Red Team Too

DARPA Grand Challenge 2005

Technical Paper

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Abstract

Novel approaches that distinguish Red Team Too's desert racing include multifusion, which combines on-board sensing with preplanning information, drive-by topography for pre-mapping terrain, stabilized sensor pointing which facilitates superior world modeling and swerving to achieve high-speed avoidance maneuvers. These distinctive technologies, combined with solid implementation of well-known basics like pose estimation, waypoint following and path tracking drive the Red Team's H1 Hummer, H1ghlander, which has logged 800 miles of autonomous driving including Grand Challenge-like distance and qualifier and speed scenarios. This paper profiles the configuration, operation and testing of H1ghlander.

Introduction

The Red Team Too is a collaborative enterprise of students, volunteers, professionals and corporations led by Carnegie Mellon. H1ghlander is the Red Team Too's autonomous ground vehicle.

A vigorous testing program has demonstrated reliable, high-speed navigation including a 7-hour 200-mile endurance run, reliable obstacle avoidance at 35 mph and peak speed of 40 mph.

1 Vehicle Description

1.1 H1ghlander– 1999 H1 Hummer Sport Utility Truck

H1ghlander is a modified 1999 AM General H1 Hummer Sport Utility Truck (Figure 1). The H1 is selected for its ground clearance, dynamic stability, large payload capacity, ruggedness, and electronic controls. A 340 V generator driven by the engine belt provides 4 kilowatts of power to the electronics payload. H1ghlander includes electrohydraulic steering. The vehicle is 84 inches (2.13 m) wide, 185 inches (4.67 m) long, and 102 inches (2.59 m) tall. Fueled race weight is 10,300 lbs.

1.2 Drive Train and Suspension Modifications

H1ghlander's drive train features a 6.5 liter turbo diesel, automatic transmission, four-wheel drive transfer case, electronic differential lock, and half-shafts with final gear reduction in its hubs. The chassis suspension utilizes custom coil-over struts with nitrogen reservoirs and a central tire inflation system (Figure 2). H1ghlander's electronics enclosure sits on a semi-active modified Stewart Platform. Each shock isolator of the Stewart platform is a coil-over strut with a magnetorheological fluid damper (Figure 3). These two levels of suspension serve to protect H1ghlander's sensitive electronics and computing hardware.

Figure 1 – H1ghlander shown operating at the former LTV Steelwork site, Pittsburgh, PA.

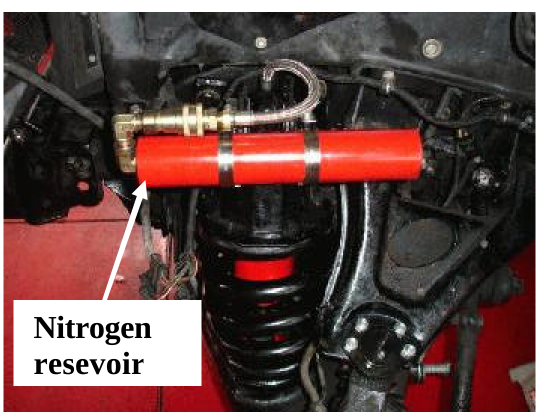

Figure 2 CustomCoil Over Strut Suspension

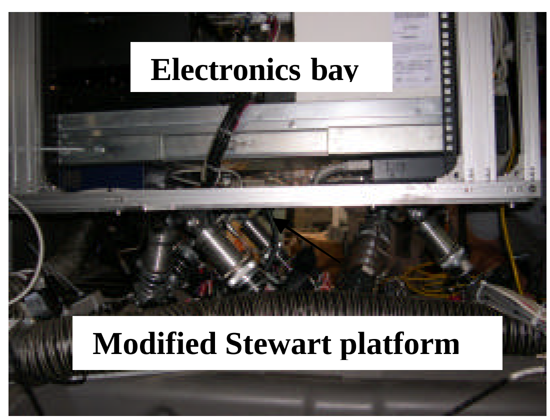

Figure 3 Electronics Bay with Shock Isolation

2 Autonomous Operations

2.1 Processing

H1ghlanders' processes sensing, planning, and driving in a repetitive, end-to-end navigation loop that typically cycles in a fifth of a second. Nested loops within this processing cycle are typically 100Hz. Processes are distributed over eleven (11) general purpose computers more fully described below.

