TerraMax: Team Oshkosh Urban Robot

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Abstract. Team Oshkosh, comprised of Oshkosh Corporation, Teledyne Scientific and Imaging Company, VisLab of the University of Parma, Ibeo Automotive Sensor GmbH, and Auburn University, participated in the DARPA Urban Challenge and was one of the eleven teams selected to compete in the final event. Through development, testing, and participation in the official events, we have experimented and demonstrated autonomous truck operations in (controlled) urban streets of California, Wisconsin, and Michigan under various climate and traffic conditions. In these experiments TerraMax™, a modified Medium Tactical Vehicle Replacement (MTVR) truck by Oshkosh Corporation, negotiated urban roads, intersections, and parking lots, and interacted with manned and unmanned traffic while observing traffic rules. We have accumulated valuable experience and lessons on autonomous truck operations in urban environments, particularly in the aspects of vehicle control, perception, mission planning, and autonomous behaviors which will have an impact on the further development of large-footprint autonomous ground vehicles for the military.

In this article, we describe the vehicle, the overall system architecture, the sensors and sensor processing, the mission planning system, and the autonomous behavioral controls implemented on TerraMax™. We discuss the performance of some notable autonomous behaviors of TerraMax and our experience in implementing these behaviors, and present results of the Urban Challenge National Qualification Event (NQE) tests and the Urban Challenge Final Event (UCFE). We conclude with a discussion of lessons learned from all of the above experience in working with a large robotic truck.

1 Introduction

Team Oshkosh entered the DARPA Urban Challenge with a large footprint robotic vehicle, TerraMax™, a modified Medium Tactical Vehicle Replacement (MTVR) truck. By leveraging our past experience and success in previous DARPA Challenges, the combined multi-faceted expertise of the team members, and the support of a DARPA Track A program award, we demonstrated various autonomous vehicle behaviors in urban environments with excellent performance, passed through many official tests at the National Qualification Event (NQE), and qualified for the Urban Challenge Final Event (UCFE). TerraMax completed the

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first four sub-missions in Mission 1 of the UCFE before being stopped after a failure in the parking lot due to a software bug. We brought TerraMax to UCFE test site in Victorville in December 2007 where TerraMax completed successfully three missions totaling over 78 miles in 7 hours and 41 minutes.

Team Oshkosh is comprised of Oshkosh Corporation, Teledyne Scientific and Imaging Company, VisLab of the University of Parma, Ibeo Automotive Sensor GmbH, and Auburn University. Oshkosh provided the vehicle, program management, and overall design direction for the hardware, software and control systems. Oshkosh integrated all the electrical and mechanical components, and developed the low and mid-level vehicle control algorithms and software. Teledyne Scientific and Imaging Company developed the system architecture, mission and trajectory planning, and autonomous behavior generation and supervision. University of Parma's VisLab developed various vision capabilities. Ibeo Automotive Sensor GmbH provided software integration of the LIDAR system. Auburn University provided evaluation of the GPS/IMU package.

Although there are substantial hurdles that must be overcome in working with large vehicles such as TerraMax™, we feel that large autonomous vehicles are critical for enabling autonomy in military logistics operations. Team Oshkosh utilized a vehicle based on the U.S. Marine Corps MTVR which provides the majority of the logistics support for the Marine Corps. The intention is to optimize the autonomous system design such that the autonomy capability can be supplied in kit form. All design and program decisions were made considering not only the Urban Challenge requirements, but eventual fielding objectives as well.

Our vehicle was modified to optimize the control-by-wire systems in providing a superior low-level control performance based on lessons learned from the 2005 DARPA Grand Challenge (Braid, Broggi, & Schmiedel, 2006, Sundareswaran, Johnson, & Braid, 2006). Supported by a suite of carefully selected and military practical sensors and perception processing algorithms, our hierarchical state-based behavior engine provided a simple yet effective approach in generating the autonomous behaviors for urban operations. Through the development, testing and participation in official events, we have experimented and demonstrated autonomous truck operations in (controlled) urban streets of California, Wisconsin, and Michigan under various climate conditions. In these experiments, TerraMax negotiated urban roads, intersections, and parking lots, and interacted with manned and unmanned traffic while observing traffic rules.

