MOBILE MAPPING AND AUTONOMOUS VEHICLE NAVIGATION

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ABSTRACT:

Land-based Mobile Mapping Systems (MMS) are widely used in a variety of applications; these systems generally capture image data along the corridor the vehicle travels and the collected imagery gets processed offline. The output of a state-of-the-art MMS system includes a surface description, visualization data and an inventory of major objects positioned along the mapped corridor. This is exactly the information an autonomous vehicle needs for navigation, except that it is needed in real-time, and not only the static objects but the moving ones should be mapped too. The on-the-fly mapping of the vicinity of an autonomously navigated vehicle posed a formidable challenge for the participants of both DARPA Grand Challenges. This paper provides an analysis of the real-time mapping effort through the experiences of the Ohio State University Desert Buckeyes 2005 DARPA Grand Challenge autonomous off-road vehicle entry.

1. INTRODUCTION

DARPA Grand Challenge (DGC) events were organized to accelerate the development of autonomous vehicle technology (www.darpa.mil/grandchallenge/index.asp). In February 2003, the Defense Advanced Research Projects Agency (DARPA) announced the first Grand Challenge for unmanned and autonomous off-road ground vehicle development. Vehicles and development teams were to be entirely self funded. The vehicles should be able to navigate a course of several hundred miles of off-road terrain in the desert southwest region of the United States, following a path defined by a series of waypoints unknown to the teams until immediately before the race, and negotiating natural and man-made obstacles and terrain features without outside intervention. Once the race began, no contact or communication with the vehicle or its systems was allowed.

DARPA conducted the first Grand Challenge event in March 2004. The course, defined by over 2000 waypoints, would take the vehicle across approximately 175 miles, beginning at Barstow, California and ending at Primm, Nevada. A prize of $1 million (US) would be awarded to the fastest vehicle that completed the course in less than ten hours. 106 teams expressed interest at the initial orientation meeting, although the number of teams went down to 25 by the pre-race Qualification, Inspection and Demonstration (QID) event that each vehicle was required to pass. A dozen of finalists actually made it to the starting line on race day. Nobody won - in fact, the furthest distance traveled was 7.2 miles (Gibbs, 2004; Kumagai, 2004).

The second Grand Challenge event was held in October 2005. A 150-mile course, defined by almost 3000 waypoints beginning and ending at Primm, Nevada, traversed rocky trails, dry lake beds, and mountain passes. This time, 5 teams finished the course (4 within the allowed 10 hours), and the vehicle Stanley, developed by the Stanford Racing Team, took the $2 million (US) prize by completing the course in 6 hours and 53 minutes, with an average speed of 19.1 mph.

The Grand Challenge involved a number of severe challenges:

– Position and orientation localization, with GPS blackouts
– Sensing of vehicle environment and state in a complicated, off-road, semi-structured environment
– Long term autonomy and vehicle control over an unknown course and terrain
– Long term robustness of both hardware and software in a bumpy, dusty, hot, and occasionally wet environment
– Safe behavior and performance of the vehicle in the absence of an onboard human driver
– Significant testing and validation efforts

Figure 1. Intelligent Offroad Navigator (ION).

For the 2004 Grand Challenge our team, in partnership with Oshkosh Truck Corporation, developed Terramax'04 (Ozguner *et.al.*, 2004; Chen *et.al.*, 2004; Chen *et.al.*, 2005, Toth and Paska, 2005), an Oshkosh Truck Corporation Medium Tactical Vehicle Replacement (MTVR) 6-wheel drive heavy duty vehicle, as our autonomous off-road vehicle entry. Of 106 applicants, it traveled 6th furthest. In 2005, our "Desert Buckeyes" team outfitted ION – the Intelligent Off-road Navigator – (http://www.ece.osu.edu/ion/), based on the (much smaller) 6x6 Polaris Ranger utility vehicle shown in Figure 1. As in 2004, we provided drive-by-wire capability to control steering, throttle, brakes, and transmission. Various sensors, including GPS, inertial measurement units, multiple digital cameras and image processing systems, LiDARS, radars, and other sensors were integrated. Additional electrical power generation, equipment enclosures and cooling, and safety systems were also implemented. Of the 196 applicants, ION traveled 29 miles and 10th furthest.