2.1.1 Computing Systems

H1ghlander's sensors, controllers, and devices embed DSPs, FPGAs, and ASICS, but general purpose computers provide the main processing power.

2.1.1.1 Hardware

H1ghlander has eleven (11) general purpose computers. There are four (4) Pentium III PC 104 stacks and seven (8) Pentium M Compact PCI computers. Table 1 indicates the function of each. The selection of the computing hardware was based on processing capacity, form factor, interface extensibility and power consumption. H1ghlanderis equipped with a 1 Gbit/s Ethernet network. Interface to H1ghlander's drive by wire system is via Controller Area Network (CAN) bus. The interfaces for H1ghlander's sensors are listed in Table 2 in the Environment Sensing subsection.

Type	Quantity	Function
Pentium III PC104 stacks.	4	1. 360° RADAR interface 2. Long range LIDAR interface 3. Power switching control 4. Gimbal control
Pentium M Compact PCI computers.	7	1. Short range LIDAR interface 2. POSE data acquisition 3. Terrain analyses 4. Map data management 5. Data transfer to path planner 6. Path planning and tracking 7. Drive-by-wire interface

Table 1 – H1ghlander's Computing Hardware

2.1.1.2 Software

A million lines of code compute models from sensor data, plan paths and speeds, command devices, and navigate H1ghlander. The software, written in C++, runs under a Fedora Core kernel running a 100 Hz clock.

2.1.1.3 Reliability

Mean Time Between Failure (MTBF) for computing and network hardware is 20 hours and MTBF for utility software is 200 hours. Navigation MTBF (for incidents like clipping a berm or grazing an obstacle) is highly dependent on route difficulty.

H1ghlander's control system is single string with a few instances of redundant sensors but has no command redundancy. A Vehicle Health Management (VHM) system monitors the run status of processes via a UDP based shared memory status message. The status message includes start time, last run time, cycle time, initialization time and heart beat counter. From these status messages the health manager can determine the following:

- Initialization Successful if ((Current Time – Start Time) < Initialization Time) and (Heart Beat Counting)
- Process Blocked if (Last Run Time > Cycle Time) and (Heart Beat Counting)
- Process Health Good if (Last Run Time < Cycle Time) and (Heart Beat Counting)
- Process Dead if Heart Beat Not Counting

In the event a process is determined to have failed initialization, is blocked or is dead, the health manager restarts the process. The health of H1ghlander's 11 computers is determined by a periodic TCP/IP Ping from the health manager to each computer. In the event that any of the computers fails to respond, the health manager pauses the vehicle (Remove throttle and apply full brake) power cycle the machine and waits for it to reinitialize and activate its processes. Machine and process restart is managed by the health manager.

H1ghlander's hardware configuration has been frozen since June 1, 2005. H1ghlander was assembly complete on July 23, 2005. The Red Team Too sustains a rigorous reliability program that identifies incidents, fixes faults, tests results and tracks recurrence. Mean-time-to-repair a fault is 18 days.

