DARPA Grand Challenge Technical Paper for Team CyberRider

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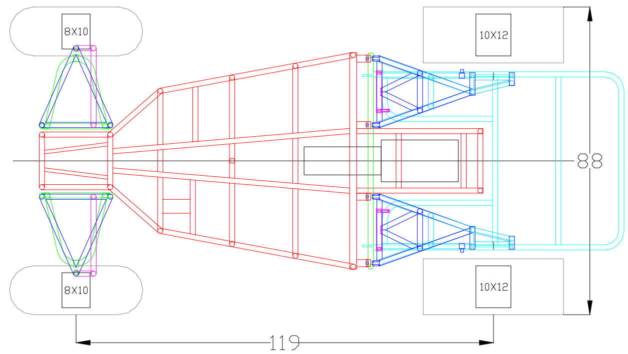
Summary: A robust vehicle with long travel suspension enables traversing rough terrain at high speeds. The main sensing unit – a dual beam sweeping laser, easily detects the edges of obstacles and terrain gradients in real time, regardless of vehicle pitch and roll, by differentiating each beam return signal sequentially and comparatively.

1. System Description: Figure 1:



a. Mobility:

1. Ground contact:

Four wheels with pneumatic rubber tires. Rated tire diameter is 39" front, 44" rear. Ground contact area (8x10;10x12) is shown in rectangles. (unit of measure: inches)

2. Locomotion:

A six cylinder internal combustion engine (GM V6 3.1L) provides power thru a 3 speed automatic transaxle (P-R-N-D-2-1) The transaxle outputs to 2 drive shafts, each having 2 constant velocity (CV) joints. Each drive shaft is connected to a drive sprocket on a bearing supported shaft, anchored to the frame, which is in line (concentric) with the pivot of the rear trailing arm. A driven sprocket is bolted to the hub axle, turning the rear wheel. A chain on each side transmits power between the sprockets (similar to a motorcycle).
Steering: Howe quick turn power steering rack connected to front wheels thru 2 tie rods. Front wheels are supported by pivoting knuckles with long arm suspension members. Rear axle incorporates minimal roll steer geometry but no active steering.
Brakes: Dual hydraulic ABS system, front and rear vented disc brakes.

3. Actuated mobility components:

Steering: Hydraulic, modified Howe power rack with custom torsion bar controlling hydraulic valve, actuated by Hitec power servo.
Brakes: Customized Hydratech hydro boost system actuated by stepper motor lead screw, with parallel mechanical linkage to emergency brake air cylinder to provide power off fail safe.
Shifter: Pneumatic cylinder, two 3-way solenoid valve with flow restrictor, six position limit sensing stops to provide Park, Reverse, Neutral, 3,2,1 gear selection
Throttle: HiTec power servo; Ignition bus: electric relay; Starter motor: electric relay
Main fuel valve: electric solenoid

b. Power:

1. Power sources:

For propulsion and battery charging systems: Internal combustion engine (GM 60V6, 3.1L) equipped with 140 Amp alternator. One 12V starter battery, 2 x 12V auxiliary batteries, 1 smaller 12VDC battery for auxiliary disable circuit. Switching power supply will provide 5V and 3VDC. A 10 pound CO_2 cylinder provides gas pressure to actuate the transmission shifter, emergency brake system and other pneumatic components.

2. Power Consumption:

Approximate peak propulsion system power 140kW, Navigation system 1.5 kW.

3. Fuel type:
33 gallons of Propane, nominal.

c. Processing:
1. Hardware:
The computational systems on-board the vehicle are divided into several functional blocks, each aligned to a particular system or task, and interconnected via Ethernet in order to send and receive commands and sensory data. The architecture follows a “Sense-Model-Plan-Act” model for autonomous vehicle control, with adaptations to provide for data access and logging across these functional blocks:

