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The TerraMax Autonomous Vehicle concludes the 2005 DARPA Grand Challenge

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Abstract— **The TerraMax autonomous vehicle is based on Oshkosh Truck's Medium Tactical Vehicle Replacement (MTVR) truck platform and was one of the 5 vehicles able to successfully reach the finish line of the 132 miles DARPA Grand Challenge desert race. Due to its size and the narrow passages, TerraMax had to travel slowly, but its capabilities demonstrated the maturity of the overall system.**

Rockwell Collins developed the autonomous intelligent Vehicle Management System (iVMS) which includes vehicle sensor management, navigation and control systems; the University of Parma provided the vehicle's vision system, while Oshkosh Truck Corp. provided project management, system integration, low level controls hardware, modeling and simulation support and the vehicle.

I. Introduction

The TerraMax vehicle, shown in figure 1, is based on Oshkosh's Medium Tactical Vehicle Replacement (MTVR) truck platform. The MTVR was designed with a 70% off-road mission profile. It can carry a 7-ton payload off-road or a 15 ton payload on-road. All-wheel drive, TAK-4™ independent suspension, and central tire inflation make rocks, dips, holes and crevasses easier to handle. And the truck can handle 60% grades and 30% side slopes. A 425-hp Cat C-12 engine powers the truck.

Figure 1: The TerraMax Vehicle

This kind of vehicle was chosen for the DARPA Grand Challenge (DGC) because of its proven off-road mobility, as well as for its direct applicability to potential future autonomous missions.

Two significant vehicle upgrades were carried out since the 2004 DARPA Grand Challenge event namely the addition of rear-wheel steering and a sensor cleaning system.

Rear steer has been added to TerraMax to give it a tighter 29-foot turning radius. Although this allows the vehicle to negotiate tighter turns without needing frequent back ups, the back up maneuver is required to align the vehicle with narrow passages.

The cleaning system keeps the lenses of the TerraMax sensors free of debris such as dust, water, and mud. The main components of this system are; Cleaning Controller, Valve Array, and Washer Tank. The Cleaning Controller controls the sequence and duration the sensors are dusted, washed, and dried. The Valve Array has electrically controlled valves that pass pressurized water and air through pattern nozzles to the sensor lenses.

This paper presents the sensor suite of TerraMax, the overall architecture, and the key software for autonomous operations.

II. TerraMax Sensing Capabilities

The sensors were carefully selected to provide the required navigation and perception capability. Figure 2 shows the sensor locations on TerraMax. The sensors selected for the DARPA Challenge 2005 are as follows:

- Forward-looking Vision System
- Single-plane LIDAR
- Multi-plane LIDAR
- Oxford GPS/INS
- Trimble GPS

Figure 2: The TerraMax sensor suite: three cameras and two Sick LIDARs are installed on the rollbar; two IBEO Laserscanners are installed inside and over the front bumper; GPS antennas are visible on top of the vehicle's roof

A. Trinocular Vision System

The vision system is based on multi stereoscopic vision (forward looking trinocular system). It consists of 3 identical cameras mounted on a rigid bar on top of the hood. The two lateral cameras lay at a distance, which is about 1.5 meters, while the central one is placed asymmetrical at about 0.5 meters from the right one. Thanks to a precise calibration of the cameras -performed on a graduated grid- the three degrees of freedom specifying cameras orientation are fixed to known values: in particular, in order to ease and speed-up the subsequent processing, the yaw and roll angles are fixed to zero for all cameras. The pitch angle is chosen so that the cameras frame only a small portion over the horizon (to limit direct sunlight) and frames the terrain at about 4 meters from the vehicle.