2.1.2 System Architecture

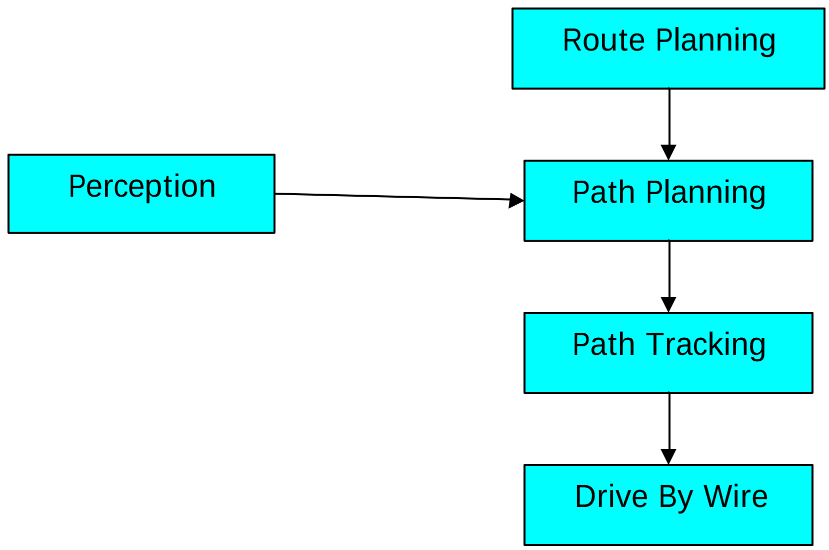

Figure 4 H1ghlander's System Architecture

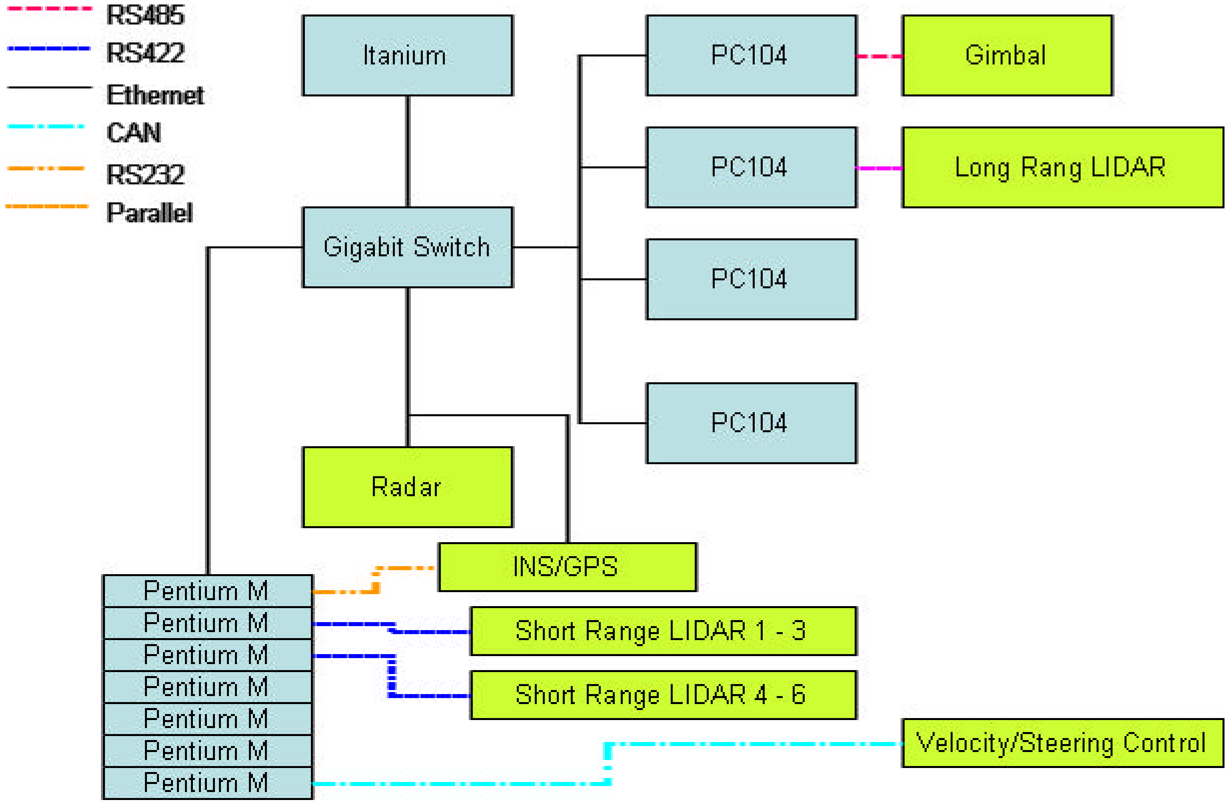

Figure 5 H1ghlander's Network Topology

2.1.3 Development Process

Red Team Too set goals and established evaluation criteria at the beginning of each 100-day development phase, then produced, tested and evaluated capabilities to meet 100-day goals.

