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Team TerraMax and the DARPA Grand Challenge: A General Overview

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Abstract—**The Defense Advanced Research Projects Agency (DARPA), an agency of the United States Government, has issued a challenge to developers of off-road autonomous ground vehicles to design and build a vehicle that can complete a lengthy and difficult off road course across desert southwest areas of the United States. A one million dollar US prize is available to the team that completes the 200-250 mile course first and in less than 10 hours. This paper describes the Team TerraMax entry to the March, 2004 race event. Vehicle hardware and drive by wire actuators, internal and external sensing systems, sensor fusion, and high and low level control systems are described.**

I. INTRODUCTION

THE Defense Advanced Research Projects Agency (DARPA), an agency of the United States Government, has issued a challenge to developers of off-road autonomous ground vehicles to design and build a vehicle that can complete a lengthy and difficult off road course across desert southwest areas of the United States[1]. A one million dollar US prize is available to the team that completes the course first and in less than 10 hours. The course was expected to be approximately 200-250 miles long, with over 90% of the course to be off-road. The course could include gravel roads, paths, switchbacks, open desert areas and dry lakebeds, mountain passes, and some paved roadways. Possible routes are shown in Figure 1. The course is to be described using several thousand waypoints expressed as latitude/longitude pairs coupled with allowable path widths and speed limits. The vehicle must be able to navigate within the race corridor as well as negotiate or avoid other vehicles, fences, utility poles, stones, trees and bushes, ditches, and other natural or man-made obstacles within the route corridor. The vehicles must also incorporate safety systems to provide reliable remote control pause and kill functions.

The vehicles must also be completely autonomous: no remote control capabilities are allowed. They may carry any combination of onboard sensors, both for sensing the position of the vehicle and the surrounding environment, as well as use any available, non-classified map and terrain databases. They only external signals allowed are the pause and emergency stop remote control signals and publicly available navigation aids, such as Global Positioning System (GPS) signals and commercial differential correction services available to all teams. The vehicles must be capable of navigation, path planning, obstacle avoidance, and terrain differentiation.

This paper describes the Team TerraMax entry for the March, 2004 race event. Team TerraMax is an Oshkosh Truck Company [2] and Ohio State University [3] partnership team, with a technical alliance with the University of Parma for image processing related environment sensing technologies. Vehicle hardware and drive by wire actuators, internal and external sensing systems, sensor fusion, and high and low level control systems are discussed.

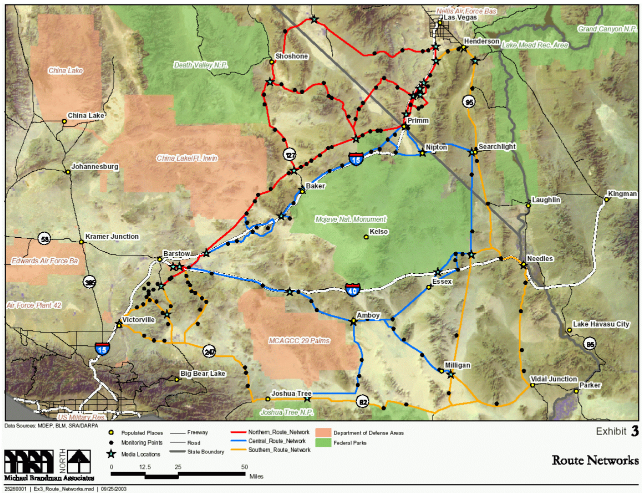

Figure 1: Possible Routes for the Grand Challenge

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II. VEHICLE HARDWARE

A. Vehicle Platform

The vehicle platform used by the team is an Oshkosh Truck Company Medium Tactical Replacement Vehicle (MTVR) Model MK-23 [4], as shown in Figure 2. The vehicle is approximately 3.2 meters (8.2 feet) wide, 8 meters (26.4 feet) long, and 3.2 meters (8.2 feet) tall as configured for the competition. The cab and the exhaust stack were shortened, and the side mirrors removed, to meet known dimensions of paths with obstacles along the race corridor. The vehicle weighs approximately 32,000 pounds as configured. An additional diesel fuel tank was mounted on the truck bed to increase operating distance and time. An automatic fire detection and suppression system was installed to cover the fuel tanks, engine and power train, exhaust, and cab areas of the vehicle. Audible alarms and flashing visible strobe lights were also installed to warn bystanders of autonomous vehicle operation.

