Terra Engineering's DARPA Grand Challenge 2005 Technical Paper

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ABSTRACT

The TerraHawk vehicle created by Terra Engineering for the 2005 DARPA Grand Challenge represents the culmination of three years of imagination and creativity. The physical vehicle design with six wheels, trailing arm suspension and three segment articulation is unprecedented in the engineering world.

Extensive system engineering was used to address the impact of the requirement of autonomous navigation and control on the physical vehicle, sensors and computation system. The chosen system approach was implemented within the limitations inherent in a volunteer program with limited funding.

1. Vehicle Description

1.1. The TerraHawk Vehicle (THV)

TerraHawk is a unique vehicle custom designed for extreme rough terrain navigation and exploration. The six wheeled vehicle is made up of three segments. The segments are articulated in the vehicle yaw axis to allow steering. Each segment contains the drive and suspension for two wheels along with all the controls for that segment. For the 2005 Grand Challenge, extensive modification was made to the 2004 vehicle to both address weaknesses discovered in the original design and to simplify subsystems.

This vehicle was not specifically designed for the DARPA Grand Challenge but was created to be an integration friendly autonomous test platform. After the Grand Challenge race, the vehicle will be used in the development and testing of future combat payload systems.

1.2. Drive Train and Power

The THV generates torque with six 10 hp electric motors. Each motor is coupled to one wheel through a gear reduction, an external belt drive and a final gear drive within the wheel hub. Four of the six wheels have pneumatic/hydraulic brakes.

Steering is generated in a progressive manner. Inter segment articulation provides a turning radius as small as 17 feet for higher speed turning. Low speed turning down to zero radius is accomplished with differential drive to the motors.

There are three prime movers in the vehicle. The first two provide up to 20kW of 48VDC power for locomotion. The battery banks provide both surge and reserve capacity. The third prime mover is a single 110 AC diesel power plant to provide power for the computational blade server. Output from this generator is routed through a power conditioner/uninterruptible power supply that is in turn connected to the 48VDC bus.

2. Autonomous Operations

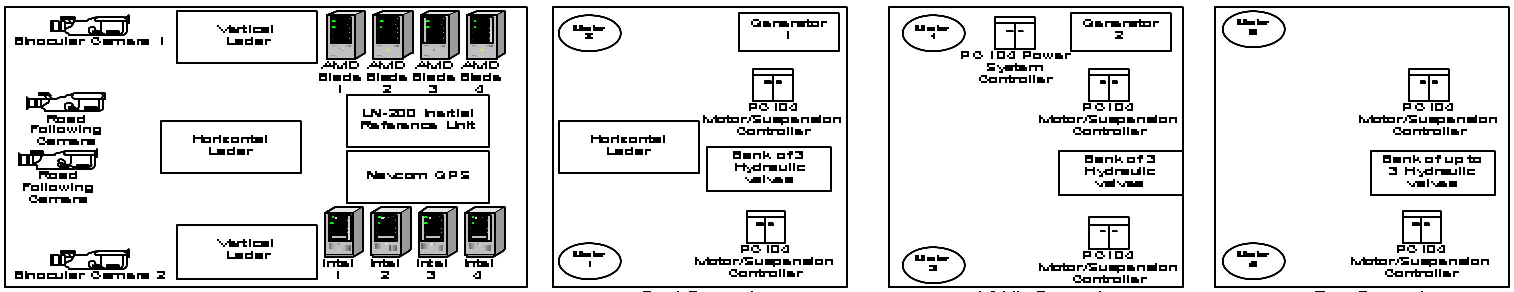
2.1. *Processing*

2.1.1. Computing Systems

For 2005, the four Intel Pentium 4 processors residing in 4 1U servers have been replaced with a single 4U Tatung blade server. The blade server houses 8 independent blades. Four blades contain dual AMD Opteron processors and four blades contain dual Intel Xeon processors. All blades have 2GB of memory and a single 2.5” 80GB hard drive.

The AMD blades run RedHat 9.0 Linux for hardware compatibility reasons. The Intel Xeons run Fedora Core 3.0 Linux to minimize computational latency.

