MOVING TOWARD REAL-TIME MOBILE MAPPING: AUTONOMOUS VEHICLE NAVIGATION

C. K. Toth[a], U. Ozguner[b] and D. Brzezinska[a,c]

[a] Center for Mapping, 1216 Kinnear Road, Columbus, OH 43212-1154, USA – toth@cfm.ohio-state.edu
[b] Department of Electrical and Computer Engineering
[c] Satellite Positioning and Inertial Navigation (SPIN) Laboratory
The Ohio State University, Columbus, USA

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ABSTRACT:

The recently growing interest the autonomous vehicle navigation has directed a lot of attention to technologies that are capable of mapping the environment around a moving vehicle in real-time. The two past Grand Challenges and the upcoming Urban Challenge, organized by the US Defense Advanced Research Projects Agency (DARPA), created not only a lot of interest in robotics, but resulted in major developments in the past few years, including the capability for effective real-time mapping of the vicinity of the robots. Autonomous vehicle navigation is primarily based on waypoint navigation, but to stay on track and avoid obstacles the vehicles must have sophisticated sensor systems. In particular, this is the case in urban environments, where the robots deal with a number of moving vehicles. From a conceptual perspective, the required sensing capability of an autonomous vehicle is comparable to that of a mobile mapping system, and the major difference is the real-time processing of the raw sensory data into high-level object space information. This paper will review the recent developments in real-time mobile mapping, and will provide an analysis of the real-time mapping effort through the experiences of the OSU DARPA Ground Challenge group that raced as the TerraMax team in 2004 and Buckeye Deserts in 2005.

1. INTRODUCTION

Mobile mapping systems, based on the integration of digital imaging with direct georeferencing, have seen remarkable developments over the last two decades (Schwartz and El-Sheimy, 2007). Although the concept has not changed much over the years, the lack of affordable digital technologies initially prevented the wider use of mobile mapping, and it has been only the last 5-10 years when mobile mapping has seen a proliferation as a mainstream geospatial data acquisition methodology.

Digital imaging sensor technology has seen phenomenal developments in the last decade. The CCD sensor manufacturing improved substantially, and allowed for the first time to build fully digital large-format aerial cameras that not only match, but significantly outperform their analog film-based counterparts. Furthermore, new active imaging sensors, such as LiDAR (Light Detection And Ranging), and IfSAR (Interferometric Synthetic Aperture Radar), were introduced and soon became the primary source of surface data. In addition, the performance of multi- and hyper-spectral imagers improved significantly, and their use is rapidly growing.

Direct georeferencing, the technology to provide position and attitude information for the mobile data acquisition platform, has seen gradual improvements in the last decade. The core GPS and IMU-based navigation solution changed only modestly, and the primary navigation solution is still based on a loosely- or a tightly-coupled GPS/IMU (Inertial Measurement Unit) integration model, using the Extended Kalman Filter (EKF) technique. Notable developments are the increasing use of GPS-network based solutions, and the growing interest toward using medium- and lower-grade IMUs, such as MEMS systems.

The processing aspects of the data acquired in mobile mapping have been of great interest since the beginning. The need to partially automate the feature extraction processes was already critical for the first land-based mobile mapping systems, as savings in the data acquisition was about to offset the increased need for processing the imagery in the post-mission mode. As image resolution increased, and the number of imaging sensors used in a single mobile mapping system multiplied, combined with the higher image capture rates, the importance of automated or semi-automated processing became even more crucial. Intense research in computer vision and digital photogrammetry has produced significant advancements, and the availability of effective algorithms is now a main factor of the growing use of mobile mapping systems.

In summary, the developments mentioned above indicate that the currency of mobile mapping data was not too important initially; the processing time was the least discussed aspect of mobile mapping systems in the past. With the recent changes in applications' requirements, the time scale is becoming crucial, and therefore, the real-time capability will likely be an overarching theme of future systems. The research aimed at providing accurate platform georeferencing in real-time has already been of interest in the navigation community. Once sensor orientation data become available in real-time, it is up to the algorithmic performance of the imaging processes and the availability of sufficient computer power to create accurate geospatial data in real-time or in near real-time. Autonomous navigation is an emerging discipline where the real-time sensing/mapping of the vehicle surrounding is absolutely essential. This paper reviews recent developments in this field through the experiences of the Ohio State University autonomous navigation team.