The trinocular system sends 3 video streams at 10Hz (640x480, color with Bayer pattern) to the vision PC via a firewire connection. The PC selects which stereo pair to use depending on the speed of the vehicle. Since the baseline of the stereo vision system influences the depth of view, the large baseline is used at high vehicle speeds so that a deeper field of view is obtained, the medium one at medium speeds, and the short baseline is used at low speeds. This is one of the very few examples of very large baseline stereo systems (1.5 m) used on rough off-road terrain and delivering a robust environmental perception at more than 50m, regardless of terrain slope.

Vision provides sensing for both obstacle detection and path detection; examples are given in figures 3 and 4.

1. Image disparity is first used to estimate the average terrain slope in front of the vehicle. Slope information is then used for both obstacle detection and path detection. Any significant deviation from the average smooth slope previously detected is then identified as an obstacle. The exact location of obstacles is then obtained via stereo triangulation between the two views of the object. A fairly precise localization is obtained, but nonetheless it can be further refined via sensor fusion with raw data coming from the multi-plane lidar (discussed in the next paragraph). In this way it is possible to detect also thin vertical posts and fence poles, which are difficult to be detected using laser-based sensors.

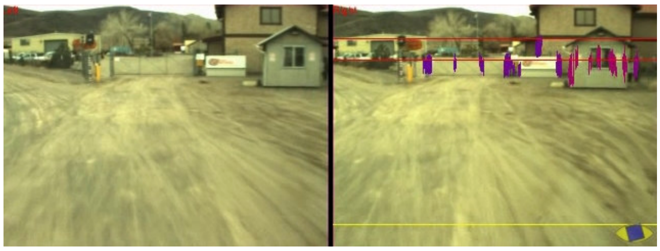

Figure 3: left and right stereo images; on the right image, colors show the presence of detected obstacles. Different colors mean different distances.

2. Image disparity is also used to compute the area in front of the vehicle which features a smooth slope, the so-called free-space. The free-space is one of the features that concur to construct a representation of the path to be followed by the vehicle: also similarity in texture, similarity in color, and shape information are taken into account, fused together, and delivered to the following path planning module. Path detection is also used to deliver one more bit of information to the path planner: 'straight-road' detection is used to trigger the path planner to increase speed when the vehicle is facing a straight road.

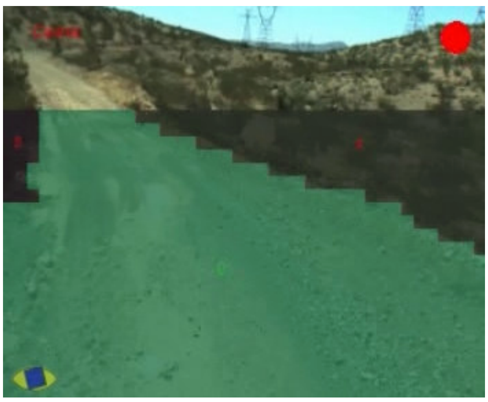

Figure 4: the result of path detection in green; the red dot in the top right corner represents the status of the 'straight-road'-detection: in this case 'red' means curved road.

Vibrations are automatically filtered out since the slope detection algorithm, which is the first step of the processing, also extracts information that is used to electronically stabilize the oncoming image streams.

The camera boxes have a sun shade aimed at reducing to a minimum the quantity of direct sunlight hitting the cover glass, in order to avoid over saturation and reflections due to dirty glass. Nevertheless, different lighting conditions and levels are handled by the automatic gain control scheme integrated into the vision module: this method, together with polarizing films, allows the cameras to sense the environment even in conditions of direct sunlight into the camera. (See Figure 5).

Figure 5: Image representing the view without and with the developed camera gain control scheme; in the right image, although a part of the image is oversaturated, the terrain is visible and the algorithms for obstacle and path detection can be run

B. Single-plane LIDAR

There are two SICK LMS-291 LIDARs used for positive and negative obstacle detection. They are mounted on the outermost edges of the front rollbar. They are pointed 10 degrees down and 25 degrees outward from the truck so that there is good coverage on extreme turns. The two LIDARs are configured to scan a 100-degree scan area with a 1-degree resolution. Three separate algorithms are used for negative edges (cliffs), positive and negative obstacles at close range, and path center detection.