2.2 Localization

2.2.1 GPS/INS

H1ghlander estimates 6-axis pose, velocity and acceleration (latitude, longitude, altitude, roll, pitch, yaw) by combining inertial sensing, GPS data and odometry using a Kalman filter. The INS/GPS (Applanix POS LV) is a strapdown inertial navigation platform, featuring high-bandwidth, low-latency, GPS with azimuth measurement and distance measurement indicator. A differential GPS receiver (Trimble AG252 with Omnistar VBS corrections) augments the INS/GPS's two antennas to enhance position estimation. The INS/GPS platform typically calculates vehicle position and orientation data with ½ meter accuracy. It sustains usable pose estimation despite GPS dropouts lasting over several minutes.

2.2.2 Map Data

An off-board route planning system incorporates elevation topology, satellite imagery and drive-by topography data. The map data is sparse relative to the possible GC routes. The planning process designates contexts like paved road, dirt trail or underpass. The race planners refine a preplanned route and set intended speeds compliant to the race data definition file. Just prior to race start H1ghlander receives a path definition file (PDF) consisting of Waypoints, coordinates, speeds and contexts defined for every meter along the race route.

2.3 Sensing

H1ghlander employs long range LIDAR, short range LIDAR and RADAR sensors for mapping terrain and detecting obstacles, roads, and other vehicles. Table 2 lists H1ghlander's perception sensors with their primary functions, sensing horizon, and mode of operations.

2.3.1 Sensor Mounting Locations

An actuated three-axis gimbal points and stabilizes the long range single line LIDAR used for mapping terrain topology and detecting obstacles (Figure 6). Stabilization of the LIDAR increases the fidelity of the terrain map and the accuracy of the obstacle localization. Pointing enables H1ghlanderto look aside before turning and to rescan missed or questionable portions of the terrain map. The effective field of view with pointing is 240 degrees (180 degree gimbal yaw plus 60 degree laser scanner field-of-view) with sensor coverage of 5-150 meters. The gimbal resides in a protective carbon fiber dome on top of H1ghlander's roof.

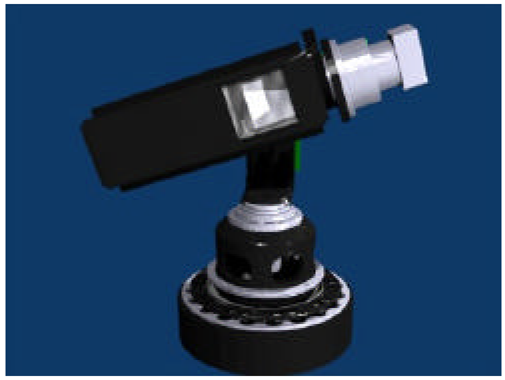

Figure 6 Three Axis Gimbal with Long Range LIDAR Payload.

Four (4) short range LIDAR line scanners (+/- 90 degrees 50 m) are mounted on the brush guard on the front of the vehicle. These LIDARs detect obstacles and characterize the terrain. Two short range LIDARs are mounted next to the gimbal on the superstructure of the roof. These sensors are used for terrain topology mapping and for obstacle detection. Fusion of these sensors generates a range model that spans 200 degrees. The 360 degree RADAR used for obstacle detection is mounted on the brush guard. Most of the RADAR's scan is obscured by the vehicle or brush guard. Its effective field of view is 70 degrees 40-70 meters in front of the vehicle. Figure shows the mounting configuration of the sensors.