The main objective of the mapping support for every team was to provide reliable geospatial data in the waypoint corridors for safe navigation and path planning during and prior to the race. In theory, an accurate terrain model combined with thematic information and a description of all the natural and man-made objects along the waypoint corridor would suffice for the requirements of the mapping. In reality, however, these geospatial data are not current and exist at neither the required spatial resolution nor accuracy for the DGC area. Furthermore, obstacles such as fallen trees, abandoned and moving vehicles, people, and animals can appear anywhere and anytime. Therefore, on-the-fly mapping became a necessity for any team to succeed. Mobile mapping systems (MMS) developed a decade ago and now widely used (Grejner-Brzezinska, 2001) form the main mapping technology for sensing the vehicle environment, but with the caveat that existing systems are not built to operate in real-time. A great deal of effort was devoted to the implementation of a real-time mapping system to support the needs of autonomous vehicle navigation for the OSU race team. This paper describes the OSU DGC autonomous vehicle navigation system, including a brief overview of the sensor configuration and major tasks of the supporting mapping components.

2. SENSOR CONFIGURATION OF THE REAL-TIME MOBILE MAPPING SYSTEM

The process of transforming a regular vehicle to an autonomous robot vehicle included the installation of a large number of sensors and actuators, and fairly massive hardware with control software to support the sensing, navigation, and vehicle driving tasks. For the two OSU DGC vehicles, an almost identical suite of imaging and navigation sensors, shown in Figure 2, were installed to support the real-time mapping operations.

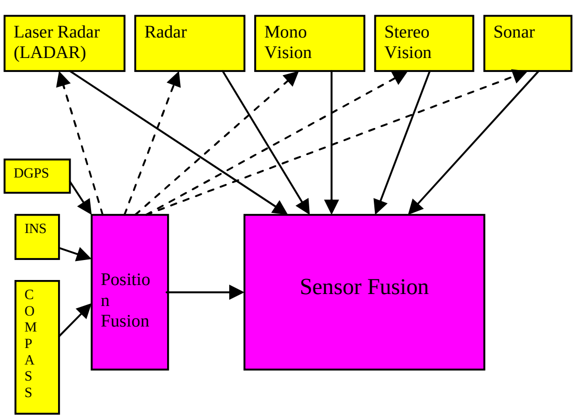

Figure 2. Navigation and imaging sensors.

The navigation sensors included two Novatel Propak-LB-L1/L2 GPS receivers with OMINISTAR, a Crossbow VG700AA INS system, a Honeywell HMR3000 electronic compass, and the standard vehicle sensors, such as odometer, brake, and steering sensors. Due to the fairly open race area, the GPS signal reception was generally excellent and except for a few underpasses or tunnels, the vehicle position as well as its attitude was known at decimeter-level at 10 Hz rate (Xiang and Ozguner, 2005).

The mapping sensors included four different imaging sensors. Sony DFW-V500 digital cameras were installed at maximum height on both sides of the front of the vehicle to form a stereo image acquisition configuration. The primary objective of using stereo cameras was obstacle detection, i.e., to identify objects in front of the vehicle. Four SICK LMS-221 laser rangefinders were installed at various heights and orientation from the front bumper to the top of the vehicle to provide horizontal and vertical obstacle detection around the front of the vehicle. In particular, the vertically mounted laser rangefinder was aimed at identifying "negative" objects, anything that is below the road/terrain surface such as ditches and down slopes. An Eaton-Vorad EVT-300 radar unit was mounted in the center of the vehicle's front bumper, providing a 12-degree scanning field with a range of approximately 140 meters and was used to detect and track targets moving relative to the vehicle. Finally, twelve Massa M5000/95 ultrasonic rangefinders were installed along the perimeter of the vehicle to support low speed, short distance maneuvers, and robotic motions. The sensing area of the various imaging sensors of ION, shown in Figure 3, clearly illustrates the redundancy not only between different sensors but in identical sensors covering the same area. A more detailed description of the sensors including the schematic overview of the sensors, actuators, and computing hardware on the TerraMax system can be found in (Yu et.al., 2004; Xiang and Ozguner, 2005). More info on the Desert Buckeyes ION can be found at http://www.eleceng.ohio-state.edu/ion .

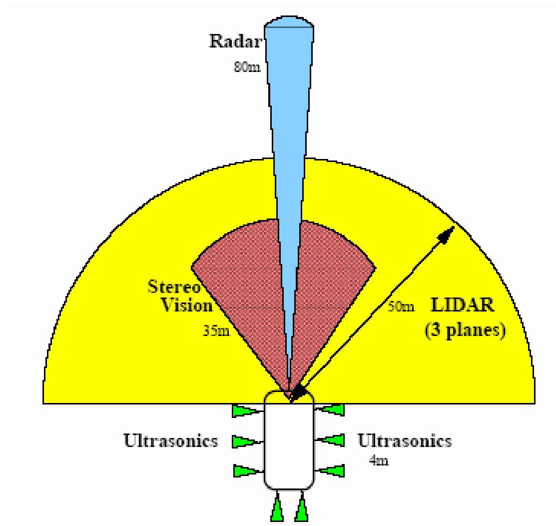

Figure 3. Surround sensing of the various imaging sensors (horizontal FOVs).

