inch at 40 feet.

Road boundaries and obstacles will be reliably detected when the vehicle is bouncing over rough terrain and turns. We will use a rapid shutter speed of 1/8000 sec. to minimize blurring. We will mount the camera and other sensors on a platform designed to absorb shock. Inertial data will normalize the image perpendicular to the ground when the vehicle is tilted one direction or the other. In addition, when the vehicle is driving over uneven terrain, the normalization process attempts to use information from previous images to locate the horizon and road. Topographic information may also be used to locate the horizon and road. Images that do not normalize to recognizable data can be skipped because the frame rate of 30 frames/sec. is more than sufficient to allow us to dispose of "bad frames." If the vehicle is tilted upward or downward so that the camera is facing images of sky or ground, the autonomous control can use pitch information to discard those frames.

The laser system will be a LMS 211 or 221 device manufactured by SICK, Inc., whose web site is located at http://www.sickusa.com. Both systems are categorized as class 1 (eye safe), and scan a maximum arc of 180°, with an angular resolution of ¼ °, or 2.5 inches at 50 ft distance.

The vehicle state includes engine speed, wheel rotation speed, ground speed, current direction and current steering wheel position. In addition, sensors will provide vehicle attitude with respect to the horizon and 3-axis acceleration. The EMC AEVIT system interfaces with the vehicle control module providing some of these parameters. Additional sensors will be identified or designed to provide the rest. The state is read directly into the control computer via digital interface.

Sensors that facilitate moving in reverse with a maximum range of 6 feet (such as a sonar collision avoidance system like the Sonar Wireless Backup Alert made by Assis-tech) may be used to assist the Dune Buggy should there be a situation where it must back up. However, in consideration of the timeline and final simplicity of our design, these sensors may not be used in the initial version of the vehicle. Also, any such system would be a consumer-grade product generally recognized as safe and non-interfering.

Geo-location

The system uses GPS to determine its geo-location with respect to the Challenge route. On-board topological data will also be used to determine possible pathways between waypoints.

In the event of a GPS outage, the vehicle will continue in the direction last computed as the direct route t

In the case of an underpass (or other narrow path with obstacles on the sides), in addition to the above processing, ROAP will detect the underpass walls as potential obstacles. Since ROAP takes precedence over GPS, the system will attempt to locate the underpass corridor precisely by detecting obstacles (the underpass walls) on either side that define the corridor.

The system computes the approximate distance away from the imaginary line between waypoints and attempts to reduce that distance to zero, while remaining on the road or path. Ideally, the system would try to stay at least 2 meters away from the boundaries at all times, except for when the challenge route boundaries are too small to allow such margin of error, or when the only identifiable route is that close to the boundaries.

The GPS units are NAVMAN TU60-D120 12 channel GPS, ASHTECH DG16, and GARMIN GPS16A, all of which are 12-channel WAAS-enabled, with a 95% position accuracy of 3 meters. (e.g. see http://waas.stanford.edu/metrics.html) . WAAS is critical to keep us within the corridor and on the course.

Communication

Telemetric data concerning vehicle status and position will only be broadcast from the Doom Buggy during testing. Telemetry will be disabled during the race, and the vehicle will not broadcast any wireless signals. Input from the camera used for autonomous guidance and/or a separate camcorder will be recorded on-board the vehicle for analysis after the race.

Except for GPS and the E stop, the challenge vehicle will not accept any wireless signals.

Autonomous Servicing

The vehicle will follow waypoint directions for the checkpoint and will drive itself to the required position. However, the vehicle will not receive any autonomous servicing or refueling during the race. The vehicle tank will contain all of the fuel that will be needed to complete the challenge course. Minor servicing, such as keeping the sensor apertures clean, will be performed by systems on the vehicle.

Testing

Testing of the vehicle is conducted via a thorough structured test plan. The test plan requires intensive testing of the vehicle and algorithms both independently and integrated. Testing will be performed in environments increasingly similar to the challenge route, beginning with paved parking lot testing and ending with a mock off-road route.

During testing the vehicle will be able to send and receive wireless commands. However, as the wireless equipment must be disabled or removed before the QID and the race, the only way to manually control the vehicle is by connecting a laptop via a cable and sending commands through that. Most gross movement of the vehicle before the race will be accomplished by towing the vehicle.

Wireless command and control and telemetry will be used during testing. The vehicle will have had the ability to accept wireless instructions. However, all equipment to send or receive wireless signals other than GPS will be removed from the vehicle before the QID and race.

We are currently using a golf cart as our sensor/processing test bed while the actual vehicle is being readied. At this point, we have run several tests concerning the stability of our sensor platform as well as the control dynamics and implementation of mechanical control on the golf cart and final vehicle. We are planning extensive testing of the autonomous systems. A golf cart is ideal as it is easy to implement control devices and allow a human to physically control the brake as an emergency stop system. The vehicle will also be tested with a human backup driver who can readily control the vehicle.