C. Multi-plane LIDAR

The IBEO ALASCA LIDAR is a 4-plane scanner that is used for positive obstacle detection. The LIDAR is mounted in a frontal position and is oriented so that two planes scan towards the ground and two planes scan towards the sky. With a range of 80 meters and a resolution of 0.25 degrees it can detect obstacles accurately at long and close range. The 170-degree scan area allows seeing obstacles around upcoming turns.

The LIDAR sends scan data via Ethernet to the LIDAR PC via a TCP connection. An algorithm then transforms the raw scan data into obstacles by looking for large positive slopes in the scan data.

D. Oxford GPS/INS

The OXTS RT3100s are mounted on the floor of the cab on the approximate centerline of the vehicle. In order to obtain a more accurate position solution and eliminate any errors over time, the position solutions from the two RT3100s were averaged together. In the case of a failure of one of the RT3100s, the system will switch to using the remaining RT3100 as the sole GPS source.

E. Trimble GPS

The Trimble GPS is an agriculture GPS unit used to receive differential corrections used by the GPS receivers embedded in the Oxford RT3100's. The Trimble receiver outputs differential corrections at 1Hz through RS232. In order to output the differential corrections the Trimble receiver is placed in base station mode and must also have a subscription.

III. Vehicle Management System

The Intelligent Vehicle Management System (iVMS) consists of hardware and software components that together provide an extensive set of autonomous capabilities. In order to accomplish this, the iVMS interfaces with the vehicle systems and all onboard sensors. The primary commands to the vehicle interface are throttle, brake, steering, and transmission.

The general architecture for the iVMS software is a set of applications that communicate to each other over a 100BaseT Ethernet network utilizing TCP and UDP protocols and a commercial Ethernet switch. The iVMS software has the key role of performing all autonomous behavior and interfacing to numerous LRUs (line replaceable units) and the key vehicle systems. The software applications are as follows:

- **Vehicle control** - controls and receives feedback from the throttle, brakes, and steering in order to control the vehicle while in autonomous mode.
- **Real time path planner** – computes the real time path utilizing the desired path while avoiding the obstacles along the desired path
- **Obstacle detection** – uses LIDAR and Vision to detect positive and negative obstacles. Obstacle data coming from the various sensors are merged into a single obstacle database used by the real-time path planner.
- **Behavior management** – decides what mode the vehicle should be in based on the current conditions of the other functions
- **Navigation** – computes present position and provides a dead reckoning function.

A Graphical User Interface (GUI) provides multiple functions to the user including data visualization, recording, and playback. The GUI is primarily a development tool and is not considered to be an integral part of the real-time iVMS system. Figure 6 shows the GUI displayed on a monitor in the cab.

Figure 6: The driving cabin, with the monitor showing the graphical user interface.

A system management function is also implemented that provides a user interface for execution control and status display for the iVMS applications. Once the system has been initialized, the system manager performs a health management function that continuously monitors the status of the application and automatically stops and restarts applications as necessary to maintain normal functionality. The iVMS can continue to operate normally without the system manager once initialized so it is, therefore, not included as one of the iVMS applications. The software architecture can be viewed in Figure 7.

The following sections of this paper will go into further detail on each of the iVMS functions.

A. *Vehicle Control*

The vehicle control function of the iVMS provides the TerraMax control actions that emulate the actions a human would perform when driving the truck. The controls provided by the iVMS are steering, throttle, brake, and transmission control. Steering control is provided through an electronic servo connected directly to the MTVR steering gearbox. The standard MTVR steering gearbox has dual inputs so the steering servo for autonomous operation and hand wheel are both connected to the steering gear allowing the steering control to be switched between manual and autonomous operations without changing mechanical linkages. The steering control uses capture and track steering control modes. Capture steering control is used for initial course capture and track steering control is used during normal operation. Capture and track control modes are automatically selected based on current conditions.