System	Purpose	Hardware
PROPULSION (single node)	Dedicated control and supervision of vehicle locomotion, including engine, braking and steering. Responds to commands issued by the **DRIVER** node within the vehicle safety and performance envelope. Implements the response to a hardware E-Stop.	Implemented on a single CPU, currently specified as an Intel IXCDP1100 board running QNX Neutrino. 512MB SDRAM
SENSOR (multiple nodes, currently specified at two)	Management and data processing for one or more sensor packages (Ladar, GPS, compass, etc.). Includes hardware interface to the sensor(s).	Implemented using VIA Mini-ITX small-footprint PC motherboards, with EDEN ESP 1GHz processor running the GNU/Linux operating system. 512 MB SDRAM
SUPERVISOR (single node)	Central node in a star topology for communication, collects, logs and distributes information from multiple sources. Also performs high-level watchdog functions for the system.	Implemented using VIA Mini-ITX small-footprint PC motherboards, with EDEN ESP 2GHz processor running the GNU/Linux operating system. 1GB SDRAM
NAVIGATOR (single node)	Repository for terrain database, including digital elevation maps, vector representations of environment. Pre-loaded with available data, this node also collects and records sensed navigation data. Aligned to the “Plan” functional block, this node performs the macro navigation tasks.	Implemented using VIA Mini-ITX small-footprint PC motherboards, with EDEN ESP 1GHZ processor running the GNU/Linux operating system. 1 GB SDRAM
DRIVER (single node)	Responsible for sensory fusion and high frequency decision making, this node issues commands to the PROPULSION node. Part of the “Plan” functional block, this node is responsible for the real-time, micro navigation tasks.	Implemented on a single CPU, currently specified as an Intel IXCDP1100 board running QNX Neutrino. 512 MB SDRAM
VISION (single node)	Gathers and processes camera data into digested data products for the **DRIVER** and **NAVIGATOR** nodes, primarily obstacle avoidance, lane following and surface characterization information.	Implemented using VIA Mini-ITX small-footprint PC motherboards, with EDEN ESP 2GHz processor running the GNU/Linux operating system. 1GB SDRAM

All nodes use compact Flash cards for ‘hard’ memory.

A separately powered independent stand-alone PC board with hardwired logic monitors the 'hard' E-stop binary signal output and the manual E-stop switches and implements the disable mode (communicating directly with affected actuators) in case of a commanded 'hard' E-stop.

2. Control methodology:

Following a "Sense-Model-Plan-Act" cycle, sensor data is gathered by **SENSOR** nodes and digested and/or filtered into a data product for communication to the **SUPERVISOR** node. This data is supplied to Model nodes (**DRIVER** and **NAVIGATOR**) for time-offset correction and integration into a pose estimate and environment model. The environmental model is based on a discrete occupancy grid, each grid step being .000001 nautical degrees or 4.4 inches. The grids horizontal and vertical axis represents latitude and longitude, allowing direct correlation to waypoints tracks etc. Each grid location is assigned a value that represents the probability that it is occupied by an obstacle. Initially all grid values are set at 50%, except the course boundary which is locked at 100%. As the sensors scan the surrounding terrain, particularly in the direction of the planned path, the grid values are adjusted. The objective is to 'clear' the grid points in the planned path as quickly as possible so it can be traversed. The dual beam scanning laser is perfect for this task. After clearing the points immediately in front of the vehicle the laser is aimed progressively further and further away till a distance is reached compatible with the planned speed and related avoidance maneuvers. By continuously comparing the distance of adjacent points, comparing the distance between contemporaneous signals from the 2 beams, and differentiating the distance between each sweep, comparing to expected values for 'flat terrain', changes in the terrain due to the terrain itself or obstacles can be detected within 25 mS. Progressive scans yield information of the (vertical) size of the threat. The radar complements the Ladar by giving information about larger objects further away, plus moving objects in a wider field of view. Likewise, the sonar sensors and the tactile sensors yield information of objects close by for slow, precise speed navigation. The stereo camera helps further define objects in case of need. A drivable (safe) path is calculated based on examining each initial path grid points (imported from the navigator) location to a potential threat, and modifying the initial path for fastest travel (optimizing distance with path curvature. Here the size of the vehicle is also taken into account, and its dynamic steering capabilities. Max speeds defined in the course are taken into account. The **SUPERVISOR** node establishes the control regime for the entire system based on sensory data and mission phase, and is part of a global data set that any system node may use to establish operating parameters. The **SUPERVISOR** is also tasked with asserting a software E-Stop signal if the system health is degraded below minimums. The **NAVIGATOR** determines goal-based routes subject to problem constraints such as course definitions and a priori knowledge of terrain navigability from databases. These routes are fed to the **DRIVER** and updated based on the most current pose estimate. The **DRIVER** node maintains the local environment model and uses it to calculate locomotion commands based on input from the **NAVIGATOR**. The environment model includes elements describing "threats", further classified as either static or dynamic threats, the latter being a moving object such as another vehicle. Based on sensory inputs and the database, objects (obstacles) in the vehicle path are classified as permanent or temporary. Temporary obstacles are objects that either move or are expected to move in the grid. For example see exhibit A. The **PROPULSION** node receives commands from the **DRIVER** and may decline or modify the command based on safety or performance parameters.