2. AUTONOMOUS VEHICLE NAVIGATION

Autonomous vehicle navigation was a less visible narrow research field for a long time. A major change occurred in February 2003, when DARPA announced the first Grand Challenge for unmanned and autonomous off-road ground vehicle development, with the primary objective of accelerating the development of autonomous vehicle technology. By opening up this, up to that point, exclusive discipline to the more general science and engineering community, the autonomous vehicle technology research field has seen a staggering increase in developments, measured in substantial technological advancements and by the formation of a stronger research community, all along with the broader public acceptance of the new technology. The first two large-scale autonomous vehicle races, DARPA Grand Challenge (DGC), took place in the Mojave Desert on March 13, 2004, and October 8, 2005, respectively. At the first race none of the contenders completed even 10% of the about 143 miles between Barstow, California, and Primm, Nevada. The second race, however, became a big success, as five vehicles completed the 132 mile course in the Primm, Nevada area. More details about the DARPA Grand Challenge (DGC) can be found in (Gibbs, 2004, and Kumagai, 2004), and at http://www.grandchallenge.org and http://www.darpa.mil/grandchallenge).

The date for the next race, DARPA Urban Challenge (DUC), is set for November 3, 2007, and the challenges will be much more complex, as compared to the earlier competitions. The environment for the upcoming 2007 DUC will be significantly different from the past Grand Challenge races, which represented GPS waypoint-defined off-road vehicle navigation in open areas, as, besides the GPS waypoints, route network description will be provided, including the stop sign locations, lane width, checkpoints, and parking locations. More importantly, this type of environment will require much more sophisticated sensing capabilities to cope with the object-rich urban setting, where moving objects will also be present. In addition, achieving the required navigation performance will be more difficult in the GPS-denied/impeded urban landscape.

The autonomous vehicle navigation involves a number of severe challenges:
- Position and orientation localization, with GPS blackouts.
- Sensing of the vehicle environment and state in a complicated, off-road/urban, semi/well-structured environment.
- Long term autonomy and vehicle control over an unknown course, and terrain or road network.
- 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.
- Tracking other vehicles, observing traffic signs/rules, etc.
- Significant testing and validation efforts.

The Ohio State University autonomous vehicle navigation team participated in both past races and registered for the upcoming UGC 2007. The OSU team, supported by Oshkosh Truck Corporation, raced as TerraMax in 2004 (Ozguner et.al., 2004; Chen et.al., 2004; Chen and Ozguner, 2005; Toth and Paska, 2005), and then had its own vehicle ION –

the Intelligent Off-road Navigator (http://www.ece.osu.edu/ion/) – in 2005, racing under the name of Desert Buckeyes (Toth et.al., 2006; Toth and Paska, 2006). Figure 1 shows the 2005 race vehicle.

Figure 1. Intelligent Off-road Navigator (ION 2005).

For the 2007 UGC race, DARPA introduced stricter requirements for the vehicles, limiting the race to commercially proven stock-vehicles. Figure 2 shows the new OSU Toyota Highlander Hybrid race vehicle for 2007, indicating initial sensor configurations.
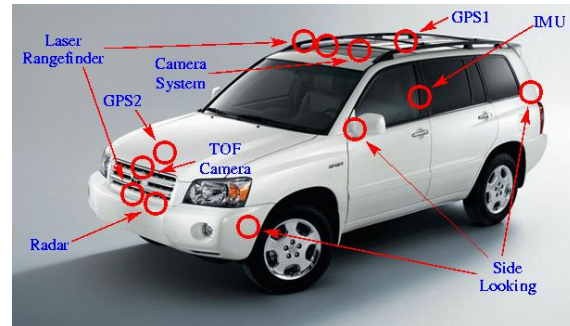

Figure 2. The OSU ACT – The OSU Autonomous City Transport.

3. REAL-TIME MOBILE MAPPING

The motivation for real-time, or near real-time, mobile mapping comes from several existing and emerging applications, including the following three key areas, where it becomes critical:

Defense
- There is an increased sensitivity to personnel's life, and therefore, the use of autonomously driven vehicles is highly sought; about 30% of the cargo transportation of US combat forces is expected to be autonomously driven within a decade (Section 220, 2001).
- Personal navigation of both soldiers and "robots" as soldiers in a battlefield situation requires instantaneous reconstruction of the surrounding object space.
- War theater simulations, both training and in situ, need up-to-date spatial data.

