# R&D OF MOBILE LIDAR MAPPING AND FUTURE TRENDS

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## ABSTRACT

Mobile terrestrial mapping systems have seen remarkable developments recently. Fueled by an unprecedentedly strong demand for high-resolution and accurate 3D geospatial data, these systems serve the probably fastest growing market segment: city modeling. In particular, the recent introduction of powerful mobile laserscanning systems is of main interest, as the direct acquisition of 3D data greatly simplifies downstream processing, where until now stereo-based extraction was the most widely used feature extraction tool, requiring significantly more complex processing compared to the straightforward processing of explicit LiDAR data. This paper reviews the recent developments in Mobile Mapping Technologies with a special focus on the mobile laserscanner sensor component.

## INTRODUCTION

Mobile Mapping Systems (MMS) were introduced in the early 90's, when, for the first time, the fledgling GPS system was able to provide absolute positioning of mobile sensor platforms (Novak, 1993). Besides satellite-based navigation, imaging technology formed the second fundamental component of MMS, although at the beginning it was mainly limited to video-logging. The first research systems were simultaneously developed at the Center for Mapping, The Ohio State University (Bossler and Toth, 1996), and the Department of Geomatics Engineering at The University of Calgary (El-Sheimy, 1996). As technology continued to advance, both the georeferencing and imaging components improved significantly and commercial systems were introduced and became operational in the industrialized parts of world by the late 90's (Grejner-Brzezinska, 2001).

During the last millennium, geospatial information science saw a major paradigm shift (Grejner-Brzezinska *et al*., 2004), triggered by the completion of the transition from analog to digital geospatial technologies. The debut of the first digital large-format aerial cameras in 2000 was the last needed development to achieve an entirely digital technology in airborne surveying (Petrie, 2003). The totally digital workflow, including sensors, georeferencing, data acquisition, and processing, allowed for fundamentally different approaches. In addition, new sensors, such as laserscanners and interferometric RADAR (IfSAR) supported by enabling georeferencing technologies were introduced and started producing highly accurate data in large volume that was unprecedented. In a short time, MMS became pervasive and ubiquitous. In fact, as the complexity of MMS systems increased, the name was slightly changed and now Mobile Mapping Technology (MMT) is widely used to reflect the stronger dependency on technology and the more sophisticated design, data processing and information extraction processes (Schwartz and El-Sheimy, 2007).

More recent developments include the introduction of Internet mapping, which has significantly increased the need for geospatial data worldwide. Initially, visualization, based on satellite and airborne imagery, was the main objective, but as the market started to develop, the need for 3D visualization started to grow, in particular, for major metropolitan areas. Demand for current airborne and terrestrial data has skyrocketed in a short time. In response, fleets of terrestrial mobile mapping vans with panoramic imaging capabilities were deployed in a short time. Similarly, airborne capacity to collect oblique and traditional vertical imagery has dramatically increased. The most notable data provider of oblique imagery, Pictometry, Inc. operates a fleet of 70+ aircraft just in North America. The continuing trend is to move to full 3D city modeling, which means that besides imagery, terrain surface models and object descriptions are needed. While airborne LiDAR has been generally available, to accommodate this data need on the ground, mobile laser scanning is the feasible technology, which has seen phenomenal development in the last few years.

The need for emergency mapping, such as to provide rapid mapping capabilities for man-induced and natural disasters, requires a fast response time, and thus, there is a growing need to improve real-time (or near real-time) MMT capabilities. The totally digital workflow provides the basis but communication is also essential in most applications. An area where real-time operation is a must is autonomous vehicle navigation, which is still under intense research but expected to be operational in the next decade.

## MOBILE MAPPING CONCEPT

The two fundamental components of MMT, GPS/INS-based direct georeferencing and digital imaging sensor(s), are usually modeled separately with further differentiating the laser and optical imaging sensors. Here a combined representation is provided for the sensor model that can be equally applied to laser and optical camera systems, including both frame and line camera (pushbroom) models. Figure 1 shows the coordinate system definitions; note that the sensor frame is defined according to the conventional LiDAR notation, which is rotated180° around the $X$ axis compared to the standard image sensor frame. Also, a polar coordinate system definition ($\alpha,\beta$) is used to allow for a common treatment of the laser and image sensors.