The capture controller uses course error as the control parameter. The controller creates a steer angle command that aligns the ground track of the vehicle with the direct bearing

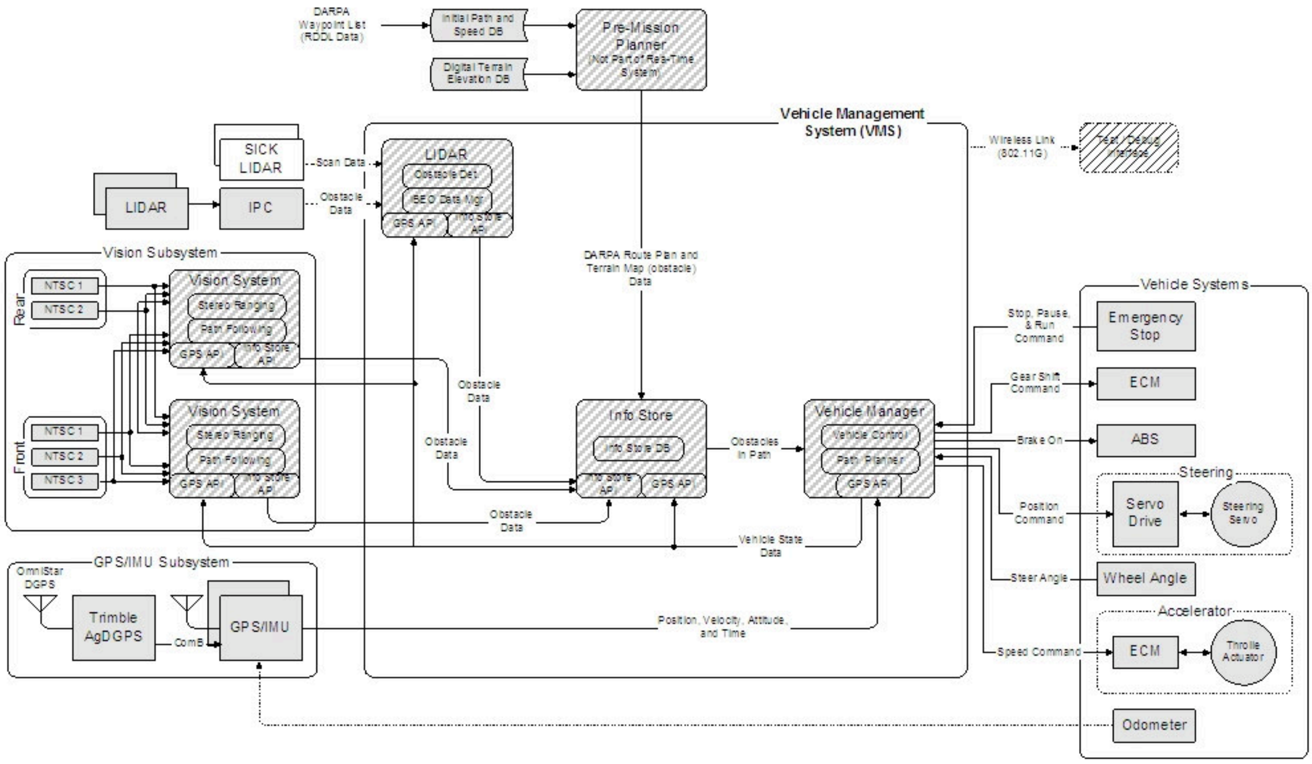

Figure 7: iVMS Software Architecture

to the active (TO - “next”) waypoint.
The track controller uses linear cross track deviation and cross track deviation rate to align the vehicles path along the ground with the active TO waypoint course. Turn anticipation for waypoint sequences is also used so the transition onto the new course is accomplished without overshoots.