The software is developed according to well defined formal methods based on the SEI-CMM; with design documents, coding standards, and state and timing charts. The majority of the software is developed in the C programming language, with some assembly language routines as needed for custom hardware initialization. Each processing node will send a heartbeat notice to the SUPERVISOR module, and the SUPERVISOR module will regularly broadcast a heartbeat message to the other processing nodes. In the event of two missed heartbeat messages, the SUPERVISOR node will trigger an e-stop and a soft reboot of the failed processing node. In the event that the SUPERVISOR module fails to issue a heartbeat message, any other processing node can trigger a restart of the SUPERVISOR node. The processing nodes will be protected from power supply failures by an auto-switching dual power supply; other critical subsystems will be monitored by watchdog routines in the processing nodes and can take appropriate actions based on the cause of failure. Flow chart see exhibit B.

d. Internal Databases:

The on-board terrain database is composed primarily of digital elevation models, typically sourced from USGS. A commercially sourced composite database (from Terrain Navigator and Lowrance) of man-made features such as roadways, railroad tracks, power lines and fence lines, has been digitized to matching format and is used in the path planning. Other layers, such as the hydrological features of the region, are stored for use in calculating navigability or sensor disambiguation. The database will be augmented with layers describing desirable routes across specific terrain that **NAVIGATOR** may use to construct routes during the mission. The terrain database is populated with sensed data during the mission and discrepancies from pre-stored data are managed to optimize route calculations in scenarios such as backtracking.

e. Environment Sensing:

1. Sensors:

Main Ladar unit: Dual laser beams.
Dual purpose: create forward looking terrain profile and detect positive
and negative obstacles in forward field of view.
It will detect 2" diameter objects (fencepost).
Side Ladar units:(angular left and right).
Dual purpose: detect road edge and marked side boundary
(fencing, concrete barriers, highway guardrails etc), create close up forward looking terrain profile.
Radar unit: (Epsilon Lambda Electronics) Selectable 40/16 degrees azimuth field of view, 2 degrees resolution, range 400 ft. Purpose: detect large obstacles far away, detect and track moving large objects (other vehicles, trains), back up for main Ladar unit.
Sonar array: 3 front, 4 per side, 3 rear. 40 kHz. Range 1 -15 ft, cone angle 15 degrees. Purpose: low speed collision avoidance. Low relative speed maneuvering close to other moving vehicles (Passing, yielding).
Tactile sensors: 3 front, 2 per side, spring loaded, front sensors with single micro switch, side sensor with dual position micro switches. Purpose: front sensors back up for sonar in close range maneuvering. Side sensors to detect and track close range distance to objects like barbed wire and chain link fencing.
Stereo camera: (Point Grey Bumblebee) Purpose: Assist in determination of ‘road surface type’, road edge detection. Identify type of and distance to obstacles (vehicles, brush, plants, barbed wire, fence openings) in low speed exploratory phases, detect dust clouds.
Conductivity sensors: (2) for water presence sensing.
Depth finders: (2) 200 kHz sonic sensor) to detect water depth in front of each wheel.

2. Sensor location and control:

Main Ladar unit: mounted on table that can pan 360 degrees and tilt 45 degrees. Table mounted on cross tube 3 ft behind front wheels, tube located on top (6 ft above ground).
Side Ladar units: fix mounted 4 ft above ground in center of front swingarm support. Aimed 45 degrees forward/down/left, forward/down/right.
Radar unit: Antenna can pan 350 degrees. mounted right side on cross tube 5 ft behind front wheels, tube located on top 6.5 ft above ground.
Sonar array: fix mounted right above 'bottom' frame tubing approx 2 ft above ground. Front

and rear center mount plus one each at 2 ft spacing, side units mounted equidistantly 5 ft apart.
Tactile sensors: fix mounted, spring loaded, side sensor normally folded along side of vehicle, 2 ft and 4 ft above ground, extending 2 ft sideways when actuated by pneumatic cylinder.
Stereo camera: mounted on table that can pan 180 degrees and rotate 90 degrees. Table mounted 1 ft in front and 8 inches below main Ladar unit.
Conductivity sensors: mounted below front bumper, 4 ft apart, 2 ft above ground.
Depth finders: mounted in front on pneumatically activated retractable arms, that when extended, position depth finders 1 ft in front of each front wheel, 1.5 ft above ground.

f. State sensing:

1. Sensors:

1 Two axis inclinometer. 20 degrees tilt, 8 bit precision.
4 Rotary wheel-speed sensors, 61 tooth front wheel, 69 tooth rear.
6 Linear motion position sensors, shock absorber position sensor, 8 bit precision.
2 Gyros, .5 – 75 degrees per second.
2 Accelerometers, .05 – 3g.
1 engine tachometer, 0 – 8,000 rpm.
1 cooling water temperature sensor, 120 – 260 degrees F.
1 shifter position sensor, binary 6 outputs.
4 pressure transducers, 0 –100 psi.
2 pressure transducers, 0 –2000 psi.
Certain other sensors are present in self regulating systems (i.e alternator, ignition, gps)

