TerraHawk DARPA Grand Challenge Entry Technical Paper

Terra Engineering

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This document describes technical aspects of the TerraHawk autonomous vehicle. This vehicle is designed for competition in the DARPA Grand Challenge.

1. System Description

A) Mobility

1. Ground Contact

The TerraHawk Vehicle (THV) is propelled by force generated from contact between its six tires and the ground. Figure 1 shows the general layout of the vehicle.
The six wheeled vehicle is made up of three segments. The segments are articulated in one degree of freedom relative to each other to allow limited steering. Each segment contains the drive and suspension for two wheels. The front and back segment each contain a generator and the middle segment houses the core computer systems.

2. Locomotion, Steering and Braking

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 30 feet for higher speed turning. Low speed turning down to zero radius is accomplished with differential drive to the motors.

3. Actuation

All components that require physical motion use either pneumatic or slow electric actuators. This includes the suspension, steering, isolator platform and brakes. Reserve volume for the pneumatic actuators is kept within each segment.

B) Power

1. Source

The THV generates power using two 14kW DC diesel generators. Temporary additional demand is met with 18 packs of NiCad batteries capable of sourcing up to 54 kW of power.

2. Peak Power

The peak power required by the vehicle is dominated by the very short startup transient of the DC motors. All six motors can consume a total of ~99 kW of power for about a second.

3. Fuel

Two segments contain two 7.5 gallon diesel tanks for a total of 30 gallons of diesel on board.

C) Processing

1. Type of Processors

Figure 2 shows the overall layout of the computer processing system. There are two types of processors in a dual loop net. The first are referred to as "Core" processors and use commercial 1U Pentium IV processor-based servers within an isolated 19 inch rack. The second are compact standard PC 104 processors.
The primary functions for each processor type are listed below:

PC 104
Motor Control
Generator Control
Pneumatic Control
Vehicle Control
IMU data Processing
LIDAR Data Processing

Core Processors
Sensor Fusion
Road ID algorithms
Radar Processing
Solid Model Construction
Mode Determination
IMU data Processing
LIDAR Data Processing
Kalman Filter Processing

2. Processing Sensor Data, Route Planning, Vehicle Control

All sensors except the primary vision system are hosted remotely (relative to the core) on PC 104 processors. The PC 104 processors perform scaling and initial data processing within their limited computation capability.
Route planning is all accomplished in the #1 core processor. This machine contains all *a priori* data and receives all processed sensor data for integration into the local solid model.
Sensor information is fused into a local solid model of the terrain. The model is centered around the isolated platform on the vehicle. The orientation of the data remains fixed in the Earth Centered Earth Fixed (ECEF) reference frame. The integer multiple mapping allows us to perform the vast majority of map moves by shifting pointers in software.
The #1 core processor selects a route based on the solid model information it has and then passes that information along to the motion control code. The motion control code sends the commands to the vehicle motion processor (three PC 104 boards).

D) Internal Databases

1. Pre-Stored Data

The #1 core processor stores all *a priori* map data locally. This is limited to string data on routes navigated during testing.

E) Environmental Sensing

1. Sensors

Sensor processing is mode dependent. The following table shows the type of sensors used in each mode of operation.

Table 1 Sensor Usage By Mode

Mode of Operation	Binocular Vision	Road ID Camera	Lidar	Radar	GPS	IMU	Boundary Cameras	Coarse Heading
PreRace	No	No	No	No	Yes	Cal	No	Cal
Emergency Stop	No	No	No	No	Yes	Yes	No	No
Narrow Passage Navigation	No	No	No	No	Yes	Yes	Yes	No
Solid Model Based	Yes	No	Yes (data)	Yes (data)	Yes	Yes	No	No
Pre-traveled Road Following	**No**	**Yes**	**Yes (OA)**	**Yes (OA)**	**Yes**	**Yes**	**Yes**	No

The sensors are used in one of three ways. The first is to derive state data for the vehicle. The second is to gather data for the solid model generation. The third is to gather focused data as directed by the navigation system.

GPS

The Navcom GPS provides position data in Earth Centered Earth Fixed (ECEF) coordinates when the appropriate signals are present. When all signals are present in sufficient strength, the GPS can provide location information to 10 cm accuracy.

IMU

The Northrop Grumman LN-200 IMU provides 6 DOF worth of data at high rates to propagate the vehicle state when the GPS signal is not available. The IMU data is combined with the GPS data within a 15 state Extended Kalman Filter (EKF) when both are present.

Coarse Heading Sensor

The coarse heading sensor contains three magnetometers, three gyros and three accelerometers of moderate quality. The sensor provides near instantaneous heading information with a resolution of less than 1 degree and an accuracy of 5 degrees.