The vehicle can travel up to 65 mph. It has full 3 axle 6x6 all wheel drive capability, and is able to traverse a 60% grade and a 30% side slope, ford 5 feet of water, and surmount a 24 inch step. The minimum turning radius is 42 feet, although tighter corners can be accomplished using robotic multi-point turn maneuvers. The vehicle also is equipped with a 6 wheel antilock braking (ABS) and automatic traction control (ATC) system, automatic transmission, and a central tire inflation system.

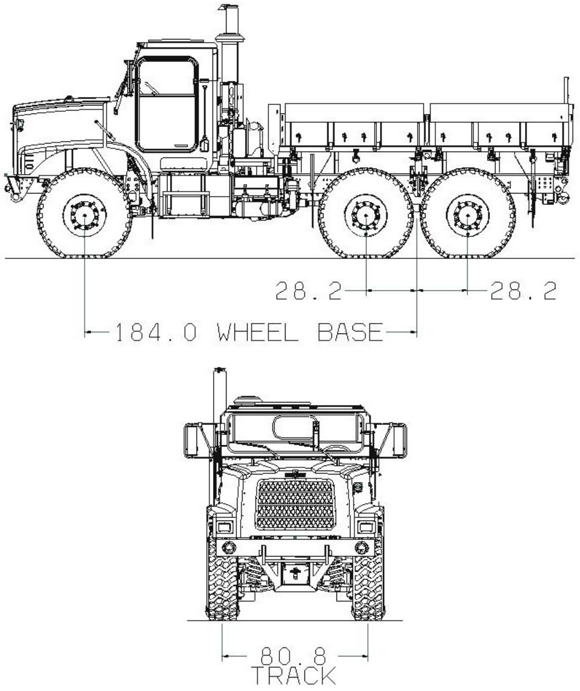

Figure 2: Oshkosh MTVR Vehicle Platform

B. Drive by Wire Hardware

The vehicle was retrofitted to provide drive by wire capabilities. Throttle control was accomplished with a variable duty cycle pulse width modulated (PWM) signal that replaced the normal throttle pedal position sensor signal supplied to the vehicle's existing electronic control unit (ECU). Automatic braking was accomplished using a second brake manifold and check valves installed in parallel with the existing pneumatic brake system so that the driver's brake pedal remained fully functional. Air pressure into the brake by wire manifold was regulated by an electro-pneumatic regulator supplied from the wet air tank and controlled by an analog voltage input. The outlet pressure of the electro-pneumatic regulator is also validated using a pressure sensor. Control of the automatic transmission, providing neutral, reverse, drive-7, drive-3, and drive-2 selections, was accomplished by providing open collector optoisolated voltage inputs to the transmission ECU mimicking the signals from the driver's touch control panel. Steering actuation was accomplished using a Rockwell Automation motor and controller connected to an auxiliary input shaft on the steering gear. The Rockwell controller provided a position control loop, with the set point changed using an analog voltage input. The driver's steering wheel allowed for manual override.

The vehicle interface electronics were designed to completely isolate the stock vehicle electronics from the autonomous control systems, and to provide a fail-safe operating condition in the event of power loss or emergency stop.

C. Electrical Power

The vehicle operates with a 24 VDC power bus. To insure adequate power availability, the stock alternator was replaced by one with larger capacity. Two 24 VDC to 120 VAC power inverters along with two ruggedized uninterruptible power systems (UPS) were installed. The 120 VAC outputs of one UPS were used to power the "clean" electronics, including sensors and computers. The outputs of the other UPS were used to power "dirty" electronics, including the steering motor and controller and equipment cooling.