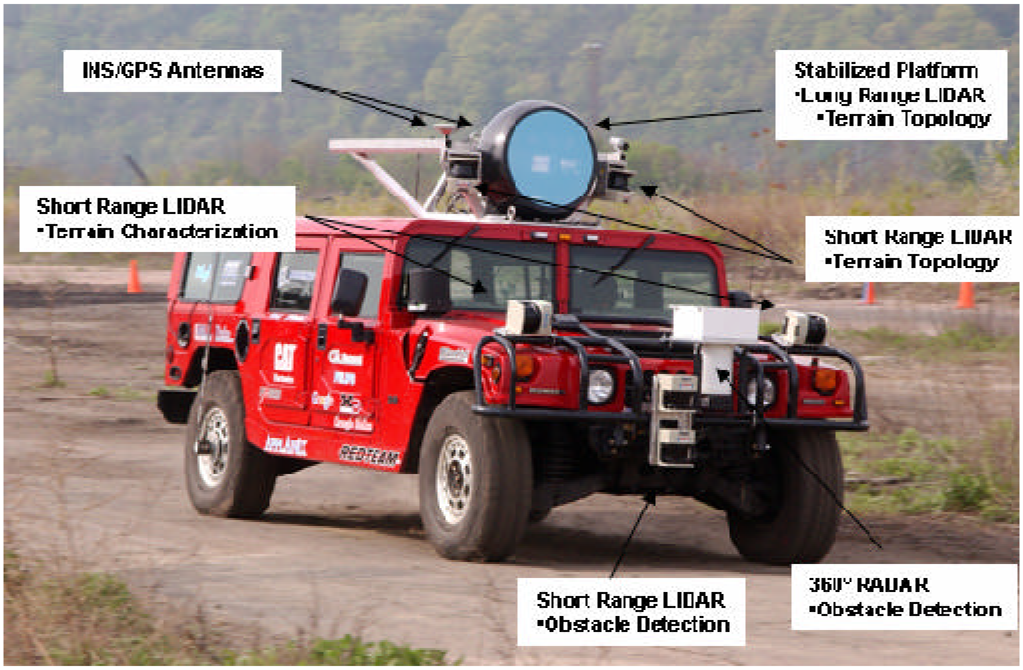

Figure 7 Sensor Mounting Locations

Sensor	Quantity	Interface	Range/Field of View	Primary Function
Long Range LIDAR line scanner	1	ECP compatible Parallel Port	150m (varies with gimbal pitch) with 60 degree field of view	Terrain topology mapping, obstacle detection and characterization
LIDAR line scanner	6	RS422	50m (Shoulder mounted pointed with 15m look ahead) with 180 degree field of view	Terrain topology mapping, obstacle detection and characterization
360° RADAR	1	Ethernet	200 meters (Effective range is 40 to 70 meters) Using ~70 degree field of view	Obstacle detection
Video Camera	1	IEEE 1394	N/A	Visual documentation
GPS/INS	1	Ethernet/RS 232	Position, velocity and acceleration for all axis. Antennas mounted along the top of the fin.	Position sensing and pose estimation.

Table 2 - H1ghlander's Sensors

2.3.2 Sensing Architecture

H1ghlander's perception system field of view is shown in Figure (The 60 degree wedge of long range LIDAR can be swept 180 degrees by the gimbal for a total field of view of 240 degrees). Fusion of perception data is via a terrain cost map and binary obstacle map. Terrain cost maps are generated by evaluating the relative height of a sensed area to its neighbors and assigning a cost of 0 to 255 to that area. Binary obstacle maps are created in a two step process. First, an object detection algorithm, customized for each sensor group, detects and localizes obstacles. Second, detected obstacles are written into a map at the detected location.

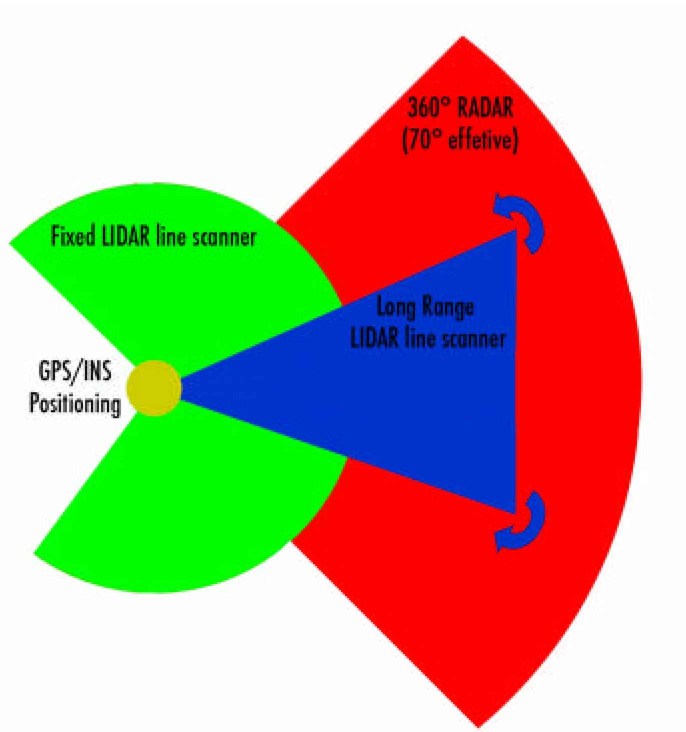

Figure 8 H1ghlander's Perception Field of View

2.3.3 Vehicle State Sensing

H1ghlander's state sensing monitors and measures equipment temperature, actuator position, velocity and acceleration. State is sensed via optical encoders, potentiometers, rotational variable differential transformers (RVDT), thermocouples, current and voltage sensors. Vehicle state sensors feed Vehicle Health Management which monitors state and restarts some resources via power cycling in the event of a sensed failure