2. The tachometer is used to verify that the engine is running (start, idle) and prevent the engine from over-revving. The cooling water temperature sensor is used to turn on cooling fan when needed and limit throttle position at excessive temperatures. The shifter position sensor generates feedback during shifting and stops the actuator in the desired position. One linear motion position sensor is used to generate feedback on actual throttle position. One linear motion sensor generates feedback on the steering rack position. The 2000 psi transducers generate feedback from the brake lines.
One gyro determines yaw rate and in combination with the front wheel speed sensors are used to correct steering maneuvers as well as for odometric localization in areas of poor gps reception. 4 linear position sensors monitor shock absorber extension and generate feedback on ride height, wheel vibration (sense road surface condition), flats, the health of the suspension components, all information used in determining speed. The the 2 axis inclinometer determines the operating plane (tilt measurement) of the vehicle. It is used to create an absolute reference plane for some of the environment sensors (i.e the Ladars and radar). It is used if he sun is obscured. The tilt measurements are also used to determine the vehicle's risk for a roll-over. Two gyros are used to measure rate of change in vehicle tilt during pitch and roll, inputs also used for stability control. The 2 accelerometers are used to measure vehicle acceleration and braking as well as compensating input to the inclinometer readings.

g. Localization:

1. Geolocation:

The primary method of geolocation used during the mission is a system of multiple Differential GPS receivers, including a Real-Time Kinematic receiver (CSI Vector) that is used for heading determination at zero velocity. Each component of the system outputs an independent estimate of location and these data streams are compared to detect system anomalies. A faulty receiver, or one that has lost signal, is dropped from the composite location estimate. System performance can be maintained at a degraded level after the loss of some system components.

2. Loss of GPS signal:

In the event of a total loss of GPS signals, the system can maintain an accurate location estimate by "dead reckoning", using the four independent wheel rotation encoders in conjunction with two independent heading determination subsystems, a gyro and an electronic compass sensor.

3. Challenge Route boundaries:

Challenge route boundaries are integrated into the **NAVIGATOR** database and are considered a maximum static threat, so a route can not planned to intersect a boundary.

h. Communications:

1. Broadcast signals:

There are no contestant supplied transmitters or other intentional radiators for communications on-board the vehicle. Provisions for the DARPA-supplied E-Stop unit have been made in the power budget.

2. Received signals:

There are two types of receivers in operation on-board the vehicle.

The first type of receiver is a system of L1 (1575.42 MHz) Global Positioning System receivers utilizing the freely available Standard Positioning Service. Additionally, these receivers will typically make use of the satellite-based augmentation system "WAAS", which is also freely available. The use of these signals is intended to comply with sections 6.1 and 6.7 of the Grand Challenge Rules (v1.2).

The second type of receiver is for Differential GPS. The vehicle will carry a tunable receiver operating between 283.5 KHz and 325 KHz to receive DGPS corrections broadcast by the United States Coast Guard. As these transmissions are freely available for use, this receiver is intended to comply with sections 6.1 and 6.7 of the Grand Challenge Rules (v1.2). The coverage and effectiveness of the USGS DGPS corrections is uncertain in the region of the course, so the need for additional DGPS resources is anticipated. Pursuant to section 6.7 of the rules, the use of a subscription-based service is requested. This service will be provided by OmniSTAR USA, Inc. and will consist of an L-band satellite receiver. This will receive only DGPS correction information and is compliant with section 6.1 of the rules in that the data received is entirely beyond the control of the team.

i. Autonomous servicing:

1. Refueling:

None planned at this time. The vehicle's design includes sufficient consumables to complete the mission without replenishment.

2. Additional check point service:

None planned at this time.

j. Non-autonomous control:

During pre-race preparations, and upon race completion, movement of the vehicle under its own power will be accomplished using a tethered joystick control. An electronic steering wheel, gas and brake pedal connected to the DRIVER node can be activated with a switch.

2. System Performance:

a. Previous tests:

1. A trinocular camera system (3 fire-I cameras) plus a regular digital video camera was hard mounted to a 4WD vehicle and operated while traversing various types of roads and terrain in the Mojave desert area.

Results: 6 different road types were characterized and classified: paved line marked 2 lane, paved unmarked rural, gravel rural, 'cut' dirt road, jeep trail, off-road race course trail. In addition the following terrain was traversed and characterized: a pond, river washes with flowing water, dry washes, dry lakebeds. The latency of the trinocular system was found to be 200 mS.