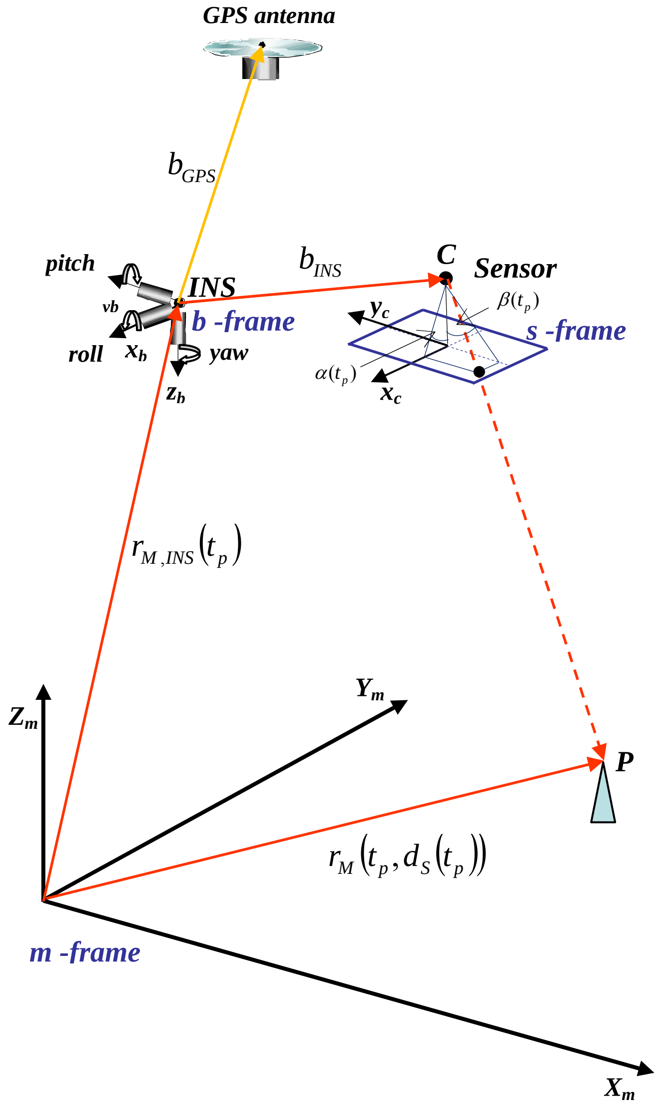


**Figure 1.** Coordinate system definitions.

The mapped object point coordinates are computed according to the sensor equation:

$$r_M\left(t_p, d_S\left(t_p\right)\right) = r_{M,INS}\left(t_p\right) + R_{INS}^{M}\left(t_p\right) \cdot \left(R_S^{INS} \cdot R_Y(\alpha(t_p)) \cdot R_X(\beta(t_p)) \cdot d_S\left(t_p\right) + b_{INS}\right)$$

where

| | | |
|---|---|---|
| $r_M\ (t_p)$ | — | 3D coordinates of the sensed object point in the mapping frame |
| $r_{M,INS}\ (t_p)$ | — | 3D INS coordinates (origin) in the mapping frame, provided by GPS/INS (the navigation solution typically refers to the origin of the INS body frame) |
| $R_{INS}^{M}\ (t_p)$ | — | Rotation matrix between the INS body and mapping frame |
| $R_S^{INS}$ | — | Boresight matrix between the sensor frame and INS body frame |
| $R_X^S$ , $R_Y^S$ | — | Rotation matrix to describe the rotation of the sensing direction around the *X* and *Y* axes of the sensor frame, respectively |
| $\beta(t_p)$ | — | Sensing direction angle from the *X* axis of the sensor frame ($x_S$ is flight direction, $y_S$ goes to the right, and $z_S$ goes down) |
| $\alpha(t_p)$ | — | Sensing direction angle from the *Y* axis of the sensor frame |
| $d_{S\ (tp)}$ | — | Range, either measured or unknown (distance from sensor reference point to object point) |
| $b_{INS}$ | — | Boresight offset vector (vector between laser sensor reference point and the origin of INS) defined in the INS body frame |

This formulation provides the first estimate for the geospatial positioning accuracy of a system, by defining an error boundary envelope. For LiDAR systems, all the parameters and measurements are known, so except for the effect of the footprint size and various object-space specific conditions, the accuracy estimates can be directly computed. For optical imagery, the scale (object distance) is unknown, so only a line with an error cone can be computed— the line on which the object point should lie. Then depending on the method, such as intersection with another line (stereo technique) or surface (DEM), additional computations are needed to determine the accuracy estimate of an object point; more details can be found in (May, 2007).