Boundary ID Cameras
The Boundary ID cameras are low resolution video sensors primarily used to identify artificial boundaries installed by the DAPRA Grand Challenge staff.

Road ID Camera
The road ID cameras use texture ID algorithms to identify roads/trails along with associated confidence levels.

Binocular Vision
The matched set of machine vision cameras are the first of three sensors used to construct a near real time solid model for low to moderate speed navigation.

Radar
The Eaton VORAD radar provides tracking data on up to 20 objects. This data includes azimuth, distance and closing speed. It is the second sensor used in the solid model construction.

Lidar
The Lidar sensor is the final sensor used for solid model construction. It is the primary obstacle avoidance sensor.

2. Sensor Control and Location

As shown functionally in Figure 1, the THV contains is a boom and platform that houses the most shock sensitive equipment. That platform represents the center of the vehicle reference frame. It isolates the GPS antenna, the Binocular Vision cameras, the road ID camera, the boundary ID camera and the Northrop Grumman IMU.
The boom is deployable upward to present a better aspect angle to allow the sensors to detect ground depressions.

F) State of Health Monitoring

1. 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.

Pneumatics
There are two pressure sensors per suspension cylinder and steering cylinder set (one on each side of the piston), two for the brake actuators and one for each storage tanks. There are a total of 19 sensors.

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/wheel speed.

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, speed sensors and water temperature sensors.

2. Decision Making From State of Health Data

State of health data is used to help select modes of operation. Certain modes require supporting states like a minimum state of charge in the batteries.

G) Localization

1. Geolocation

Geolocation of the sensor platform is accomplished with the Navcom GPS and LN-200 inertial reference unit. A 15 state extended Kalman filter is used to combine input from all available sensors.

2. GPS Outages

If the GPS signal drops out or becomes unfavorable, the Kalman filter will automatically shift gains and de-weight that input.

3. Challenge Route Boundaries

When the boundary cameras detect artificial boundaries or the lateral boundaries become very small, the narrow passage navigation mode will be entered and speed will be reduced to minimum.

H) Communications

1. Broadcast Information

No information will be broadcast from the vehicle.

2. Receive Information

No information will be broadcast to the vehicle.

I) Autonomous Servicing

1. Refueling

There is no refueling required.

2. Servicing

There is no autonomous servicing required.

J) Non-Autonomous Control

Prior to autonomous control, the THV will be controlled manually through a remote tether (no RF control). When the tether is inserted, the system will recognize and reconfigure for local manual control. Under manual control, the top speed will be limited to just a couple of miles per hour.

2. System Performance

A) Previous Tests

N/A

B) Planned Tests

N/A

3. Safety and Environmental Impact

A) Top Speed

The top speed of the vehicle is expected to be ~25 mph.

B) Vehicle Range

The expected range of the vehicle is ~400 miles on a flat surface at 15 mph.

C) Safety Equipment

1. Fuel Containment

The diesel fuel is divided up into four 7.5 gallon tanks. The tanks are protected against spillage in the event of a rollover.

2. Fire Suppression

Due to the significantly reduced volatility of diesel fuel, no active fire suppression systems are installed on board.

3. Audio and Visual Warning Devices

The THV will meet all established requirements set forth in the 1.2 version (current) version of the rules as outlined below:

6.4.2.1 Audible Warning–Vehicle Operating

We are currently baselining the commercial siren Crimestoppers # CS-194C.

6.4.2.2 Visual Warning–Vehicle Operating

We are currently baselining the commercial amber light set #47911 from Waytec Wire.

6.4.2.3 Visual Warning–Vehicle Brake

We are currently baselining the commercial brake light set #47930 from Waytec Wire.

D) E-Stops

1. ESTOP Execution

Upon receiving the electronic E-Stop, the THV will go through the following steps.

i) The vehicle will enter E-Stop Mode
ii) The navigation algorithm keeps its last computed trajectory but begins to command controlled deceleration.
iii) The individual motor controllers begin to ramp up regenerative braking. As long as the wheels are not slipping, the braking force will be increased.
iv) If the motor controllers reach full regenerative braking and the wheels are not slipping, mechanical brakes will be added until limited slipping occurs.
v) The vehicle will continue to brake in a controlled manner and follow the computed trajectory until a full stop is achieved.
vi) The mechanical brakes will be fully engaged.
vii) The Audio and Visual warning devices will be deactivated.
viii) The system will enter Pre-Race mode and continue calculating routes.
ix) Upon clearing of the E-Stop bit, the system will enter Start Mode and resume operations.