2. 3 different WAAS corrected GPS systems (Garmin, CSI and Cultiva) were tested at an OHV area near Barstow. At the same time data was logged from a digital compass/inclinometer combination sensor (PNI TCM2). Data was also logged from a Motionpac II from Systron Donner consisting of 3 gyroscopes and 3 accelerometers. All instruments fed a ruggedized laptop that was mounted on a class 10 off-road race car. Python software was used to keep track of the serial stream. A separate video camera recorded the terrain independently. A practice race course was traversed at speeds of 10 - 55 mph. Results: Both the Cultiva and the CSI units output signals at 5 Hz and seemed to be accurate within 3 ft. Repeatability was better than 1 ft. The gyros from the Motionpac drifted and their AD converter was too slow for real time use. The PNI module performed well at 10 Hz.

3. An air bag suspended class 1 race vehicle was tested for performance characteristics also at the Barstow OHV area. Braking, acceleration and maneuverability thru a slalom course was recorded. A video camera was mounted and roll and pitch recorded over a practice race course . Results: safe brake force .7g, max lateral acceleration .5g. Max roll +/-12 degrees, max pitch +/- 5 degrees. Max roll/pitch angular velocity 20 degrees per sec. This vehicle is now being converted to become the Autonomous Ground Vehicle (AGV) for our race entry.

4. A Ladar system from Laseroptronix was tested outside Stockholm, Sweden. The laser created a forward looking horizontal line scan. When aimed at the ground it creates a cross-sectional ground profile. Results: The receiver sensitivity threshold was 400m in daylight (1m object). Distance measurement accuracy 5 cm. Max speed 40 Hz. The paved road edge was clearly detectable up to 45m away. A ditch running along side of the road was detectable up to 250 m away. A 30 cm tall box was detectable.

5. A simple path planning algorithm was tested on a small robot with proportional steering and speed controls. Results: Communication between the DRIVER node (in this case a laptop) and the wheel motors was successfully established. Path following was not precise as an internal clock was used in an open loop. (rather than position feedback).

Planned Tests:

1. The application and driver software will be verified using formal methods based on UML for Real Time, as well as other methods such as Rate Monotonic Analysis and Dynamic Monotonic Analysis as appropriate. Each software module will have a formal test plan and software test harness that can be executed on the development machines, and there will also be formal integration and performance tests.

2. The small robot is being outfitted with rotary encoders, a digital compass, a GPS receiver and 4 sonic sensors. The robot will be used as a scalable test bed for the computer hardware, algorithms and software, as well as the communication protocol for the various nodes of the computational system.

3. A street-legal 4WD is outfitted with the Ladar, Radar, Camera and Sonic sensors described above, connected to corresponding sensor nodes. The signals are recorded to establish signal signature strength and noise level for different road (ground surface) types; lane-, side- and path-markers, rocks and vegetation, fencing, power lines, static and moving obstacles etc.

4. The AGV is fitted with all the state sensors described above and a video-camera. The nodes responsible for signal processing are used to record signals and generate a time stamp for the video-camera while the AGV is driven in different terrains. Several tests are expected until all sensors perform satisfactory in the mobile environment.

5. The AGV is fitted with the GPS receiver and the Ladar systems and its sensor nodes. Algorithms for mitigating effects of vehicle movements (as defined by various state sensors) on the Ladar tracking system are verified and refined. The main Ladar system's capability of detecting and locating obstacles on a reference grid is verified. The side Ladar systems capability of detecting road-edges, snow fencing, concrete barriers, and guardrails is verified.
6. The AGV is retrofitted with actuators for 'drive-by- wire' operation, an electronic steering wheel and electronic brake and gas pedals. A manual switch allows switching between manual and automatic operation for each function. Response and feedback is verified. An unobstructed GPS track is generated and then followed manually. The commands from the DRIVER node are displayed and recorded. When in close approximation, actual driver actions, autonomous steering, acceleration and finally braking are progressively enabled and tested.
7. After the computer software and hardware have performed successfully in the small robot test bed, it is moved over to the AGV. The AGV is now also fitted with all remaining sensors, safety features etc. A check-out procedure for testing the condition and state of each component is established. All systems are activated and the AGV operated for an extended time period.
All components are checked for excessive temperature. Battery voltage is recorded to ascertain that the alternator can keep up with actual power demand.
8. A sample route within a sample area will be requested from DARPA. A data base containing information about terrain and road alternatives within the sample area will be processed together with the provided sample route (containing waypoints, lateral boundary offset and max speed). The algorithms selecting best path within the lateral offsets are tested and evaluated. When deemed reasonable, the best path will be loaded into the NAVIGATOR node's memory and the AGVs performance will be tested under progressively more difficult situations: Static obstacles of various sizes (positive and negative) will be added, and finally moving obstacles. Maneuvers such as car following, car passing, merging into a single lane with car on side will be tested.
9. The AGV will be given a wide boundary track through a wash, a dry lake bed, and a lava field with little or no road definition, and the algorithms for best path selection based on the fusing of data from Ladar/radar/vision sensors will be tested and evaluated.
10. The AGV's capability to follow a boundary consisting of a barbed wire or chain link fence as well as finding an opening therein will be tested. The AGV's capability of finding and negotiating an underpass will be tested.
11. The AGV's capability to detect a water hazard and find shallowest crossing area will be tested.
12. The AGV's behaviour in a simulated hard and soft E-stop, a simulated refueling area and crossing a finish line will be tested.