Natural disasters
- Improving prediction models needs up-to-date spatial data, preferably in real-time (need for sustained data acquisition).
- Rapid "mapping" of disaster affected areas is needed to support rescue operations.

Terrorist threat to civilians
- Increased demand for security requires better geolocation and tracking capabilities.
- Growing need for "indoor/outdoor" map data, including both real-time mapping and timely updates.

Reviewing the time requirements of these applications indicates that the autonomous vehicle navigation presents clearly the most demanding case, although rapid mapping is a close second. In fact, the first demonstration of an experimental airborne mobile mapping system, dedicated to emergency response included a real-time data downlink to support near real-time spatial data processing (Schuckman and Hoffman, 2004).

3.1 Mapping Objectives

The mapping support for autonomous vehicle navigation includes two essential tasks: 1) to provide terrain, natural- and man-made feature information for global path planning, as well as for vehicle local navigation (staying on course in off-road situations), and 2) to sense/map the vehicle vicinity, and thus provide for local vehicle control, such as staying on the road (within a lane), avoiding obstacles, etc. Obviously, the second objective is equivalent to the general goal of land-based mobile mapping, except for the real-time operation.

In the first two DGC races, the main objective of the mapping support for every team was to provide reliable geospatial data in the waypoint-defined corridors for the path planning during and prior to the race. In theory, an accurate terrain model combined with thematic information and the description of all natural and man-made objects would be sufficient for the mapping requirements. In reality, however, these 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, which all necessitate real-time mapping capabilities. More details on the terrain information-based mapping support for the global path planning can be found in (Toth et. al., 2006; Toth and Paska, 2006).

In contrast, the UGC requires practically no terrain data information, as the vehicles are confined to a road network, which is well-defined by the race organizers. The adequate sensing of the vehicle vicinity, however, is crucial since the vehicles should share the road with other vehicles; thus, detecting and monitoring traffic becomes probably the most important challenge for all of the participants. Although it is difficult to assess whether the sensing of the environment of the vehicle or the processing of that object space information to drive the vehicle poses the more complex task, there is no doubt that the availability of quality geospatial data, including correctly reconstructed object space information with accurate georeferencing, is an absolute necessity. In the following, a basic review is provided on the local mapping component of autonomous vehicle navigation, based on the OSU DGC experiences.

3.2 Sensors and Methods

The imaging sensor suites installed in the vehicles participating in the first DGC in 2004 were similar to the conventional sensor configuration of land-based mobile mapping systems. Digital cameras provided the primary source of geospatial information to map the surroundings of the vehicle. Figure 3 shows the imaging sensors installed in the front of the OSU 2004 TerraMax vehicle. The two stereo cameras were supposed to map the near- and mid-distance area in front of the vehicle to identify objects on the terrain and/or road surface to support obstacle avoidance. The mono camera, installed below the level of the stereo cameras, was primarily used to track the drivable area, such as the edge lines of paved roads or the brim of unpaved/dirt roads. The laser profiles were intended to complement the stereo vision system to provide direct measurement to the obstacle avoidance process. The RADAR aimed at detecting vehicles at mid- and far-distance.
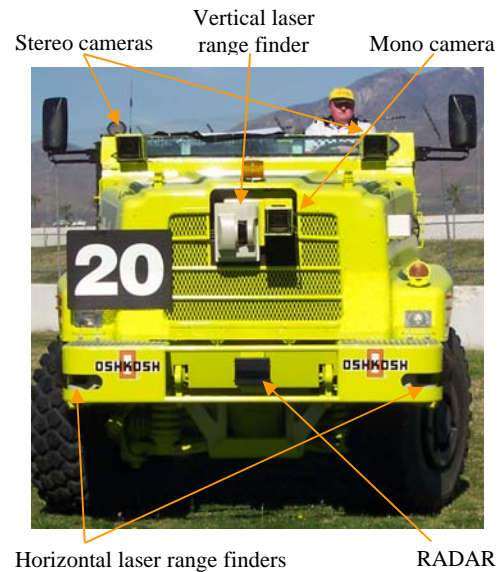

Figure 3. Imaging sensors of the OSU 2004 TerraMax vehicle.