In this article, we present our experience and lessons learned from autonomous truck operations in urban environments. In Section 2 we summarize the vehicle and hardware implementation. In Section 3 we present the overall system architecture and its modules. In Section 4 we describe TerraMax's sensor and perception processing. In Section 5 we present TerraMax's autonomous behavior generation and supervision approach. In Section 6 we discuss TerraMax's field performance and experience in the NQE and the UCFE. We comment on lessons learned in Section 7.

2 TerraMax: The Vehicle and Hardware Systems

2.1 Vehicle Overview

The TerraMax™ vehicle (see Figure 1) is a modified version of a standard Oshkosh Medium Tactical Vehicle Replacement (MTVR) Navy Tractor[1], which comes with a rear steering system as standard equipment. The MTVR platform was designed for and combat-tested by the U.S. Marine Corps. We converted the vehicle to a 4X4 version by removing the third axle and by shortening the frame rail and rear cargo bed. The TAK-4™ independent suspension allowed rear axle steering angles to be further enhanced to deliver curb to curb turning diameters of 42 feet, equivalent to the turning diameter of a sport utility vehicle. In addition to the enhancement of turning performance, Oshkosh developed and installed low-level controllers and actuators for "by-wire" braking, steering, and powertrain control. Commercial-off-the-shelf (COTS) computer hardware was selected and installed for the vision system and autonomous vehicle behavior functions.

2.2 Computing Hardware

We opted for ruggedized COTS computing platforms to address the computing needs of TerraMax. Two A-Plus Mobile A20-MC computers with Intel Core Duo processors running Windows XP Pro were used for autonomous vehicle behavior

Fig. 1. TerraMax: the vehicle.

[1] Oshkosh MTVR. http://www.oshkoshdefense.com/pdf/Oshkosh_MTVR_brochure_07.pdf.

generation and control. The four Vision PCs use SmallPC Core Duo computers running Linux Fedora. One PC is dedicated to each vision camera system (i.e. trinocular, close range stereo, rearview, and lateral). Low-level Vehicle Controller and Body Controller modules are customized Oshkosh Command Zone® embedded controllers and use the 68332 and HC12X processors, respectively. To meet our objectives of eventual fielding, all the computing hardware was housed in the storage space beneath the passenger seat.

2.3 Sensor Hardware

2.3.1 LIDAR Hardware

TerraMax™ incorporated a LIDAR system from Ibeo Automobile Sensor, GmbH that provides a 360° field of view with safety overlaps (see Figure 2). Two ALASCA XT laserscanners are positioned on the front corners of the vehicle and one ALASCA XT laserscanner is positioned in the center of the rear. Each laserscanner scans a 220° horizontal field. Outputs of the front scanners are fused at the low level; the rear system remained a separate system. The LIDAR system native software was modified to operate with our system architecture messaging schema.