3. Safety and Environmental Impact:
a. Vehicle top speed: approximately 80 mph

b. Maximum Range: 320 miles

c. Safety Equipment:
1. Fuel containment:
Manchester 33.2 Gallon ASME rated propane tank (41.5 gal water capacity). Excess flow valve (stops fuel flow if fuel line ruptures). All fuel plumbing per ANSI 58.
(note if DARPA or SCORE will not allow propane fueled vehicles, We will convert to gasoline and use a 35 gallon roll-over safe fuel cell)

2. Fire Suppression:

Spark arrestor, 2 fire extinguishers (1A10BC) with quick release handles mounted on each outboard side of vehicle. Other safety equipment: Neutral/park switch. Vehicle can only be started if in neutral or park.

3. Audio and visual warning devices:

Electronic horn: (Ademco 702) modulated to 60 x .5 second pulses per minute, 118 dBA at 10 ft distance in front of vehicle, controlled via optocoupler from main PLC, powered by starter battery thru modulated HexFET, with Manual On and Off override.

Visual Warning Device: Amber flashing strobe light (Federal Signal FB2PST), controlled via optocoupler from main PLC, powered by starter battery thru HexFET.

Brakelights: Two red 3" LED lights controlled by limit switch in dynamic braking system, powered by starter battery.

d. Emergency Stop (E-stop)

1. Normal E-stop mode:

An I/O board from one of the SENSOR nodes monitors the logic (binary) output from the on-board E-stop receiver. The output can be either STOP or GO and can switch between the 2 states. The PLC outputs visually (LED) the input from the E-stop.

E-Stop during Start routine: See exhibit B for start-up procedure prior to E-stop activation. If the start sequence is proceeding, at this point the operator removes the shifter lock bar, removes the wheel blocks, verifies that the E-stop output is STOP, and closes a third switch for full autonomous operation. The challenge vehicle now waits, engine at idle speed for the E-stop signal to change. Once the E-stop signals GO, the onboard computer activates the audio and visual warning devices, waits 5 seconds, increases throttle, activates brakes, shifts to Drive, deactivates brakes and starts moving on planned path.

E-stop while moving: If the E-stop is activated (binary output changes from GO to STOP) during operation of vehicle, throttle is immediately reduced to idle, and brakes are applied for max deceleration without losing traction. Steering follows preplanned route while vehicle slows to a stop. Once stopped (verified as 0 wheel motion, and 0 speed from GPS if signal available), brakes are kept applied, keeping vehicle motionless for 30 seconds while waiting for GO signal. If after 30 seconds the stop signal is still present the onboard computer shifts the transmission to Park and turns off the audible and visual warning devices. Once the STOP is cleared, the onboard computer reactivates the warning devices, waits 5 seconds then proceeds as described in the start sequence.

E-stop while parked in mandatory check-point area: The Challenge vehicle will go to its assigned area in the mandatory check-point area, stop with brakes, shift to Park, wait for 10 minutes and then resume its course, if no E-stop signal is given. If E-stop signal (STOP) is received, the vehicle will wait till the signal has been cleared or 10 minutes has passed, whatever is longer, before resuming its path.

E-stop disable mode: A second binary output from the E-stop receiver is monitored by both the main onboard computer and a secondary independently powered small processor. If a stop signal is received, the main computer reduces throttle to idle, and applies maximum braking power. Simultaneously, the secondary processor immediately disables the main fuel-valve (normally closed solenoid-valve) as well as electric power to the engine's ignition system. A valve on a separately operated pneumatic cylinder is activated to apply additional brake pressure. The force from the pneumatic cylinder locks the brakes.

