STREETMAPPER MOBILE MAPPING SYSTEM AND APPLICATIONS IN URBAN ENVIRONMENTS

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ABSTRACT

Static terrestrial laser scanning and airborne laser scanning from helicopters and fixed wing aircraft are widely used tools for the 3D data capturing of smaller scenes and large areas, respectively. Both methods have their limitations for projects that include the rapid and cost effective capturing of 3D data from larger street sections, especially if these sections include tunnels or if dense point coverage of the facades of the neighboring architecture is required. To extend the applicability of laser scanning to these kinds of projects, terrestrial mobile laser scanning can be used. In this paper the components, the workflow and the performance of the Mobile Mapping system “StreetMapper” are described.

KEYWORDS: Mobile mapping system; lidar; laser scanning; GPS/INS; mobile mapping

INTRODUCTION

The performance and availability of modern 3D laser scanning systems has created a demand for a system that can survey many kilometres of highway very rapidly. Airborne laser scanning can offer this type of data but aircraft operations are expensive. Also this type of data can lack detail due to the distance above the area to be surveyed.

Terrestrial 3D laser scanners are commonly employed for highway and building surveys nowadays, however, these instruments are slow, therefore costly, when large areas need to be surveyed. Mounting a 3D scanner on the roof of a vehicle can improve the speed and productivity but there are still disadvantages such as uneven point spacing and the time taken to accurately geo-reference each 3D scan. For large surveys, over 100 individual scan positions must be geo-referenced which causes significant data management problems.

The StreetMapper mobile laser scanning system was developed initially to fill a demand for measurement and recording of highway assets, but has since been developed for other applications. The system uses 2D laser scanners integrated with a high performance GPS/inertial navigation system. The system is easily deployed on a range of different vehicles and the first StreetMapper system has been operating since early 2005. The significant commercial advantage of the system is that no traffic management is required to complete highways surveys to an accuracy of 30mm.

Highway surveying using videogrammetry, supported by GPS/INS systems, have been well used in many parts of the world. However, there are significant challenges in creating 3D data products with minimal human data processing. Some of these systems are now adding laser scanners to improve data processing workflows.

Several vehicle based laser scanning systems have been built in recent years (e.g. Talaya et al. 2004, Grinstead et al. 2005, Pfaff et al. 2007). Most of these systems were unique installations and developed mainly to demonstrate the general applicability of this technology. The StreetMapper is the first fully integrated, commercially available system of its type.

The performance objectives of the Mobile Mapping system “StreetMapper” are:

- Complete eye safe operation
- Operational speeds up to 80 km/h
- Operation of additional video cameras
- Full field of view
- Operation in urban environments and under tree cover

It is noted that there are the following limitations of such a Mobile Mapping system:
The field of view is line of sight from the vehicle path, so only the fronts of buildings are surveyed. The point density decreases with driving speed (similar to airborne lidar), so highest point density is captured at slow driving speeds such as 30 km/h.

SYSTEM COMPONENTS

In order to meet the performance objectives, stated above, an integrated “multi-sensor” system is required. The full 360° field of view is reached by operating multiple 2D-laser scanners simultaneously (Figure 1).

![Figure 1. Field of view of the four laser scanners, each with 80° field of view.](image1)

The mounting position and angles are carefully optimized to provide maximum coverage with some overlapping data between each adjacent scanner. In addition, there are many options of lidar sensor available with fields of view from 80° to 360° and maximum ranges up to 1,000m.

![Figure 2. An alternative configuration of two 360° 2D laser scanners.](image2)

For such a “multi sensor system” the correct time synchronization of all sub sensors is crucial. This synchronization is reached by tagging all collected data with the exact GPS time. The TERRAcontrol computer gets the actual time from the GNSS receiver and distributes a time pulse together with a time stamp to all used sensors.
To create image data of high quality, a digital still camera can be operated with resolutions varying from 4 Mpixel to 14 Mpixel. To take the full benefit of the orientations from the GNSS/IMU system, this camera is mounted together with the other sensors on the rigid platform.

**Figure 3.** Digital camera images overlaid on the lidar point cloud.

Figure 2 shows data that was captured with a StreetMapper together with a DigiCAM K14 (based on a Kodak DCS pro 14n). The camera image was overlaid on the lidar point cloud using the software PHIDIAS from PHOCAD Ingenieurgesellschaft mbH, Aachen, Germany.