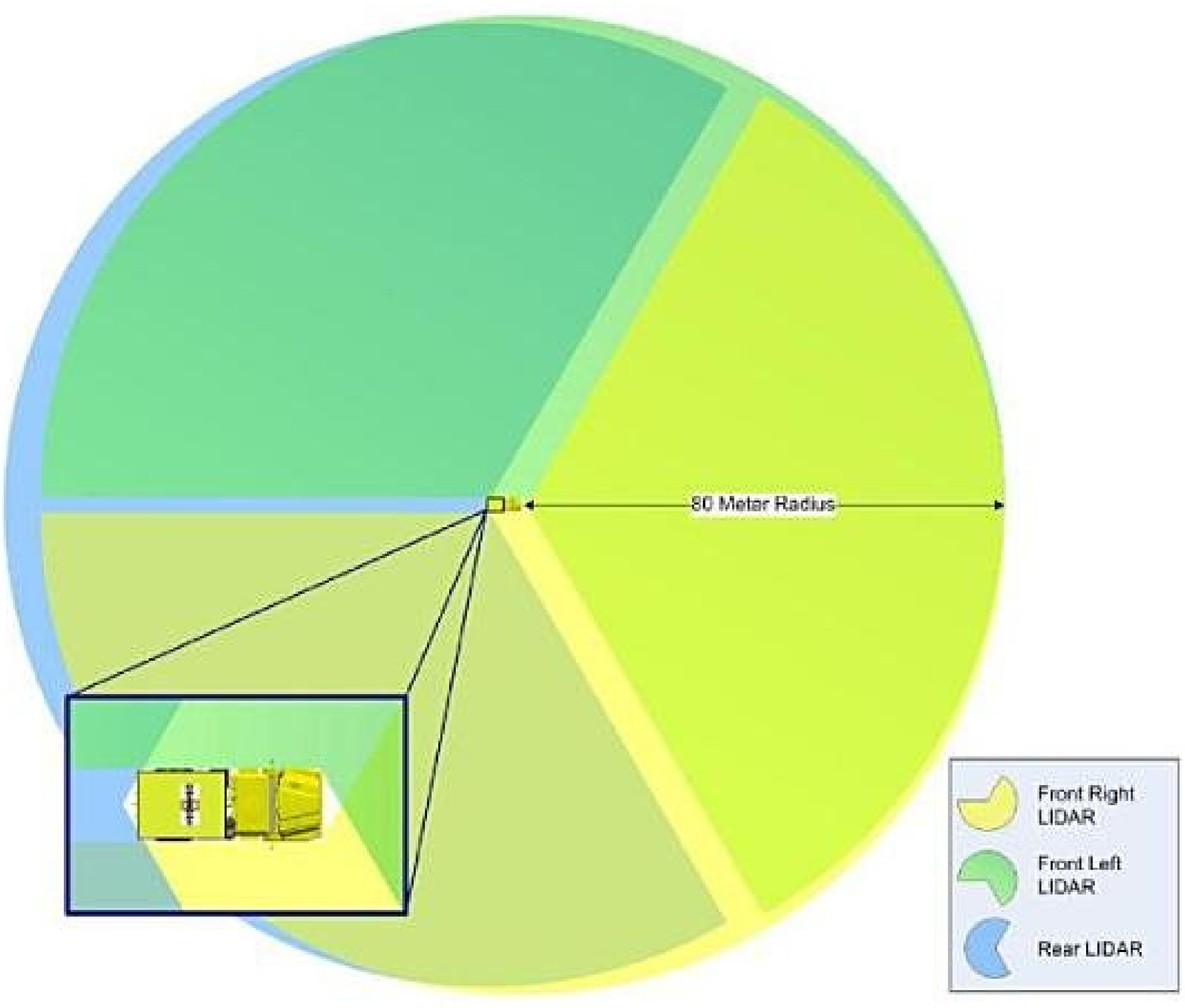

Fig. 2. LIDAR Coverage of TerraMax (truck facing right).