2. Disable Execution

Upon receiving the disable signal, the THV will go through the following steps.

i) The vehicle will enter DQ Mode
ii) All power will be pulled from the motor controls and pneumatic controls
iii) The generators will be shut off.
iv) Maximum braking will be applied.
v) If the servers happen to reboot, the system will remain in DQ mode.

3. Manual E-stop

If the vehicle mechanical E-Stop is activated manually, power to all motor drivers is immediately removed and the mechanical brakes are engaged.

4. Neutral

The direct drive electric motor system has no classic "neutral". However, the vehicle is easy to push or tow when the motor drivers are off. All that is necessary is to disengage the brakes.

E) Radiators

1. Itemized List

i) Doppler radar, CW tone at 24.5 GHz, 50 mW max power, 20 dB max antenna gain

ii) Laser rangefinder: Class 1 eyesafe, 1500 nm wavelength, pulsed, max 15 mJ per pulse, minimum 0.5 mrad divergence

iii)

2. Eye Hazards

There are no known eye hazards generated by anything on the vehicle except maybe the paint job.

3. Safety Measures

All EM emitting devices will have red "remove before flight" covers over them.

F) Environmental Impact

1. Damage

By design, no portion of the vehicle is expected to cause damage to the environment.

2. Physical Dimensions

The vehicle is 72" wide, 146" long and varies between 57" and 75" tall. The vehicle weighs around 2400 lbs.

3. Vehicle Footprint

Each of the 6 tires has around 32 square inches of contact area with the ground (nominally). That puts the average ground pressure at 12.5 psi.