The blade server is designed for high reliability. The power supplies are actively redundant. Two separate Gbit Ethernet backplanes are available to communicate with each blade. Finally, two management blades are installed that allow any blade to be reset, powered down or powered up from a remote system via Ethernet or serial communication.



Sensor Platform | Front Segment | Middle Segment | Rear Segment

2.2. *Localization*

2.2.1. Component Parts

The THV localization system combines data from two separate Navcom 2050 GPS receivers and two Northrop Grumman LN-200 inertial measurement units (IMU). Each set of a GPS receiver and IMU runs its own Kalman filter on a dedicated single board computer for timing purposes. The core navigation algorithm averages the output of both systems if they agree within tolerances. Once the systems disagree beyond the acceptable tolerances, a decision is made based on history and sensor signatures to believe one, the other, or neither.

The Kalman filters estimate the location and attitude of the vehicle as well as the gyro and accelerometer biases. No scale factors or misalignments are estimated in the filters. During GPS outages, the Kalman filter continues to propagate the location and attitude directly off of the LN-200 data. Desert testing has shown that time is more important than distance in estimating location and attitude. The LN-200 was able run for ~60 seconds before accumulating 1 m in lateral error. At moderate speeds, this allows us to navigate 500 m without any significant degradation.

2.2.2. Map Data

Map data was originally a very large part of the strategic approach to the 2005 DGC, however, since DARPA had to close the race area on July 29th, we were unable to complete our desert data gathering task. We still use USGS 10 m DEM data to get a rough idea of the course slope, roughness and average roll/pitch angles between waypoints.

2.3. *Sensing*

2.3.1. Sensors

There are four different types of sensors used on the vehicle. The Navcom GPS sensor is used exclusively for navigation. The LN-200 IMU is use for both navigation and vibration sensing. The SICK ladars are used for obstacle identification and terrain profiling. Finally, the Basler video cameras are used for road identification and binocular obstacle detection.

Most of the sensors are concentrated on the deployable sensor platform. The sensor platform also hosts the blade server to minimize the required wiring between the sensor platform and the vehicle body. The deployed natural frequency of the sensor platform is ~1.0 Hz for small motions.

As shown in Figure 1, our LN-200 Gyro, Navcom GPS, three SICK ladars, two 88 degree wide angle Basler cameras for road identification and two 26 degree narrow Basler cameras for binocular obstacle detection are all resident on the sensor platform head.

2.3.2. Sensing Architecture

The overall navigation approach is broken down into a set of minimally overlapping modes. Each mode has been designed to guide the vehicle under a given set of conditions. As external conditions change, the guiding mode changes with them. A summary of each mode is given below:

Mode of Operation	Binocular Vision	Road ID Camera	Lidar	GPS	IMU
PreRace	No	No	No	Yes	Cal
Emergency Stop	No	No	No	Yes	Yes
Narrow Passage Navigation	No	Yes	Yes (OA)	Yes	Yes
Pre-traveled Road Following (removed)	No	Yes	Yes (OA)	Yes	Yes
High Velocity + Obstacle Avoidance (OA)	Yes	No	Yes (OA)	Yes	Yes
Multiple obstacle avoidance	Yes	No	Yes (OA)	Yes	Yes

Figure 2 Sensors Used in Each Mode

PreRace

In the PreRace mode, the vehicle is calculating and storing nominal trajectory steering maneuvers from the given RDDF file. If the data for the Pre-Traveled road following mode had been completed, the system would compare the given RDDF with the pre-traveled road database to fill in areas where prerecorded data is available.

Emergency Stop

In Emergency Stop mode, the vehicle continues on its current path and reduces speed under controlled conditions until it is stopped. At that point, full brakes are applied and maintained until the E-Stop is released.

Narrow Passage Navigation

In the areas of the course that are less than 6 meters wide, there are limited decisions to be made about the path of the vehicle. In this mode, the IMU and GPS sets provide the location and attitude information. The vehicle follows the nominal middle path track and a bias is added to the track to account for the location of any perceived road detected by the road ID cameras. In the event that a single credible obstacle is detected in the path of the vehicle, the vehicle will adjust the path bias to maneuver around the single obstacle.