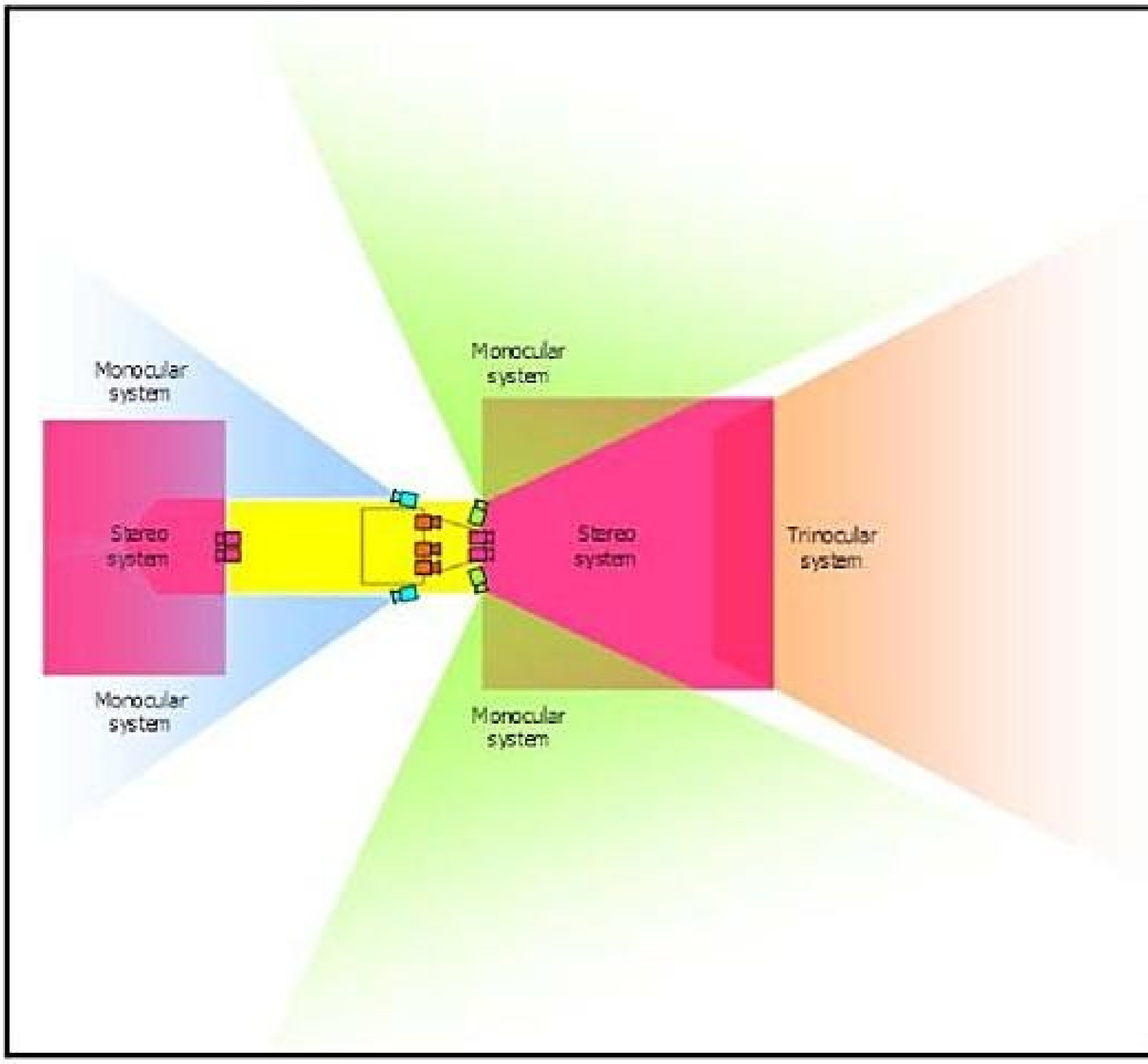

Fig. 3. Vision Coverage of TerraMax (truck facing right). Systems displayed: Trinocular (Orange) looking forward from 7 to 40m, Stereo Front and Stereo Back (Purple) monitoring a 10x10m area on the front of the truck and a 7x5m in the back, RearView (Blue) monitoring up to 50m behind the truck, and Lateral (Green) looking up to 130m.

2.3.2 Vision Hardware

There are four vision systems onboard: trinocular, stereo, rearview, and lateral. Figure 3 depicts the coverage of these vision systems. Table 1 summarizes the functions and components of these vision systems.

Each vision system is formed by a computer connected to a number of cameras and laserscanners, depending on the application. Each computer is connected through an 800Mbps, FireWire B link to a subset of the 11 cameras (9 PointGrey Flea 2, sensor: CCD, 1/3", Bayer pattern, 1024x768 (XGA) and 2 Allied Vision Technologies Pike 2. Sensor: 1", Bayer pattern, 1920x1080 pixels (HDTV)) mounted on the truck, depending on the system purpose.

2.3.3 GPS/INS

Using a Novatel GPS receiver with Omnistar HP corrections (which provides 10 cm accuracy in 95% of cases) as a truth measurement in extensive tests under