The 2004 DGC race experiences clearly proved that the stereo vision systems alone were not able to provide sufficient and reliable data for safe vehicle navigation in a rugged off-road environment. The large-scale of changes in brightness from directly facing sunshine to dark shadows imposed quite a challenge for the cameras as well as for the subsequent vision processes. In addition, the real-time requirements severely limited the algorithmic complexity, as the onboard computer processing power could not be indefinitely increased. Furthermore, dust could quickly cover the lenses. In contrast, the laser sensors performed well; they were less sensitive to the environmental conditions and, due to the direct data observation, required rather minimal processing capacity.

The 18 months between the two DGC races produced significant developments in autonomous vehicle navigation, and in 2005 five teams completed the 132 mi race course where there was a close competition of three vehicles for the first place. With respect to the imaging sensors, the focus clearly shifted toward the laser rangefinders. The 2005

winner, Stanley from Stanford, had five SICK laser rangefinders and only one digital camera (plus RADAR) installed on a roof rack of the vehicle. The laser data was exclusively used for sensing the vicinity of the vehicle up to a speed of 40 km/h; and the vision system, based on the single camera, was used only at higher speeds to extend the range of the laser sensors (Montemerlo et. al., 2006). This clearly illustrates the differences between the objectives for autonomous vehicle navigation and mobile mapping, namely, the accurate reconstruction of the object space is more important than the visual value of the images.

The design of the OSU 2005 ION vehicle shows a similar pattern, the sensor system includes four SICK laser rangefinders, a short baseline stereo vision system, RADAR, and ultrasonic sensors, all supporting the real-time mapping of the vicinity of the vehicle. The real-time navigation of ION is provided by fusing data from a GPS receiver with OMNISTAR real-time corrections, a simple MEMS IMU,

and a magnetometer. Figure 4 shows the overview of the real-time mapping system, including all the sensors (magenta), coordinate system transformations (yellow), image/object space data processing modules (green), and occupancy maps (blue). The sensors register their measurements in a vehicle-fixed coordinate system, then using the real-time navigation solution, that data are converted to a local mapping frame. The extracted object space information is stored in a moving occupancy map, which is an essential data structure of the real-time mapping system, as it reconstructs the object space from the various sensory data. The process of combining the multi-sensory and redundant data is rather complex and not discussed here. The actual vehicle drive control is accomplished by using the central part of the occupancy map, which is further analyzed and projected back to the vehicle coordinate system to control the vehicle operation.
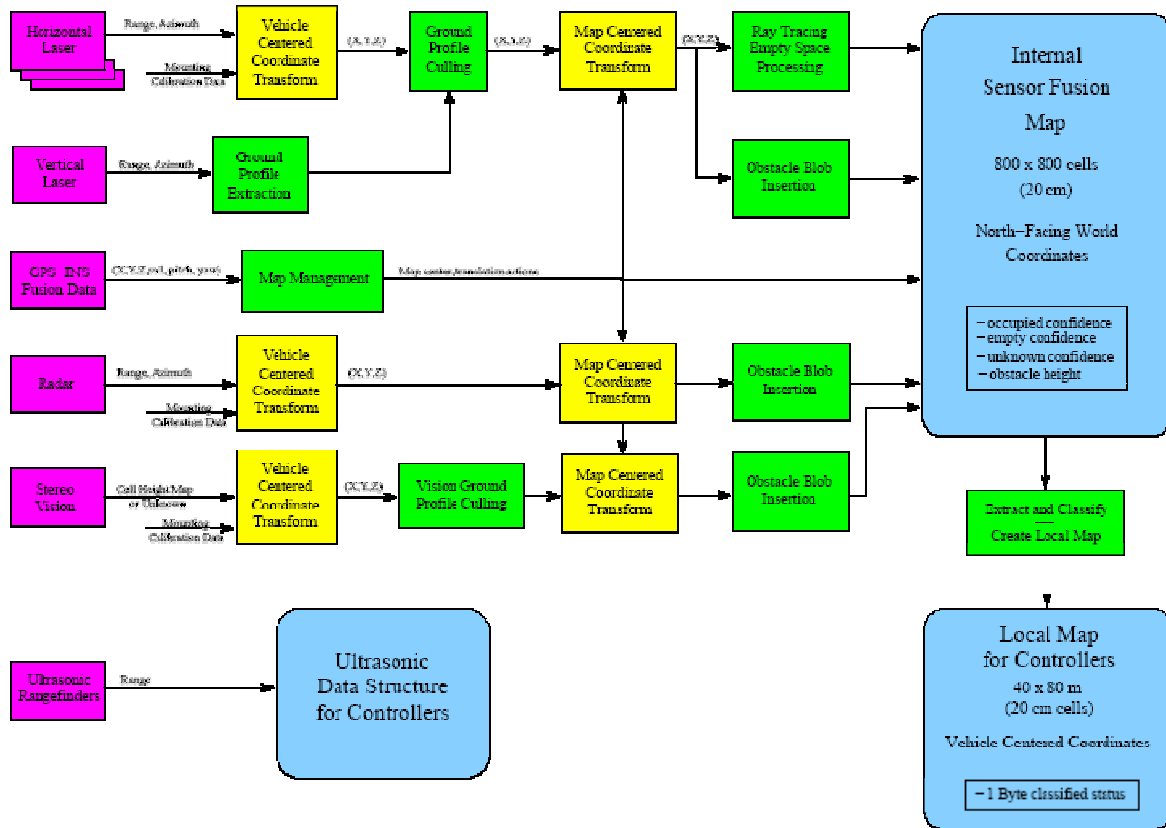