D. Computing

The vehicle was designed to operate with 6 computers: a main control and vehicle state sensing system, a map and route planning system, a sensor interface management and fusion system, two image processing systems, and a health and fault monitoring system. These were rack mounted Intel Pentium-4 based systems enclosed in two vibration damped, weatherproof enclosures mounted on the truck bed. The main control computer ran the QNX 6.21 real-time operating system, and the other computers ran Redhat versions of the Linux operating system.

III. SENSING

The overall configuration of the vehicle sensors is shown in Figure 3. The sensors divide into two groups: those providing internal vehicle state sensing, including position, orientation, and velocity information, and those providing sensing of the external environment surrounding the vehicle.

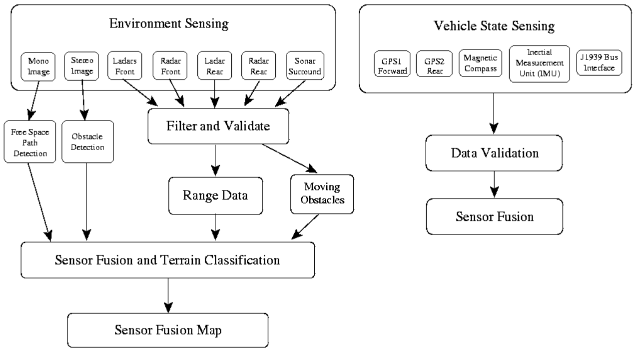

Figure 3: Sensor and Sensor Fusion Configuration

A. *Vehicle State Sensing*

In order to control the vehicle to follow a set of waypoints at a given speed, the internal or ego state of the vehicle, including position, orientation, velocity, and direction of travel, must be known accurately and with a reasonably rapid update rate. A single sensor, for example GPS, is not sufficient because of sensor dropout in certain areas, false readings during reacquisition, and limited update rates. TerraMax used a number of sensors to overcome these problems.

Two Novatel Propak-LB-L1/L2 dual frequency GPS receivers, receiving wide area differential corrections from the Omnistar HP subscription service, were used to provide position resolutions with accuracies up to 10 cm and update rates up to 10 Hz. The antennas for the two receivers were positioned as far apart as practicable to achieve a long baseline, which provided for yaw angle computation (when both sensors were available) and the highest likelihood of at least one GPS position measurement being available.

A Crossbow VG-700-AA fiber optic vertical gyroscope was used as the inertial measurement unit. It provided 3 DOF acceleration and angular rate measurements mapped into an earth coordinate reference frame, as well as pitch and roll measurements, with angular drifts of less than 20 degrees per second.

A Hewlett Packard HMR3000 magnetic compass was used to provide yaw, pitch, and roll angles at low speeds.

The J1939 vehicle bus was accessed using a B&B Electronics HDV100A1 interface to measure vehicle speed, individual wheel speeds, engine RPM and transmission gear status, and various temperature, pressure, and fluid level measurements indicative of vehicle health.

B. *Surrounding Environment Sensing*

In order to provide the vehicle with an awareness of its surroundings, a number of different sensor modalities were installed on the vehicle. By using multiple sensor technologies, the individual strengths of each technology can be exploited and the effects of individual weaknesses can be minimized.

Four SICK LMS-221 scanning laser rangefinders were installed on the vehicle. Each provides a 180-degree scanning field, with a resolution of 0.5 degrees, a maximum range of 80 meters, and a empirically determined useful range of 40-50 meters in an off-road environment. The actual range depends on the reflectivity of the target, but our experience to date is that 40 meters is a reasonable minimum operating range and satisfies the Demo III Experimental Unmanned Vehicle (XUV) obstacle avoidance requirements of approximately 110 feet stopping distance when traveling 40 mph on a 7% grade. Two sensors were installed behind the front bumper (approximately 85 cm above ground) of the vehicle and angled at 60 degrees from the forward axis. These provided overlapping coverage for obstacles in front and to the sides of the vehicle. A third sensor was mounted on the rear of the vehicle under the truck bed. These three sensors provided a 360-degree view of the area around the vehicle, excepting certain obscured areas near the vehicle. They scan approximately horizontally to avoid detecting small shrubs and rocks. The fourth laser sensor was mounted on the front of the vehicle and scanned vertically. This sensor was placed to detect both positive and negative obstacles directly ahead of the vehicle.