Appendix I
Figures

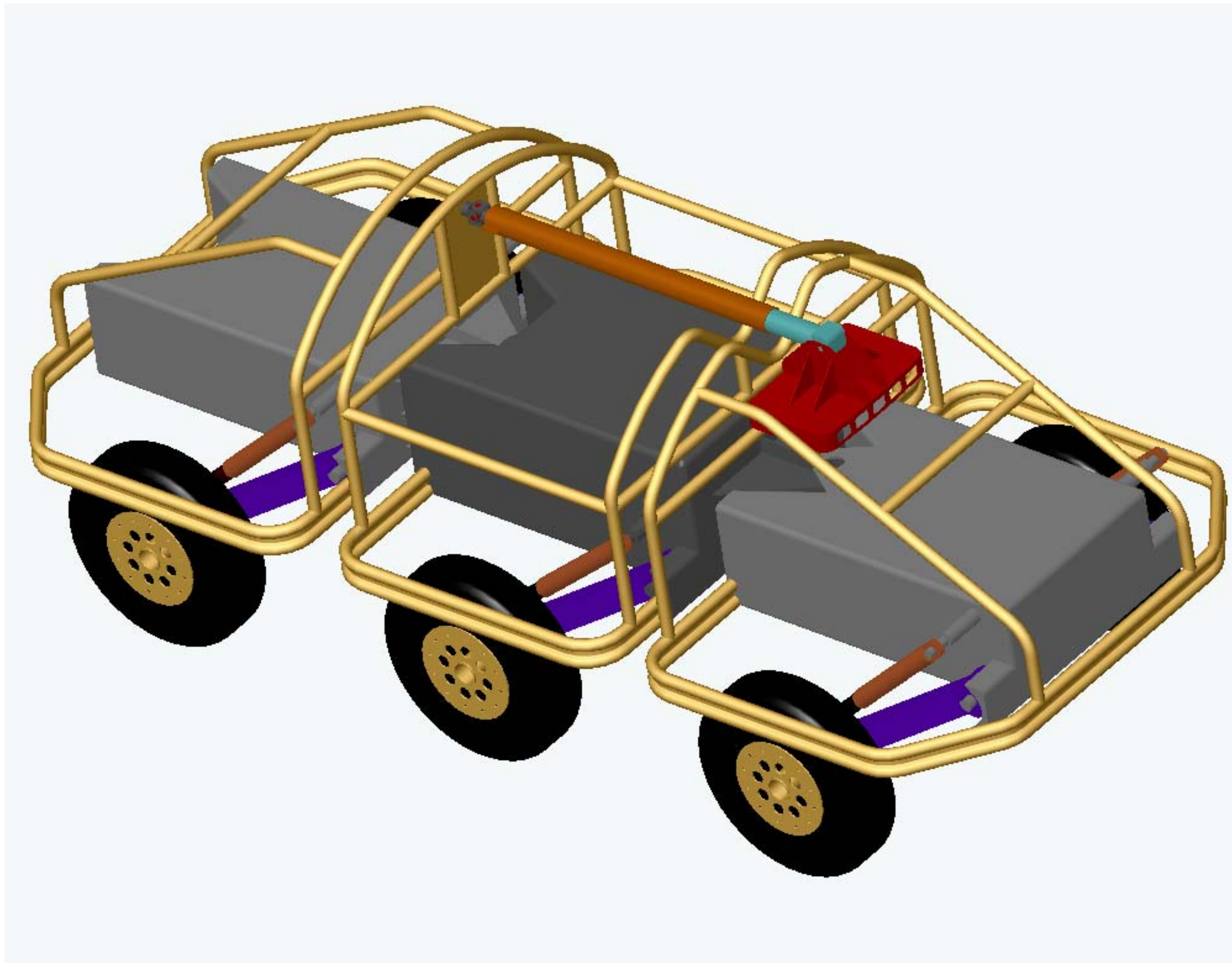

Figure 1 General Layout of TerraHawk Vehicle (THV)

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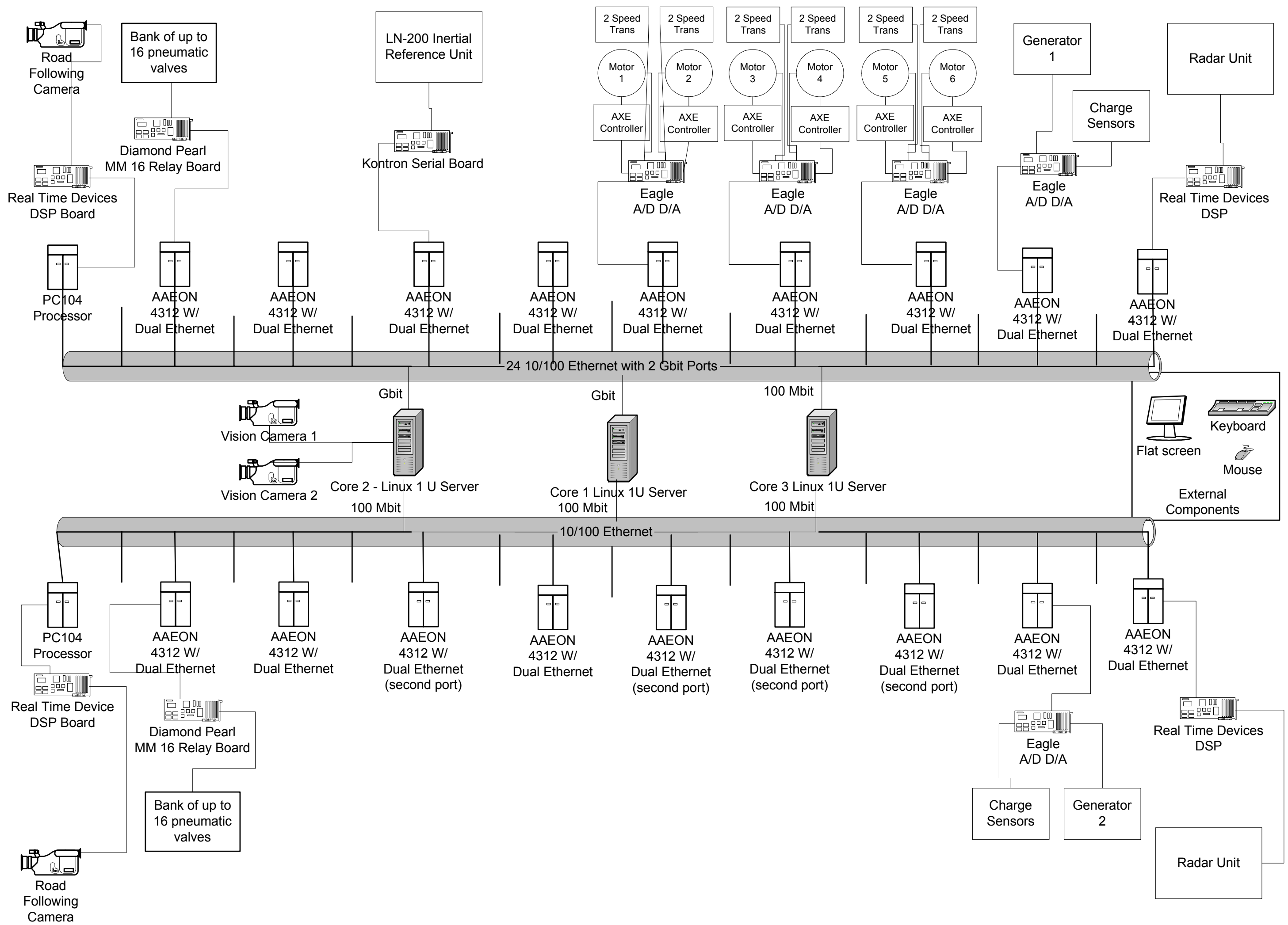

Figure 2 Processing System Layout

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