2.3.4 Sensing to Actuation System

2.3.4.1 Waypoint Following

Path tracking evaluates a best path relative to current vehicle position and pose. The algorithm sets maximum speed and curvature and constrains the trajectory to ensure against skidding and tipover. Path tracking passes calculated commands of desired curvature and speed to the vehicle's drive-by-wire system.

2.3.4.2 Path Finding

The path definition file generated from the RDDF during pre-race planning is fused along with LIDAR and RADAR data into a composite model. The world model consists of the terrain cost map and binary obstacle map discussed in section 2.3.2. Items in the binary obstacle map are fused to the terrain cost map by adding them as high or infinite cost, while clear traverses are added as low or no cost.

Path planning uses an A-star algorithm which considers multiple possible traversable arcs forward of vehicle position within the RDDF defined route corridor. Each possible arc is evaluated in terms of least cost to goal. The "best" path at any given interval is then communicated to a path tracking algorithm. Areas outside of the path definition file's route corridor are not considered in path planning.

2.3.4.3 Obstacle Detection

H1ghlander detects obstacles with its RADAR and two short range LIDARs mounted in the center of the brush guard.

Radar data is filtered to recognize returns on order of meter-scale (like people, poles and garbage cans) that are isolated from surrounding clutter like dense vegetation. Objects detected by radar are tracked and shrunk in the binary obstacle map as they are approached by H1ghlander. This shrinking accounts for pie shaped range bins and multiple obstacles detected at long range in a single bin.

The short range LIDARs are mounted in a stacked manner such that their line scans are parallel. This arrangement allows H1ghlander to differentiate between obstacles and hills.

The long and short range LIDARs mounted on the roof are primarily for terrain topography. However, these sensors will sense obstacles and mark them as high cost in the terrain cost map. H1ghlander will avoid these high cost areas.

2.3.4.4 Collision Avoidance

Collision avoidance modifies the preplanned route to swerve around a sensed obstacle represented as terrain with very high cost. The path planner generates the swerve maneuver by modifying the location of 1 meter spaced Waypoints. The path tracker limits the swerve maneuver by enforcing preset maximum speeds for vehicle dynamic performance accounting for terrain, curvature and slope.

2.3.4.5 Vehicle Control Models

H1ghlander's braking, steering and propulsion are specialized from PID fundamentals. H1ghlander's mechanical, electromechanical, electrohydraulic system dynamics and controllers are modeled using Simulink ™. The Simulink models are compiled into C code and downloaded to H1ghlander's drive-by-wire controllers. Control parameters are tuned and tested in field conditions.

2.3.4.5.1 Velocity

Velocity is regulated by a proportional integral (PI) controller that commands either a throttle actuator position or a brake actuator position. The inner loop brake actuator position controller is a PI controller and the throttle actuator is a proportional controller with different gains to account for the significant differences between the throttle dynamics and the brake dynamics. The velocity controller receives a velocity command from the path tracker. The controller senses velocity by reading odometry.

2.3.4.5.2 Steering

The steering controller uses a Proportional Integral Derivative (PID) algorithm. The controller receives a curvature command from the path tracker. The controller senses steering position through a RVDT and LVDT position feedbacks integrated into the hydraulic steering valve. The RVDT is the primary sensor for the algorithm. In the event of loss of data from the RVDT the control algorithm will operate based on the LVDT feed back.

2.3.4.5.3 Transmission

H1ghlander's transmission is an automatic three-speed. The drive by wire shifter only designates forward (drive), reverse and neutral on the transmission. The transmission automatically shifts itself among first, second and third gears within the selected range. H1ghlander shifts to forward, reverse or neutral by commanding an actuator which moves the transmission shift. The closed loop control of the linear actuator uses a proportional controller once “forward” is selected.