Figure 4. OSU ION 2005 real-time mapping system.

In summary, in the mapping processes, the shape seems to be more important than the visual information. The laser data providing the direct range measurements have definite advantage over the optical imagery, which is partially due to the higher computational complexity of the stereo and/or mono vision systems. The object space reconstruction in autonomous vehicle navigation resembles the airborne mapping case, where the general extraction process first starts with surface extraction, which is followed by object recognition, etc.

3.3 Expected Developments

Autonomous vehicle navigation is in an era of unprecedented strong developments, and there are several areas that will definitely impact the evolution of mobile mapping technology and its future practice.

The rapid development of mobile sensors driven by the needs of autonomous vehicle navigation will benefit mobile mapping at large. In particular, the increased production

volume of sensors will make sensors more affordable; moreover, new type of sensory data will be available to the mapping community. The sensors currently experimented in autonomous vehicle navigation will likely be used in regular vehicles for assisted driving. Optical imagery has been already used in the high-end stock-production vehicles; for example, cameras are used for vehicle push-back monitoring or rear mirror display. An example of a more sophisticated optical image-based system is the Mobileye AWS™-4000 driver assistance system for accident prevention and mitigation, including a smart camera located on the front windshield inside the vehicle, which utilizes advanced vision technologies to detect and measure distances to lanes and vehicles, providing the driver with timely audio-visual alerts (www.mobileye.com).
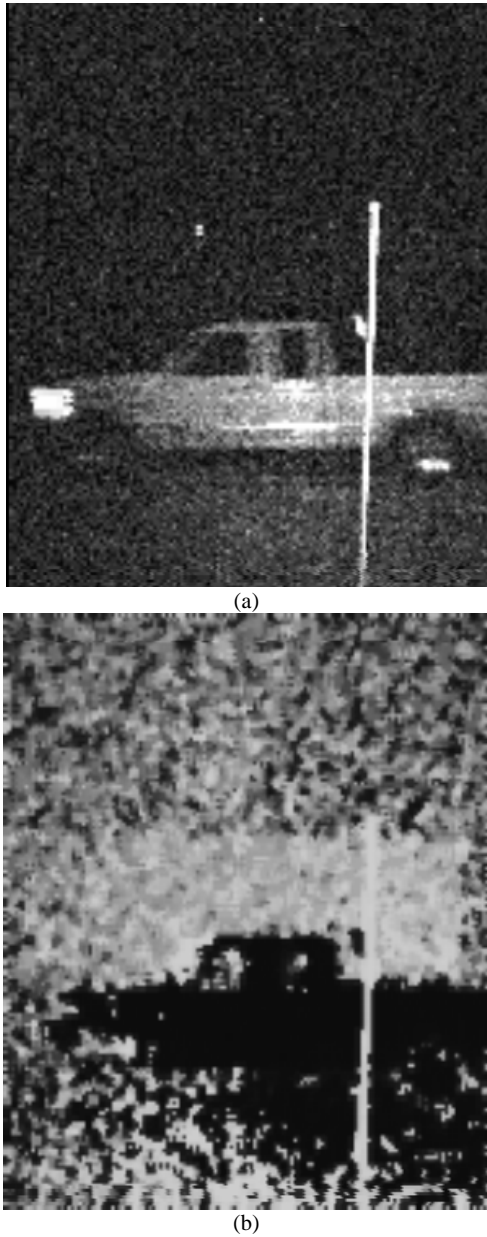

(a)

(b)

Figure 5. SR3000 imagery: (a) intensity data and (b) range data.