## MOBILE LIDAR SYSTEMS

### Technological Developments

The development of MMT systems has been always closely connected to technological progress. In particular, sensor developments, including GPS and INS navigation sensors, and, most importantly imaging sensors, have always been dependent on new technologies. The most noticeable sensor developments happened in CCD/CMOS imaging manufacturing, as the size of the sensors, measured in pixels, increased and, in parallel, the performance of the sensors improved, measured in faster image capture rates, better SNR, and less defective pixels on the area sensors (Toth, 2004; Petrie and Walker, 2007). General hardware developments also contributed to the advancement of MMT systems, as they provided the necessary computing environment to handle the significantly more geospatial data and to provide computing power, required to handle the more complex processing tasks. The key hardware and software developments that are relevant to mobile LiDAR mapping are briefly discussed below.

The last few years have seen remarkable developments in laser sensor mapping technologies on both airborne and ground platforms; the most important milestones were the introduction of the multi-pulse technique in airborne LiDAR systems (Leica and Optech) and mobile terrestrial scanners for ground-based applications (GIM, 2007). While for years airborne LiDAR was ahead of terrestrial laserscanning, now the difference has leveled out and, in fact, the mobile LiDAR area represents the fastest growing market segment of laser mapping technology, and all the major airborne LiDAR providers offer powerful mobile terrestrial systems. To better cope with environmental conditions, mobile LiDAR systems are based on pulsed laser technology. In fact, many mobile systems are derived from an airborne LiDAR sensor, such as the Riegl product family used in several operational systems. In contrast, Optech International has its dedicated LYNX mobile mapper scanner unit.

The use of laser scanners on vehicles for nontopographic purposes should also be mentioned, in particular, developments of autonomous vehicle technology have significantly contributed to sensor developments. The three DARPA organized Grand and Urban Challenges clearly proved that laser sensing is by far currently the most effective technique to reconstruct the object space in the vicinity of a vehicle, including the detection of other vehicles. There is a clear development path of the imaging sensor configurations used in the first DGC in 2004 and in the recent DUC in 2007. In 2004, there were a few SICK laser profilers installed on the vehicles but digital camera-based vision systems dominated the imaging sensor configurations. The situation was reversed by the 2005 DGC, when the winner, the Stanley vehicle from Stanford University, used five SICK roof-mounted sensors to map the area in the front of the vehicle and cameras were only used at high speed to look ahead at objects that were farther away than 40 m. Manufacturers, recognizing the potential of laser scanning, developed dedicated laser scanners for the 2007 DUC. The IBEO system provided laser profiling capabilities in four planes, thus replacing four SICK units. The most important development was the introduction of the Velodyne scanner, used by the winner, the Boss, a fully autonomous Chevy Tahoe vehicle from Carnegie Mellon University. Representing a major technological breakthrough in 2007, the Velodyne HDL-64E High Definition LiDAR sensor, shown in Figure 2, is based on using 64 laser units covering a 26.8° vertical FOV, thus eliminating the need for any vertical mechanical motion. The system sports high vertical rotation rates of the sensors, up to 15 Hz, at an angular resolution of 0.09°. The Class 1 laser works at the 905 nm wavelength with a 10 ns pulse width. The ranging accuracy is claimed to be less than 5 cm for 50 m and 120 m with reflectivities of 0.10 and 0.80, respectively. The more than one million points per second data rate is simply amazing. In summary, these unmanned vehicles have made extensive use of the laser scanners and integrated GPS/IMU systems that are the building blocks of the next generation of mobile mapping systems being developed for topographic applications (Ozguner *et al.,* 2007).