Two Eaton-Vorad EVT-300 radar units were mounted in the center of the vehicle’s front and rear bumper. These devices provide a 12-degree scanning field and a range of approximately 140 meters. Since they employ Doppler radar technology, they detect and track only targets moving relative to the vehicle.

Twelve Massa M5000/95 ultrasonic rangefinders were installed to cover the perimeter of the vehicle for low speed, short distance maneuvers and robotic motions. Two of these sensors, mounted on the front corners of the vehicle, were pointed downward to help detect roadside drop offs.

C. *Vision Based Environment Sensing*

The vision system consists of two pairs of color CCD digital color cameras (passive) to provide stereovision information (both forward and rear looking) and one each looking straight ahead and behind. The cameras were installed as high as possible on the vehicle in transparent protective casing. A periodic burst of air fed through a nozzle on the camera cover was used to dislodge dust. The vision system will sense the terrain in front of the truck and provide free-space detection/estimation and path/road detection. Vision system processing is carried out on two dedicated computers. The Sony DFW-V500 cameras are interfaced using a IEEE-1394 (Firewire) bus.

For Lane/Path determination the three algorithms developed were:

- Clustering based on color texture. This is a classical approach based on the assumption that the textures of the path and off-road present different visual characteristic.
- Boundary detection using a genetic approach. This is similar to the work done for military mobile snowcat tracks detection at the pole, performed by Parma University. The main idea is to recover path boundaries by means of autonomous agents. It has been under development for three years, and has proven to be fast and effective. For snowcat track detection the system is able to detect track boundaries at up to 40 meters and the processing time is 8.6 ms on a 1.3 GHz PC.
- Lane/Path match using multi degree-of-freedom models. This is a new, highly complex approach currently under development. It is based on a match against a number of path models generated acting on a set of parameters. A multiresolution approach will be used to increase computational efficiency: initially the match will be performed against a low resolution model, then refined using the best matching models at higher resolutions. The process will be iterated until a satisfactory result it obtained.

The “Free Space Detection” approach is based on stereo and color match and similar to pedestrian detection. Visual information is processed in order to detect the portion of the terrain ahead where is should be safe to move (the free space). Objects are not classified. A stereoscopic technique is used for the localization of potential obstacles in generic unstructured environments. Each row of the left image is matched with the epipolar row of the right image. This creates a map of each object in the scene as well as the slope of the road. This approach is particularly suited for off-road environments since it does not rely on calibration of the vision system.

D. *Internal Databases*

The software has access to several geographic databases. The first is the basic elevation map of the area derived from the United States Geological Survey (USGS) data service and other sources. This map is processed, along with manually added photographic data, to generate a hospitability map that quantifies the ease or difficulty of travel through a particular path or region. The third database consists of roads, trails, and pre-driven routes.

E. *Environment Sensor Fusion*

Each of the environment sensors produces azimuth and range, and in some cases range rate, information for detected objects within its field of view. The image processing systems produce a map of a certain area ahead of the vehicle and path data. The raw output of each sensor must be validated to remove transient noise, and translated and rotated so that the data can be represented in a fixed coordinate system. When multiple sensors provide obstruction and target information for the same space, sensor fusion and validation may be implemented. The final results are placed on a discretized world map for use by the high level controller.

IV. VEHICLE CONTROL

As is often the case is complex systems, the situation awareness and control aspects of the system can be viewed in a hierarchical framework. In the TerraMax vehicle, high-level control, consisting of situation awareness, reasoning, reacting, and planning occurs in a collection of algorithms called the Control Logic Module. Low-level control occurs in a hybrid system process consisting of rules and standard continuous control laws with variable or scheduled parameters.