The challenge route photos provided by DARPA, as well as video streams from the golf cart, are currently being used to test the processing algorithms indoors in the lab.

Safety

The top speed of the basic vehicle is in excess of 100 mph, but it is planned that the vehicle will not exceed 60 mph during the challenge race. The vehicle design has a modified fuel tank to store up to 60 gallons of gasoline, to allow a minimum range of 300 miles. Depending on the realized fuel efficiency, the maximum range could be about 600 miles, but the plan is to store less fuel to have a maximum range of about 300 miles. The vehicle design includes a modified fuel tank in order to achieve the range required for the challenge.

The vehicle design includes warning lights and an alarm as required by the Challenge rules. The vehicle will emit a warning sound measured at least 116dB 10 feet in front of the vehicle whenever it is in motion, five seconds before it will begin moving, and whenever the autonomous systems are functioning, even if the vehicle is stopped. The sound will stop as soon as the vehicle ceases to move after a normal or disable E-Stop.

The warning system includes a Code 3, Model F-LB006 amber LED 12 Head 36" lightbar, mounted on t

The audible alarm design includes a vehicle mounted loudspeaker/siren (Atlas T70G or equivalent) with

Both the warning light and the audible alarm will be activated for at least 5 seconds before the vehicle st

The fuel tank is protected from puncture both with undercarriage plate shielding and reinforcing. It is exp

For fire suppression, the design includes the FX-400 fire extinguisher manufactured by Firefox Industrie

E-Stop

When the E-Stop signal is received and the normal E-Stop is activated, a signal is sent via the onboard network instructing the processing units to a) cease accelerating the vehicle, b) apply the braking mechanism, c) continue processing and steering along the current path, and d) once the vehicle is stopped, disable any warning sirens and lights. This series of commands should stop the vehicle in a short distance without causing any damage to the vehicle or positioning itself so the vehicle cannot resume after the E-Stop is cleared. The processing units will place themselves into 'E-Stop' mode and will follow the above instructions until they are directed otherwise. When the vehicle may resume, it will simply execute the opposite instructions in reverse order, with the 5-second delay after reinitializing the warning lights.

The disable E-Stop, in addition to executing the normal E-Stop to control the processing units, also bypasses the processing system entirely, shutting off the fuel pump and engaging the parking brake. This way, the disable E-Stop will function regardless of the state of the processing equipment (damaged, infinite loop, etc)

The PV Road Warriors vehicle has an automatic transmission. The design includes an actuator to shift the vehicle between neutral and drive. This control can be activated manually or under computer control. The vehicle design includes a hitch for towing the vehicle. The vehicle is towable by a conventional automobile tow truck.

Radiators

The LASER scanner emits class 1(eye safe) laser radiation. Exact laser frequencies and power are to be determined. No other EM radiations are anticipated, except for the nominal radiation from the processing system itself.

The only device that produces a significant amount of noise, besides the vehicle engine, is the required warning siren, which produces 116dB at 10 feet under the conditions specified above.

Safety measures and procedures related to light and sound radiators are TBD and will be submitted in an addendum.

Environmental Impact

The vehicle is a standard mid-sized Sport Utility Vehicle with approximate dimensions 15 ft x 6.5 ft x 6.5 ft. The expected weight is 4000 lbs. An as yet unincorporated, but possible, design feature is side extensions (extra wheels) that would reduce the chance of vehicle roll. This would add 2 ft. to 3 ft to the width of the vehicle. The need for this will become clearer as we study the vehicle dynamics of the Doom Buggy.

The vehicle rides on four tires that are the widest that the vehicle can accommodate (9”-10”). The operational plan is to run the race with the tires slightly under-inflated to improve traction. The footprint of each tire is therefore approximately 100 sq. in. for a total vehicle footprint of 400 sq. in. The weight of the vehicle, at 4000 lbs, yields a maximum ground pressure of 10 lbs/sq. in.

Acronyms

ACU	Actuator Control Unit
AEVIT	Advanced Electronic Vehicle Interface Technology
DARPA	Defense Advanced Research Projects Agency
DSP	Digital Signal Processor
EM	Electromagnetic
EMC	Electronic Mobility Controls
GPS	Global Positioning System
INS	Inertial Navigation System
JPL	Jet Propulsion Lab
LA	Los Angeles
LLC	Limited Liability Corporation
MPU	Master Planning Unit
NASA	National Aeronautics and Space Administration
QID	Qualifying Inspection and Demonstration
RDDF	Route Description Data File
ROAP	Remote Obstacle Avoidance Processing
SUV	Sport Utility Vehicle
UCLA	University of California Los Angeles
USC	University of Southern California