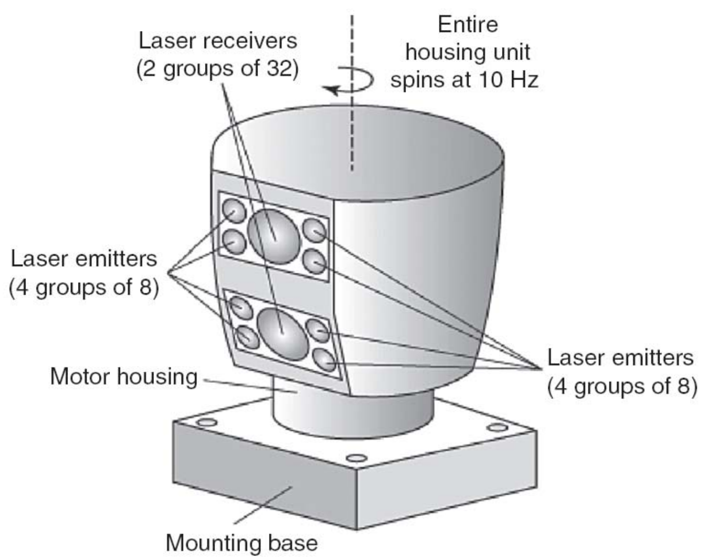


**Figure 2.** Velodyne scanner (Courtesy of M. Shand).

Flash LiDAR performance has shown improvement, yet these systems are not ready for mobile applications, as the ambient radiation, coming either directly from the sun or reflections, is just too high compared to the low emitted power, which is restricted to maintain eye-safe operations. However, these systems could be used indoors in the near future.

To provide for visual coverage, laser systems, both airborne and terrestrial LiDAR, are equipped with digital cameras, so the high-resolution point cloud can be realistically painted with color image data. The required image resolution to match the typical point cloud density is in the 2-16 Megapixel range; note that pushbroom line scanners with 2-8 Kpixel resolution are also frequently used in mobile LiDAR systems. Due to the huge consumer camera market, CCD/CMOS sensors happen to be manufactured in the largest numbers in the above-mentioned sizes, therefore, this is a proven technology, which means that high performance sensors are available at low cost.

Obviously, reliable operation under varying environmental conditions requires professional grade cameras, which provide for stabile image geometry and full control over the camera operations, including, parameter setting, triggering image capture and time-tagging. There have been successful efforts to standardize digital camera interfaces, both on the hardware level and the communication protocol. Most camera families typically support the three major camera interfaces, including FireWire (1394), the slowest, CameraLink, the fastest, and the GigE Vision, which has become very popular recently. The main attraction of the GigE Vision interface is that it does not require any frame-grabber, just a regular network connection, and it works at a speed of moving 125 Mb/sec in the ideal situation. In general, the digital camera component of mobile LiDAR systems can be easily customized to practically any application specifics. Review on digital camera developments can be found in (Petrie and Smillie, 2008).

From a sensor perspective, both the laser and digital camera can provide for real-time processing, as the data can be computed in the sensor frame without any difficulty. However, the georeferencing component is predominantly post-processed, so mapping in a local mapping frame is not feasible in real-time, and probably, it is not needed, unlike in autonomous vehicle navigation. Nevertheless, the georeferencing infrastructure will continue to develop, and thus it is likely that for applications with moderate accuracy requirements the processing can be done in real-time in the future.

Supporting hardware developments should also be mentioned, in particular, the miniaturization of various hardware components, including processors and storage devices. The importance of this trend is that it allows for smaller overall system size, which translates into two benefits. First, there is more flexibility in the installation, for both the sensor and the supporting data acquisition system. Second, more sensor units can be installed on the same vehicle, so redundancy and/or better coverage can be obtained. The lack of adequate time synchronization to GPS is still a problem on many systems, although there have been modest developments recently.

## Software Trends

The software architecture of mobile LiDAR systems is rather straightforward, as the main task is to record the sensor measurements and properly time-tag them, so the data can be accurately georeferenced based on the GPS/IMU-based navigation solution. As long as there is no need for real-time mapping capabilities, it is unlikely that the complexity of the data acquisition software will increase in the near future. Developments are more likely to happen in the user interface and in adding better diagnostics functions that can provide improved real-time capabilities for detecting any malfunctioning of the sensor and/or supporting data acquisition systems.