The throttle controller interfaces directly to the electronic engine control unit (ECU) through a digital PWM interface. The throttle controller is responsible for controlling the vehicle’s speed to the desired speed specified by the path planner.

The throttle position control uses proportional and integral control. Reset conditions to the throttle position are provided for transmission up shift and down shift and to activate the engine brake. Engine brakes are activated during engine idle so throttle position overrides are used when engine brakes are required. Throttle position faders are used to reactivate the throttle position control when the engine brake is disabled. Engine and service brakes are used primarily to control speed on steep grades and for speed management during deceleration.
The brake controller provides an analog signal to a pressure actuator connected to the air brake system (service brakes). The throttle and behavior control functions provide brake actuation parameters to the brake controller and the brake controller determines the pressure actuator signal. Brake modulation to limit slipping in full brake conditions are provided by the Anti-lock Brake System (ABS) system that is part of the basic MTVR.

B. Real–time Path Planner

The real-time path planner is responsible for deriving the desired trajectory of the vehicle and providing that trajectory to the vehicle control function. The trajectory includes a desired path along the ground as well as the desired speeds and boundary area. The path planner implements a tree algorithm that branches from the base at the current TO waypoint. Constraints for path boundary and speed are applied to the tree build function so the tree size is bounded by the constraints. Branches of the tree are computed using a model of the steering system and vehicle dynamics to insure that the candidate paths are drivable.

Once built, the tree represents a series of candidate paths, one of which is selected as the path to be used by the vehicle control. Selection of the best path from the candidate paths is based on a scoring algorithm that considers distance from the route centerline, path curvature, obstacle avoidance, boundary area constraints, and other factors. Over 2000 candidate paths are evaluated each planning cycle to determine the best path.

C. Obstacle Detection

LIDAR and vision sensors are used to detect obstacles in front of the vehicle. Obstacles detected by the sensors are registered to the vehicle navigation position and stored in an obstacle database. The real-time path planner queries the database to determine if obstacle collisions occur on the proposed paths.

Several different types of obstacle clearance information are provided to the path planner to aid in path selection. Obstacle collision information is reported by the database in terms of the closeness of the object collision to the proposed path. Buffer regions of various sizes are used to determine the collision proximity relative to the path.

Bearing and distance to the nearest collision is provided by the obstacle database that is an indication of the proximity of the obstacles to the proposed path. Obstacle distance is used primarily in the speed manager function to lower the speed if an obstacle is in close proximity to the vehicle’s planned path.

Road and cliff edges are handled as special cases by the obstacle database. Since the consequences to the vehicle of breaching a cliff edge are very severe, additional weight to negative road/cliff edges are used. The database also reports if any negative road/cliff edges are in the immediate area that is used by the speed manager to reduce speeds accordingly.

D. Behavior Management

The behavior management module is the central “brain” of the system. Its purpose is to monitor and react to dynamically changing conditions. This module receives input from the real-time path planner, obstacle database, navigation sensors and the vehicle interface module.

Several behaviors have been designed into the behavior module, using a state transition architecture. When a specific event or a change from normal operating conditions is detected, one of the behaviors is activated to handle the situation at hand. Each behavior executes an ordered list of instructions, providing a set of commands to the vehicle controller.

Some of the conditions the behavior module will react to are as follows:

- **Transition in E-Stop state:** when the e-stop is in Pause mode, a behavior will command the vehicle to come to a stop. When e-stop transitions to Run, another behavior is initiated to begin normal operation.
- **No valid path ahead:** The behavior initiated in this condition commands the vehicle to come to a stop and wait for a valid path. If no valid path is found, it will command the vehicle to back up and try again.