3. REAL-TIME MAPPING

The concept of sensing the environment of the vehicle is based on a moving sensor fusion map oriented to the North and based on local mapping coordinate system. At 20 cm spacing, the 800 by 800 grid covered a 160 m by 160 m surround area of the vehicle. The content of the grid cells were continuously updated as various sensory data became available. The data from the LiDAR sensors, profile data at 30 Hz, were ray-traced and thus provided either empty space or obstacle entries. The RADAR data did not observe the ground and mainly provided only obstacle information. The stereo image processing, shown in Figure 4, provided both ground and obstacle information.

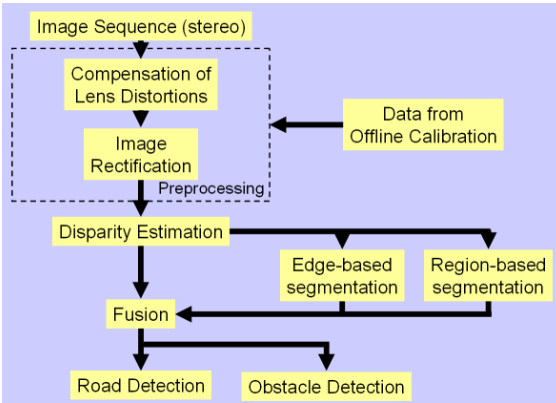

Figure 4. Stereo image processing to obtain ground surface and obstacle information.

The sensor fusion is a complex task, as all the sensory data have to be properly georeferenced and then blended into the sensor fusion map based on their figure of merit estimates. After sensor functionality and data integrity validation, the data from each sensor must be processed to remove any suspect or erroneous information before the actual sensor fusion could be performed. The cells had three confidence categories: occupied, empty and unknown. In addition, the height of the ground and detected obstacles was stored too. During the sensor fusion process, obstacles as well as ground are detected many times as the vehicle moves, and the update was primarily driven by the confidence values. Finally, a temporal erasing was applied to the entire map to reduce the impact of past measurements.

From the sensor fusion map, a smaller output map, 40 m by 80 m, is created for use by the vehicle control modules by evaluating the three confidence measures and the height information. This output map includes only classified status information for each cell, and was presented in a vehicle-centered, body-fixed coordinate system, where the location and orientation of the vehicle are fixed with respect to each map cell's coordinates. This was the most convenient representation for the path planning and high-level control functions. Figure 5 depicts the visualization of the vehicle-fixed moving map, showing the first Gate Obstacle from one of the DGC qualification runs on the California Speedway.

4. PATH PLANNING

The original DGC announcement was not specific about waypoint density and left room for free navigation on long segments of the race route. Therefore, mapping support was needed to facilitate global path planning (local path planning is based on the vehicle-fixed moving map as discussed in the previous section) and included two major components: (1) providing geospatial data for automatic path planning prior to, and mostly during, the race, and (2) tools for interactive path planning in two hours prior to the race. The automatic path planning was based on the A* algorithm (Skiena, 1990; Hwang, 2003; Dilip, 2004), which is a generic graph search algorithm, based on optimizing some cost function, such as distance traveled, slope grade, negative bias for roads, higher cost for vegetated areas, and so on.