The post-processing software of mobile LiDAR systems, however, is still rapidly evolving as better co-registration and feature extraction methods are introduced. The main challenge here is to separate the static and dynamic components of the object space (Markiel *et al*., 2008). Even for a static sensor platform, this is a formidable task, but achieving it from a mobile platform is truly a very difficult job. Having redundant points clouds, acquired at a fast rate, is definitely a necessary condition if good performance is needed in a robust solution. For example, the identification of other vehicles, both moving and still, around a mobile LiDAR system and their removal is essential for topographic mapping.

## Mobile LiDAR Systems

Terrestrial mobile LiDAR systems gradually evolved from optical imaging-based MMS systems, as laser technology improved and eventually became affordable. The transition was actually rather smooth and fast, as the georeferencing and data acquisition infrastructure were already in place and only the laser sensor should be installed and interfaced. By now, the LiDAR system is the primary source of high resolution and accurate geospatial data, and digital cameras play a secondary role, as they are only used for visualization.

Early research efforts to develop mobile LiDAR included the Vehicle-borne Laser Mapping System (VLMS) of the Centre for Spatial Information Science of the University of Tokyo (Manandhar and Shibasaki, 2003) and the Geomobil project, the upgrade from the camera-based GeoVan of the ICC, Barcelona (Talaya *et al.,* 2007). Both of these projects featured multiple cameras and laser scanners for data collection purposes. Only very recently, over the last two or three years, have these largely research-oriented projects resulted in the introduction of vehicular-based systems using laser scanners that operate on a commercial basis, when recognizing the potential of this market, manufacturers started to develop dedicated systems. The most common mobile LiDAR systems, grouped into major categories are listed below:

Commercially available systems:

- LYNX Mobile Mapper from Optech
  Spinning laser profiler designed for vehicle roof installation, maximum pulse rate is 100 kHz, maximum ranging distance is 100 m, scan rate 9000 rpm, optional digital camera, Applanix POS/LV 420 georeferencing system.
- Street Mapper from 3D Laser Mapping
  2-4 LMS Q120 laser scanners from Riegl, maximum 150 m ranging distance, optional digital video or still cameras, IGI TERRAControl georeferencing system.

Custom-built, in-house operated systems:

- TeleAtlas
  SICK laser scanners complement six digital cameras, used for road mapping to support vehicle navigation and location-based systems.
- TerraPoint
  First system was based on a modified version of the ALMIS-350 airborne LiDAR system, FOV 60°, high-resolution video camera, maximum ranging distance is 100 m, Novatel georeferencing system
  TITAN system is based on four Riegl laser scanners, optional video and frame cameras.

Research systems:

- University of Tokyo
  Ibeo laser engine, maximum ranging distance is 100 m, scan frequency is 20 Hz, pushbroom optical sensors with 80 Hz capture rate, in-house georeferencing.
- ICC, Barcelona
  Riegl Z210 laser scanner, optional digital cameras, Applanix georeferencing.

Autonomous vehicle navigation:

- Carnegie Mellon University
  The Boss, equipped with a Velodyne HDL-64E sensor, two Ibeo scanners, several SICK laser profilers, digital cameras, Applanix POS-LV 220/240 georeferencing.
- Stanford University
  The Junior, equipped with a Velodyne HDL-64E sensor, two Ibeo scanners, six digital cameras, Applanix POS-LV 240 georeferencing.

Additional details on LiDAR systems, including terrestrial laser scanning systems can be found in (Shan and Toth, 2008).

## CONCLUSION

The subject of mobile LiDAR systems is an exciting one to explore, as this application field is rapidly expanding and extends beyond conventional topographic mapping. Future developments are primarily expected in the growing numbers of sensors installed on a vehicle, improved data processing and feature extraction performance, and increasing robustness of the georeferencing component. The denser point cloud, provided by a network of sensors can mainly assure that no area in the mapped corridor will be left out due to obstruction by objects, including moving vehicles. Although, the increased data volume may seem to cause some problems at the processing and storage level, it has an additional benefit for the georeferencing solution, as the vehicle trajectory can be recovered from overlapping point clouds. This could be helpful in urban canyons where GPS signal availability is limited, even if additional GNSS systems were operational. In these situations, the point cloud can provide updates to the navigation solution to control the IMU drift. From the application perspective, it is fair to say that the need for current and accurate city models is growing, as evidenced by the increasing the number of MMS vehicles, acquiring data for Internet mapping, vehicle navigation and, in general, location-based services.

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