- **Obstacle detected behind the vehicle while backing up:** another behavior will stop the vehicle and command it back into normal operation to try to find a valid path ahead.
- **A large course change requiring a backup maneuver:** the switchback behavior guides the vehicle around a 3-point turn.
- **Narrow tunnel condition:** the tunnel behavior will guide the vehicle through a narrow tunnel, using the LIDAR scan data.
- **Stuck between obstacles:** if the vehicle cannot make progress along the route because it continues to go back and forth, getting stuck between obstacles, the stuck behavior will take over. It will first try to position the vehicle at different angles to search for a valid path. If no valid path is found, it then commands the system to ignore low confidence obstacles, in an attempt to eliminate false obstacles. The last resort is to go forward toward the DARPA route, ignoring all obstacles.

E. Navigation

Two Oxford Technical Solutions (OXTS) RT3100s supply GPS position information to the iVMS system. The RT3100 is a combined GPS/IMU sensor that provides real-time data even in the absence of GPS signal. The high 100Hz update rate has a very low latency to insure that the system is using the most accurate position possible. One RT3100 is configured to use DGPS corrections transmitted via RS-232 from an external GPS receiver subscribed to the Omnistar correction service. The other RT3100 is configured to use WAAS corrections.

In the case of loss of GPS signal, such as driving through a tunnel, the IMU portion of the RT3100 takes over and begins dead reckoning. In order to aid the INS solution in dead reckoning mode, a wheel speed sensor on the vehicle provides input to the RT3100. Tests have shown that the wheel speed input helps to keep the IMU solution stable and extends the time the RT3100 is able to dead reckon.

In the case of a failure or short-term loss of the RT3100's, a second dead reckoner is implemented using sensed wheel speed and wheel angle. This represents an independent backup navigation function. Because of the potentially large errors that can build up when it is in a dead-reckoning mode, the RDDF boundary area checks in the path planner are disabled so the vehicle can continue navigation relative to the terrain and terrain obstacles for short periods of time.

IV. Vehicle Performance during the Race

The iVMS development philosophy was to create an autonomous system that could, in the future, be utilized in military operations. This allowed for a more rugged implementation of the iVMS for real time navigation across unknown terrain. As a result, Team TerraMax was one of only five teams to traverse the 132-mile course and the only vehicle to overcome an overnight "pause" of the autonomous system. During the race, TerraMax reached a maximum speed of 42 mph. This is impressive not only due to the size and weight of the TerraMax, but due to the fact that true obstacle avoidance was achieved at these speeds.

During the race the TerraMax was paused 13 times by DARPA officials to maintain a minimum distant between the competing vehicles or for passing stopped vehicles. The TerraMax automatically stopped and realigned its path approximately 52 times during the race. The majority of the path resets occurred while traversing beer bottle pass where the road was very narrow and the turns were very tight compared to the size of the vehicle.

An automatic reversion mechanism was implemented to manage redundant sensors. The reversionary logic was activated due to sensor abnormality twice during the race. The reversionary logic correctly selected the operational sensor and continued to operate normally after the reversion.

A software application health monitor was implemented to monitor the health of the system and start and stop applications as necessary to keep the system executing normally. During the race the health monitor function was activated and correctly reset applications to keep the system operating normally with only minor interruptions in service. A periodic database integrity check was also performed to prevent fatal errors from corrupting the database and to recover data if a data error was found.

During the race the TerraMax struck the edge of one of the concrete underpass barriers. The impact of the tunnel caused the IBEO LIDAR and passenger vision camera to be severely misaligned. The misalignment caused a geo-registration error of the detected obstacles. This caused the path planner to offset the path to compensate for obstacles, slowing the progress of the vehicle for the last half of the race. TerraMax completed the 132-mile race with an official time of 12 hours, 51 minutes and over 28 hours of continuous operation.

V. Conclusions

The technology implemented onto the TerraMax vehicle demonstrated to be mature enough to let the vehicle reach the finish line of the 2005 DARPA Grand Challenge. It was an important milestone for robotics. The next challenge would be to let the vehicle perceive moving obstacles and possibly cooperate with other vehicles.