Laser rangefinders have already been used in mobile mapping practice, but most of the systems are either terrestrial laserscanners or custom-made implementations. Now a new sensor technology, Flash LiDAR (also called a 3D camera), seems to challenge the dominance of pulsed and continuous-wave laser systems. The concept is simple, similar to flash photography, a laser is flashed at the object space and an array sensor forms an image from the reflected laser light. Figure 5 shows the range (a) and intensity (b) images of a passing vehicle captured by an SR3000 camera, installed in the GPSVan™. This 3D camera has a moderate spatial resolution of 176 x 144, and the range data are visibly noisy; more details on the camera can be found at (http://www.swissranger.ch/). Clearly, the performance must improve before this sensor can be deployed, yet the advantage of the instantaneous 3D capture is that there are no motion artifacts inherent to scanning sensors in dynamic environments.

Due to increased interest in the DARPA Grand Challenges, several customized sensors were introduced, aimed primarily at the race participants. A noteworthy laser system was developed in response to the typical laser rangefinder configuration used at the 2004 DGC. The ALASCA XT laser rangefinder from IBEO, shown in Figure 6, offers the functionality of four SICK laser rangefinders. The laser ranging accuracy is about 4 cm, and, depending on the surface condition, the ranging distance can reach 200 m. The system can record multiple returns, important to vegetation detection, and the scanning rate and resolution are user configurable; for more details, see (www.ibeo-as.com). A dataset captured at OSU Campus is shown in Figure 7. Note that the simple laser point density-based clustering efficiently captures the vehicles.
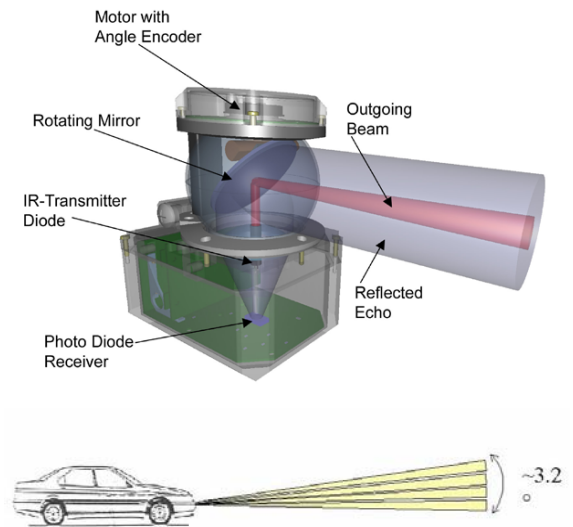

Figure 6. ALASCA XT laser rangefinder from IBEO.

As far as the future mobile mapping practice is concerned, there are important things to consider for both land-based and airborne platforms. Due to the popularization of mapping by the Internet giants, such as Google, Microsoft, and Yahoo, the demand for both terrestrial and airborne imagery is expected to grow enormously. On the supply side, the trend

is clear, i.e., the number of imaging sensors installed in vehicles will increase, mostly driven by the need for assisted driving (developed societies face the problem of aging, and therefore, both autonomous and assisted driving are becoming increasingly important). Modern vehicles are quickly being transformed to sophisticated multi-sensory systems with an ever-increasing complexity of on-board processing. Transparent to drivers, the vehicles will act as mobile mapping systems by collecting large volumes of geospatial data and even performing basic processing. Assuming a wireless connection between vehicles on the road network and road GIS/CAD systems, data can be exchanged and used for the benefit of both the driver and the transportation monitoring and management agencies.
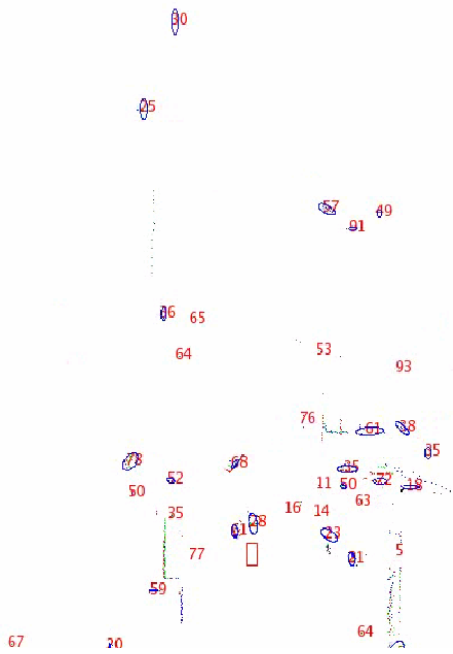