A. *Control Logic Module*

The TerraMax control logic consists of a number of modules, some always active and some active only in certain situations or on demand. The established structure allows separate and somewhat independent development. It also allows continual expansion to handle different and more complex situations throughout the development process. The following six modules were developed: Map and Route Planning Module, Surround Sensing/Sensor Fusion, High Level Terrain Classifier, Situation Analysis and Control Logic, Alarm, and Roll-back Analyzer. The following subsections will briefly introduce the modules, and their inputs, outputs, and their goals.

1) *Map and Route Planning*

This module deals with the “way points” provided by DARPA and accomplishes the high-level route pre-planning. A digital terrain map is evaluated using prescribed parameterized functions to generate a “hospitability map” and a “synthetic inclination map”. Data is also added manually from photographic data and pre-driven routes. A D-Star algorithm is then used to calculate the “best” route and provide it to the Situation Analysis and Control Logic Module. As implemented, the Map and Route Planning Module will also provide time estimates for traversing segments and alternate routes. The module also determines if the provided waypoints are too closely spaced to do further path planning. The Module may be re-called as necessary by the Roll-back Analyzer Module.

2) *Surround Sensing and Sensor Fusion*

Surround sensing was described previously. It generates a local map of the surrounding environment for use by other modules.

3) *High Level Terrain Classifier*

The High Level Terrain Classifier Module identifies the surrounding terrain, thereby affecting the local behavior and goals of the vehicle. We have initially identified the following terrain classes: roadway, open smooth, open rough, uphill rough, downhill rough, one-sided drop off, and robotic maneuvering.

The "Behavior" is a group of set points and weights and is set by the Terrain Classification together with the pre-established "Personality" of TerraMax. For example, in roadway or open-smooth conditions speed can be increased and higher speed lateral controllers can be utilized, whereas in uphill or downhill rough conditions speed can be reduced, engine braking enabled, and a different transmission gear may be selected. The Personality will be established during tuning tests. However, the Personality may become more aggressive when the schedule slips during the course of the race.

Two particular special cases are the one sided drop off and the robotic maneuver conditions. The one sided drop off class is specifically identified so that motions to the dangerous side can be curtailed. This terrain can be identified from map data and verified using sensors.

The robotic maneuvers condition is a special terrain or location where the vehicle has to go through a specific exercise, possibly with a set of predetermined operations, to avoid an obstacle or pass through a narrow constrained passage. Examples where Robot behavior may be needed include underpasses, gates, sharp turns at roadway intersections and possible passage through mazes of natural and synthetic obstacles.

4) *Situation and Control Logic*

The "Situation Analysis and Control Logic" module, shown in Figure 4, is the Module that manages the full system. It establishes a multi-level hierarchy to provide situation awareness, behavior mode selection and real-time control. It generates a desired local trajectory as a set of position coordinates and speed set points. Obstacle avoidance is accomplished using a path-elimination approach or a simplified potential field approach. A simulation example of path planning results is shown in Figure 5.

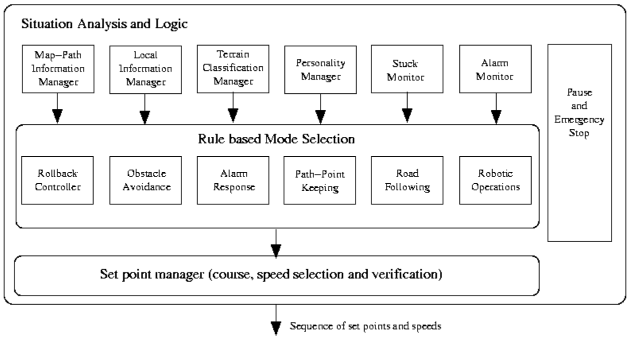

Figure 4: Situation Analysis and Control Logic

5) *Alarm*

The Alarm Module is continually active to monitor overall system conditions, for example sensor and computer heartbeats, and failure conditions such as sensors with unreasonable data or extreme controller commands. The module could also be expanded to handle emergency conditions, sensor reconfiguration and failover, and personality adjustment.