2. Manual E-Stop switch:
Two 40mm diameter red 'mushroom' style externally actuated push-pull switches (ECI 114889), one on each side of the vehicle. The switches are mounted on a horizontal external structural tube member at approx 4 ft above ground. Each switch has a normally open and a normally closed contact. Pushing the switch generates the same response from the onboard computer and the secondary processor as the E-Stop disable mode signal. In addition, the normally closed switches are hardwired in series with the main fuel valve and engine ignition circuit. Each switch reads EMERGENCY STOP – PARIDA DE EMERGENCIA.
3. Placing the vehicle in Neutral:
The vehicle can be placed in neutral (clearly marked on lever mechanism) by manually operating the shift lever to the automatic transmission. In case the emergency pneumatic brake cylinder has been engaged (Manual or 'hard' E-stop) a valve handle can be rotated 90 degrees to release brake. The handle is marked Brake Released/ Brake Engaged. Once in neutral, the vehicle can be safely towed for a short distance at low speed.

e. Radiators:
1.Lasers: 4 lasers; Class 1 pulsed lasers, wavelength 905 nm (nanometers) power less than 60 uW (microwatts). Radar: 76.5 GHz at 10dBm (10mW)
2. Hazards:
Possible ear hazard: Audible pulsating warning signal 116 -118 dBA. at 10 ft.
3. Safety measures:
Hitting the Manual E-stop button or electronic 'Hard' E-stop disables all radiators.

f. Environmental impact:
1. No environmental impact is anticipated with ABS braking and torque limiter to prevent wheel spin.
2. Maximum physical dimensions: length 210" (bumper to bumper), wheelbase 119", Track Width Front 85", Rear 88", height (neutral suspension) 72".
3. Area of vehicle footprint: Front approximately 8" x 10" (80 sq inches per wheel). Rear approximately 10" x 12" (120 sq inches per wheel). See also Figure 1.
Maximum ground pressure: Front; 480 lbs per wheel over approx 80 sq inches = 6 PSI.
Rear: 720 lbs per wheel over approx 120 sq inches = 6 PSI.

Exhibit A:
A competitor vehicle encountered in a narrow section of the course is considered temporary and will either be followed (if moving) or wait to be removed if it is disabled and blocking the course. A large rock, barrel, deep hole, closed gate, crossing fence line (further identified by image matching by the stereo vision sensor) will be considered permanent and a new route will be planned to try to circumvent the obstacle.

Exhibit B:

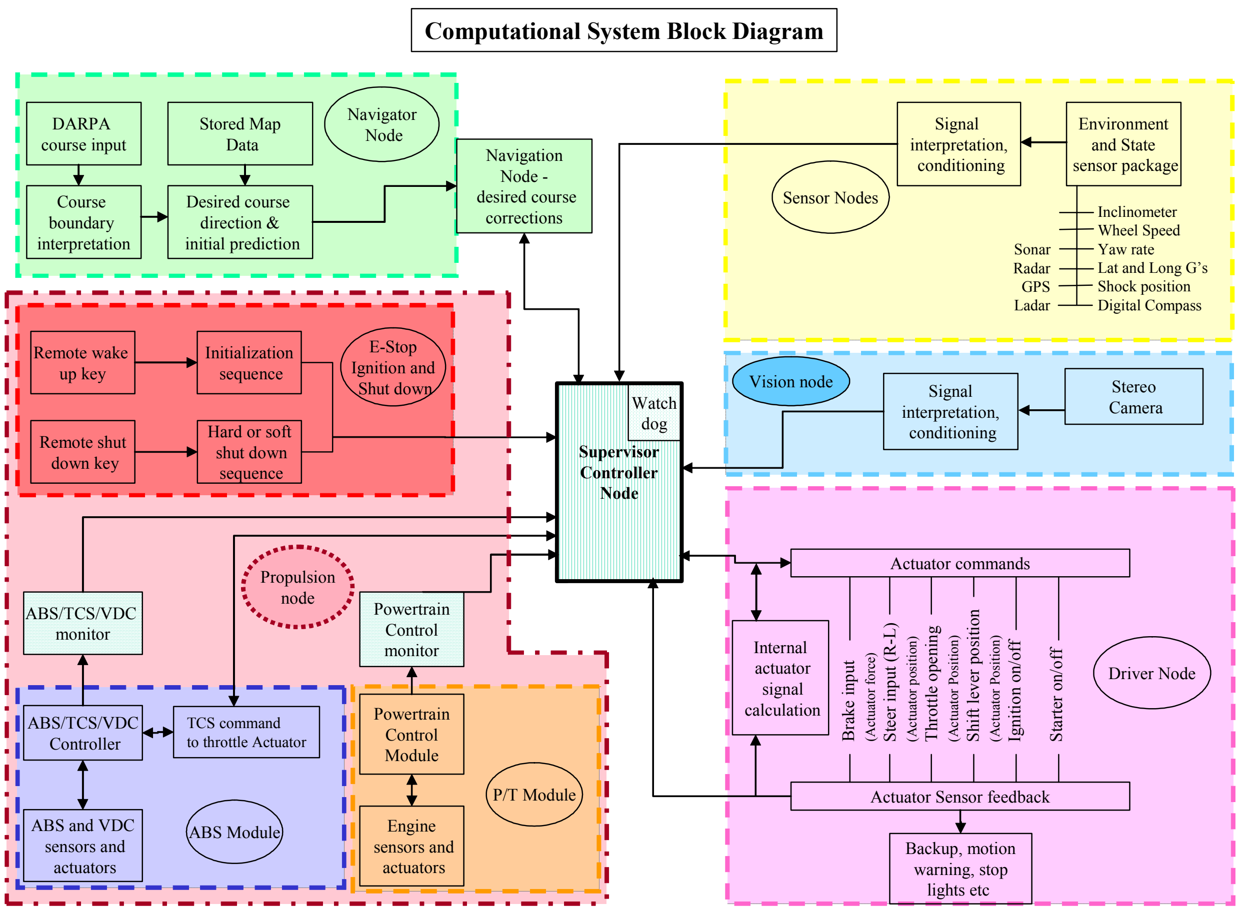


Exhibit C:
The start-up procedure at the starting line prior to first e-stop activation: Wheels are blocked. Two 3 position manual switches are accessible on the side of the vehicle. One is for the navigational system, one is for the propulsion system. The Navigational system is first energized, it performs a system check (power supplies, processors and sensors). It exercises the transmission shifter lever moving from Park to Reverse to Neutral to Drive and back to Park. The GPS starts to acquire position, and the main LADAR performs a forward terrain scan. The route definition (mandatory waypoints, boundaries, and suggested path) is loaded into onboard memory. Once a heading and initial target speed has been calculated, a navigation ready light is lit. At this point the propulsion power switch is closed. Assuming transmission is in Park (limit-switch interlock), a mechanical bar locking it in position (limit switch verified), the computer starts the engine and performs a check on steering, throttle and brake.

Addendum to CyberRider Technical Paper:

Page 1.
#1.a.3.1 Steering: The pinion gear on the Howe Power Rack is actuated by a custom-built servomotor.
#1.a.3.2 Brakes: A single acting, spring return, hydraulic cylinder is mechanically linked to a conventional racing brake pedal, that is mechanically linked via a balancing bar to 2 independent (front/rear) hydraulic brake circuits. The mechanical leverage advantage of the actuating hydraulic cylinder is approx 10 to 1. The hydraulic cylinder is normally operated by opening and closing 2 solenoid valves, connected to a pressurized feedline and a non pressurized return line respectively. Feedback is a pressure transducer. A third solenoid valve is connected to a CO_2 cylinder to provide fail safe braking incase of failure of the primary hydraulic actuating system.
#1.a3.3 Shifter: A dual acting hydraulic cylinder, 2 solenoid valves connected to the pressure feedside + flowrestrictors to the return line. A linear potentiometer provides shifter position feedback.

1.b.1. Power sources. Was 2 x 12VDC aux batteries; Is 4 x 12VDC aux batteries.

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1.b.3 Fuel type 40 gallons of Propane
1.c.1
Propulsion node Hardware: Custom made PIC controlled circuit.
Sensor node/Navigator node Software: Alternative may be W200/XP
Vision node/Supervisor node Hardware/Software: Alternative may be Laptop/ W200/XP
Alternative to (Propulsion node + Driver Node) is a Single node consisting of a Delta Tau 8 axis Programmable Controller.

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2.e.1 Sensors.
Ladar units: 2 SICK LMS 291. Field of view 110 degrees. Range 150 ft.
15,000 pulses per second.
Radar unit: Eaton Vorad VBOX 83001-001 Field of view 12 degrees. Range 300 ft.
2 degrees resolution.

2.e.2 Sensor mounting and control:
Ladars; mounted 4 ft behind c/l of front wheel on pan/tilt table approx 7 ft above ground.
Radar; mounted 1 ft in front of c/l of front wheel on pan table approx 4 ft above ground.

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2.f.1 shifter position sensor; linear potentiometer.
2.g.1 A CSI DGPS MAX sensor has been added to receive the Omnistar L band correction signal

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2.j Movement of vehicle can be accomplished from a center mounted drivers seat. Throttle is drive-by-wire, brakes, steering and shifter is manually linked.

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3.a. Vehicle top speed has been reduced (gear ratios) to 55 mph.
b. Max range has been determined to be 240 miles.
3.c.1 Fuel containment. Worthington 5 x 8 Gallon (40 gallons total) DOT approved Propane – LP fuel rated tanks.

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3.e. Radiators Radar 5mW at 24.725 GHz

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