Figure 7. Intersection traffic captured by ALASCA XT.

4. CONCLUSIONS

The rapid sensor developments in autonomous vehicle navigation will likely continue as the need for both driverless and assisted driving technologies is expected to further grow in both military and civilian applications in the future. This momentum is already strongly impacting the developments of land-based mobile mapping systems, used primarily for topographic and inventory mapping. In addition, a substantial volume of mobile mapping data will be provided by regular stock-production vehicles, as their sensor configurations, including imaging systems, is anticipated to increase. Since all these developments are related to real-time technologies, the conclusion can be drawn that land-base mobile mapping is in the transition to become real-time. Demand from applications requiring fast response, such as emergency response, is expected to drive airborne mobile mapping toward real-time or near real-time operation in near future.

REFERENCES

Chen, Q., Ozguner, U., and Redmill, K., 2004. The Ohio State University at the 2004 DARPA Grand Challenge: Developing a Completely Autonomous Vehicle, IEEE Intelligent System, Vol. 19, No. 5, pp. 8-11.

Chen, C. and Ozguner, U., 2005. Real-time Navigation for Autonomous Vehicles: a Fuzzy Obstacle Avoidance and Goal Approach Algorithm, in Proc. of American Control Conference, 8-10 June, pp. 2153-2158.

Gibbs, W.W., 2004. A New Race of Robots, Scientific American, March 2004, pp. 58-67.

Kumagai, J., 2004. Sand Trap, IEEE Spectrum, June 2004, pp. 44-50.

Montemerlo, M., Thrun, S., Dahlkamp, H., Stavens, D. and Strohband, S., 2006. Winning the DARPA Grand Challenge with an AI Robot, Proceedings of The Twenty-First National Conference on Artificial Intelligence and the Eighteenth Innovative Applications of Artificial Intelligence Conference, July 16-20, 2006, Boston, MA. http://ai.stanford.edu/~dstavens/aaai06/montemerlo_etal_aaai06.pdf

Ozguner, U., Redmill, K., and Broggi, B., 2004. Team TerraMax and the DARPA Grand Challenge: A General Overview, 2004 IEEE Intelligent Vehicles Symposium, University of Parma, June.

Section 220 of the Floyd D. Spence National Defense Authorization Act for Fiscal Year 2001.

Schwartz, K.P. and El-Sheimy, N., 2007. Digital Mobile Mapping Systems – State of the Art and Future Trends, in Advances in Mobile Mapping Technologies, Eds. V. Tao and J. Li, ISPSR Book Series, pp. 3-18.

Schuckman, K., and Hoffman, G.R., (2004): ARIES: Technology Fusion for Emergency Response, *Photogrammetric Engineering & Remote Sensing*, Vol. 71, Num. 4, pp. 357-360.

Toth, C. and Paska, E., 2005. Mapping Support for the TerraMax Oshkosh/OSU DARPA Grand Challenge Team, Proc. ASPRS 2005 Annual Conference, Baltimore, MD, March 7-11, CD-ROM.

Toth, C.K., Paska, E., Chen, Q., Zhu, Z., Redmill, K. and Ozguner, U., 2006. Mapping Support for the OSU DARPA Grand Challenge Vehicle, Intelligent Transportation Systems, 2006. Proceedings. IEEE , Vol., .pp. 1580-1585, Sept. 17-20, 2006.

Toth, C. K. and Paska, E., 2006. Mobile Mapping and Autonomous Vehicle Navigation, ISPRS Commission I Symposium, Paris, France, July 4-6.