Pre-traveled Road Following

This mode was removed when the race area was closed

High Velocity Plus Obstacle Avoidance

This mode is used in locations where the *apriori* DEM data has identified a large area where the height standard deviation is low. The vehicle travels at maximum speed (still relatively slow) and relies on the binocular cameras to identify potential obstacles at long distances. In the event that a single obstacle in the path is detected, the vehicle performs a set of S-turns to get around the obstacle.

Multiple Obstacle Avoidance

In the event that multiple obstacles are detected and a clear path is not easily identifiable, the system enters a multiple obstacle avoidance mode. This mode is based on the virtual force field (VFF) approach that takes identified obstacles and treats each like a source of force. The net force field is accumulated and the vehicle steering is driven by the net force field. The mode is relatively slow (5 mph) and requires a significant amount of steering effort.

2.3.3. Internal State Sensors

The THV has numerous internal sensors to monitor the state of health of the vehicle. The vast majority of them are attached to local 104 processors. They are listed below by subsystem.

Hydraulics

There are 10 position sensors on the vehicle used to monitor the location of the hydraulic rams. In the critical areas (steering), there are two position sensors to give redundant information. In the event that a valve, drive or cylinder fails, the controlling computer will identify the lack of movement and mark that actuation string as failed.

Drive Sets

Each segment contains a pair of motors and electronic speed controls. For each motor and driver, a small custom board interfaces with the controlling PC 104 board and provides data on motor speed, wheel speed, motor current draw, motor temperature, driver current temperature and motor voltage.

Power System

The power system controller monitors the state of charge of the batteries through voltage and current sensors. The state of the generators is monitored through voltage sensors, oil pressure sensors and water temperature sensors.

Computers

An external PC 104 health monitoring computer is used to cycle power on ladars, cameras and the GPSs. It is also capable of commanding a reset or power cycle for any blade within the blade server set via serial or Ethernet command. The PC 104 receives an “I am OK” signal from the core processor and only resets the core unit when the signal is absent.

2.3.4. Sensing To Actuation

For the majority of the modes, the vehicle uses a balanced combination of feed forward steering and feedback correction to enforce a path plan. At the beginning of the race, the given RDDF is broken down into lines and arcs along with associated transition points and pivot points. This is the basis for the feed forward into the servo steering law. Any real time changes in path bias (lateral displacement) or heading bias are treated as deltas from the feed forward control law. Total vehicle curvature commanded is the sum of the feed forward curvature, feedback curvature to maintain heading and S-turn curvature to enforce lateral displacement.

2.4. *Vehicle Control*

2.4.1. Operation Contingencies

The overall design of the vehicle minimizes anomalous operation. Although is it possible for the vehicle to get stuck, the six wheel drive, very large ground clearance and closed loop nature of the wheel control makes this highly unlikely. Since waypoints are defined by a infinite perpendicular plane, the vehicle would have to be more than 90 degrees off course to miss a waypoint.

2.4.2. Maneuvers

The master motion controller commands a speed which is enforced in a closed loop manner by the electric motors. The electric motor drives are four quadrant drives which allows them to perform regenerative braking. In the event that the motors are unable to enforce the speed commanded by the motion controller, the motor controllers request braking to assist.

A relatively unique characteristic of this platform is the ability to differentially power the wheels to perform a zero radius turn (turn in place).

2.4.4. Non-Autonomous Control

When the system is not under autonomous control, it is run via laptop connected by Ethernet.

2.5. *System Tests*

2.5.1. Testing Strategy

"Ain't nothing like the real thing". The vast majority of the sensor/navigation testing was performed on a manually driven vehicle in the desert as close as we were legally allowed to get to the 2005 race course (expected to be ½ of the Primm 300 race course). The mechanical performance of the vehicle chassis was tested locally in a field where terrain varies from smooth to extremely rough.

2.5.2. Key Discoveries

All volunteer organization do a tremendous job of generating unique and innovative solutions, however, it takes the discipline and rigor of a paid staff to bring those solutions to light in a timely manner. Without such a paid staff, the volunteer team will usually struggle to complete a project within the required time.