2.4 Vehicle Control

2.4.1 Autonomous Operation Contingencies

2.4.1.1 Missed Waypoint

H1ghlander’s navigation is robust to missed waypoints. It complies with corridor constraint, but there is no requirement that the vehicle must go through any one waypoint. The vehicle path is continuously updated with respect to the current position and the desired route through the corridor. H1ghlander continuously recomputes its desired path.

2.4.1.2 Vehicle Stuck

H1ghlander detects wheel slip by comparing the speed output from the distance measurement sensor to the speed reported by the pose estimation system. When the velocity controller detects wheel speed over 5m/sec and velocity of 0m/sec, it will back up along the path 10m, clear its current terrain cost map and binary obstacle map, pan and scan with long range LIDAR and RADAR, plan a new path and attempt to drive around any obstacles. In the event, this maneuver does not work, H1ghlander can modulate the throttle or brake in attempt to get un-stuck or can engage the electronically controlled the mechanical differential locks.

2.4.1.3 Vehicle outside Lateral Boundary

The vehicle planner operates on a world model represented as a cost map as described in section 2.3.4.2. Regions outside the lateral-boundary-offset are set at infinite cost in the map. In the event that H1ghlander ends up outside the boundary the planner will modify the path in order to get the vehicle back to an area of lower cost, which should be inside the boundary.

2.4.1.4 Obstacle in Path

Obstacles are represented in the cost map with varying costs similar to the lateral-boundary case. The planner reacts to those obstacles by planning through the path of least cost, reference sections 2.3.4.3 and 2.3.4.4.

2.4.2 Special Vehicle Maneuvers

H1ghlander has the robustness to accommodate the irregular terrain that it encounters. The control system that manages the vehicle speed has the ability to ramp the throttle and or brake to ensure that speed is maintained when traversing up or down hills. Tight and off camber turns are predicted using the pre-planned path, and vehicle speed is lowered accordingly using vehicle dynamics to ensure traction and stability.

When H1ghlander detects that its current heading is more than 30 degrees off its desired heading, it will stop and backup along a preplanned arc until an acceptable heading is achieved. This situation occurs if the vehicle has experienced a spinning slide or attempts to turn an extremely sharp curve. H1ghlander used this maneuver during the 2004 DARPA Grand Challenge after hitting a large rock.

2.4.3 Integration of Navigation and Sensing

H1ghlander drives based on a preplanned path definition file (PDF) derived from the RDDF during preplanning, reference section 2.2.2. The PDF's Waypoints are defined as Universal

Transverse Mercatur (UTM) coordinates. H1ghlander's integrated worldview (PDF, terrain cost map and binary obstacle map) is localized in UTM coordinates. Integration of PDF and cost map occurs during path planning, reference section 2.3.4.2.

2.4.4 Vehicle Control when not in Autonomous Mode

H1ghlander can be switched out of autonomous mode for manual operation. To do this a main switch disables the drive-by-wire controllers, and a secondary switch cuts the connection to the steering motor to prevent back-driving. Highlander's steering wheel governs a hydraulic pilot valve that can effortlessly overpower its steering actuator at any time, during any driving mode. H1ghlander's stock steering column is removed so there is no mechanical coupling between its steering wheel and steering linkage.

2.5 System Tests

Red Team has been testing H1ghlander's systems and subsystems since it became operational in December of 2003. H1ghlander has accumulated over 500 autonomous test miles. Notable tests include:

1. 200 miles on the Beaver Run Raceway averaging 26.4 MPH with a peak speed of 38.2 MPH.
2. Extensive Perception Planning, Perception Tracking and Blind Tracking tests on a modified ISO 3888-1 Severe Lane Change Maneuver course.
3. Repeated traverse of a 28-mile, race-realistic desert course at race speed.

In addition to these system tests, H1ghlander has tested for software endurance via simulation, dust detection, pointing, shock and vibration.

With thirty-five days remaining to the Grand Challenge qualifier, Red Team Too exhibits race-worthy performance and viable reliability. Planned tests include end-to-end race day simulations, 100 mile traverses of trails and hills with challenges like gates, high-speed, underpasses and difficult terrain.