6) *Roll—back Analyzer*

The "Roll—back Analyzer" (RBA) is a special module to handle lockup conditions. Basically, if the vehicle remains at the same site, or within a small boundary (location dependent), or cannot make reasonable progress towards the next waypoint for an excessively long time (duration dependent), the system should retrace its recent motions and reevaluate previous decisions to generate an alternate path. The module must maintain time estimates for goal completion, identify and store path decision points, and retain second and third path choices at decision points for future reference in a roll-back state.

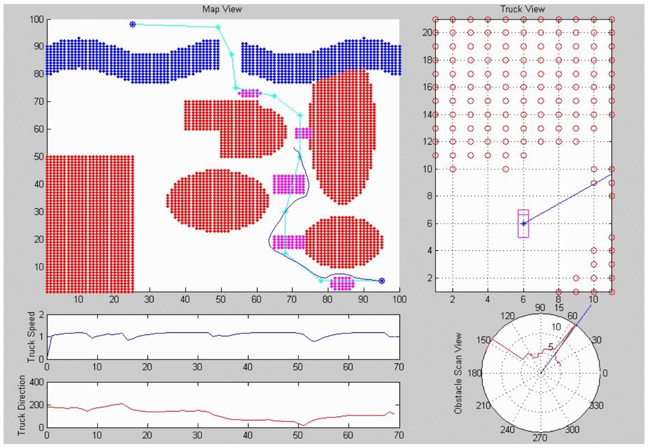

Figure 5: Path Planning and Obstacle Avoidance Simulation

B. *Low Level Control*

The task of the low-level control software is to execute the plans generated by the high level controllers: specifically to cause the vehicle to achieve path and speed following according to the supplied plan. The control sub-module is similar both to the Ohio State University Demo 97 event [5,6] in San Diego, CA and the Ohio State University 1999 demonstration event [7]. The Demo 97 vehicle had distinct longitudinal and lateral control systems. Speed set points were generated either from preplanned routes or a car following (advanced cruise control) mode of operation. Steering was sensor driven, and software initiated events could be introduced (for example, lane changes) in response to external events and objects [8]. The steering set point relied on a look-ahead scheme using either vision-based lane tracking or radar-based stripe tracking. The controllers also utilized inertial motion and radius of curvature.

The Demo 99 vehicle obtained speed set points for a specific location (speed limits in a map database) or based on road curvature (also derived from a map database). Lateral control [7] relied on fused GPS, inertial measurement, and dead reckoning data.

V. RACE RESULTS

The actual Grand Challenge event was divided into two segments. The first consisted of several days of qualification events, demonstrating the safety and reliability of the vehicles and emergency stop systems and autonomous motion capabilities on a test course at the California Speedway at Fontana, CA. The TerraMax vehicle was one of seven vehicles to complete the entire 1.3-mile qualification test course.

The actual race was held on March 13, 2004 and began in the Stoddard Valley OHV recreational area south of Barstow, CA. The race route as supplied by DARPA was 144 miles in length. The TerraMax vehicle traveled 1.4 miles along the course, the 5th farthest distance, before experiencing a software failure in its network and interprocess communication system.

VI. CONCLUSION

The DARPA Grand Challenge provided a venue for testing various approaches to designing intelligent mobile platforms. Team TerraMax is a specific attempt to underplay the mechanical design issues. The size and capabilities of the vehicle platform reduces concerns about small objects, terrain variations, and sand or water obstacles. This investigation has been able to focus more on issues related to sensing and intelligent behavior. Although time constraints precluded the completion and testing of every planned system, a serious attempt was made to produce new and innovative results in the development of situation analysis algorithms, system roll-back, multiple map-based multiresolution sensor fusion, and motion planning and control for heavy duty vehicles.

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