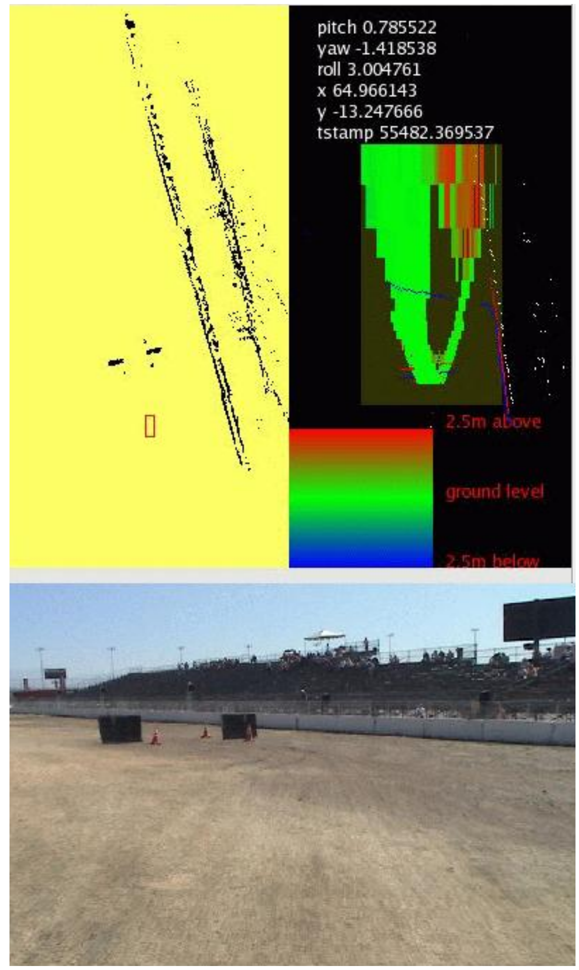

Figure 5. Sensor results from ION approaching the first Gate Obstacle from one of the DGC qualification runs in the California Speedway.

After reviewing the available data resources in terms of potential benefits for path planning, the decision was made to build a multi-layer data structure, incorporating DEM data, land cover metadata, road data and known/driven trajectory data, shown in Figure 6. To support fast data access to the geospatial database, an indexing system was introduced – the real-time operation during the race required very short response time from the path planning algorithm. The 1-byte index information was composed out of a 6-bit land cover field and two flags indicating the availability of road data and the existence of a driven trajectory, as shown in Figure 6 with the database layers.

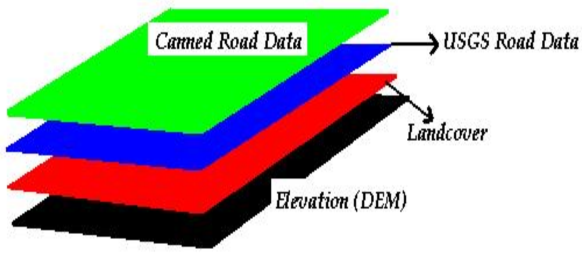

Figure 6. Database layers.

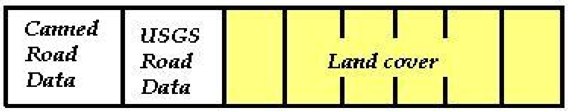

Figure 7. Database indexing – index byte definition.

In normal operation, the index plane was first searched based on the current path planning area, defined by the known vehicle location and destination coordinates. If driven trajectory data were available for the path planning area, then it was retrieved in two steps: first the GPS time tags from the driven trajectory layer were read, and then based on the time tags the actual data was retrieved from the survey file. If there was no driven trajectory data available for the path planning area, then the USGS road data flag was searched in the index plane. Similarly to the driven trajectory data, the road data, if found, was used for path planning. If neither driven trajectory nor road data existed, then the land cover and DEM, which were always available, were used for path planning. The database with supporting utilities was loaded onto the onboard path planning computer. The actual size of the database was approximately 27 Gbytes. Besides indexing, the 3° in longitude and 2.35° in latitude DGC area was segmented into 20 sub-regions, each covering 4,050 sq. km, to provide faster file access for the smaller areas, see Figure 8.

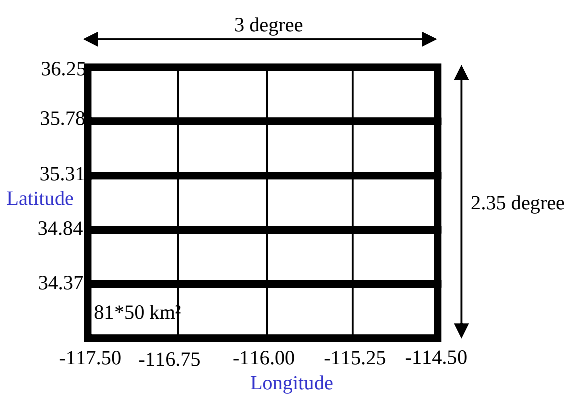

Figure 8. The segmentation of DGC area.

5. CONCLUSIONS

The organizers made several adjustments in the time leading to the races. At the beginning the objective was to provide loose control along the route and let the vehicles decide the actual trajectory. Later by reducing the possible areas, decreasing the route length, and increasing the number of waypoints, the emphasis shifted from the global path planning to a local trajectory optimization, which in turn, mainly required an accurate description of the vicinity of the vehicle. By real-time mapping of the area around the vehicle, surface data and object information reconstructed from the various sensory data provided the main support for both tasks: local path planning and obstacle avoidance.

The three most important lessons learnt from our own experiences with respect to mapping are: (1) the better use of sensors, (2) improved fusion at the sensor level, and (3) increasing redundancy of the sensors. In addition, despite the importance of the real-time mobile mapping to support autonomous vehicle navigation, the need for quality static data remains. In fact, as sensor systems improve, the demand for better geospatial data will increase.

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