**GNSS/IMU**

Like in airborne LIDAR mapping, the accuracy of mobile terrestrial LIDAR depends mostly on the exact determination of the position and orientation of the laser scanner during data acquisition. Nevertheless, the different conditions in a land vehicle compared to an aircraft lead to different requirements for the used GNSS/IMU system. The GNSS conditions in a land vehicle are deteriorated by multipath effects and by shading of the signals caused by trees and buildings. On the other hand, the distance between the scanner and the measured object is typically some ten meters, compared to several hundred meters for airborne laser scanning. Therefore the contribution of the GNSS positioning error to the overall error budget is much larger than the contribution of the error from the attitude determination.

To gain a better aiding of the inertial navigation system during periods of poor GNSS, the GNSS/IMU navigation system for the StreetMapper is extended by an additional speed sensor. Among other benefits in the processing of the navigation data, the speed sensor slows down the error growth in periods of missing GNSS, like in tunnels or under tree cover.

The TERRAcontrol GNSS/IMU system used for position and attitude determination inside the StreetMapper consists of the following components:

**Inertial Measurement Unit.** The TERRAcontrol is using the IGI IMU-Ild fiber optic gyro based IMU. This IMU is successfully operated with a large number of airborne LIDAR systems and aerial cameras. Its angular accuracy of below 0.004° for the roll and pitch angle can not be fully exploited for the short scanning distances in this application, but the high accuracy strongly supports the position accuracy in areas of weak or missing GNSS.
**GNSS Receiver.** The TERRAcontrol uses the NovAtel OEMV-3 card from NovAtel Inc, Calgary, Canada. Besides GPS, this receiver supports GLONASS and OmniSTAR HP real time corrections. In the standard configuration, the StreetMapper uses GPS and GLONASS. Since the system is optimized for data processing in post processing mode, the real time corrections from OmniStar HP are usually not used.

**Direct Inertial Aiding**
When satellite visibility in completely lost (such as in a tunnel or under a bridge), the GNSS receiver can not keep track of its position. When the satellites are visible again, the receiver can take up to six seconds to “lock on” to the signals and start computing an accurate measurement of the current position. Using Direct Inertial Aiding, the inertial navigation system sends information to the GNSS receiver that can be used to keep track of position, when no satellites are visible. This enables the receiver to “lock on” to signals much quicker when they become available again. Our tests indicate that after passing under a bridge, the GNSS receiver provides good quality position data 5 seconds earlier when using Direct Inertial Aiding compared to an unmodified GNSS receiver of the same type. The cumulative effect of this extra data in an urban environment has a significant effect on the overall accuracy.

**TERRAcontrol Computer**
The TERRAcontrol stores the raw data from the IMU, the GPS receiver and the speed sensor. It also provides the used laser scanners and digital cameras with accurate GPS time stamps for later synchronization of all data streams in post processing. With the user interface the operator can start and stop the operation of TERRAcontrol, access the actual GNSS status and synchronously start and stop the different laser scanners. The navigation raw data is stored on a PC card for later post processing.

**GNSS/IMU Post Processing Software**
The TERRAoffice software package provides all functions necessary for handling and processing the collected navigation data. Besides the routines for calculating the exact position and orientation of the sensor platform, it contains the transformation of the results into local mapping systems and various quality control tools.

**System Integration**
The StreetMapper system has a sensor platform that can be mounted on roof bars together with a movable electronic rack for versatile operation in different vehicles. The overall weight of the system of about 180 kg (incl. four scanners) and the small size allows the operation on normal passenger cars like in Figure 3.

![Figure 3. Left: StreetMapper electronic rack. Right: The sensor platform mounted on a vehicle.](image)

The instruments for the sensor operator are mounted at the co-drivers seat. He can switch the system on and off, start the operation of the different sensor groups and observe the system status and data quality. During the mission, he is also responsible to guide the driver along the planned route.
Data Processing

Although the TERRAcontrol has certain real time capabilities, the processing of the StreetMapper data is done after mission in post processing.

The data processing can be divided into two main steps. The first step includes all calculations that are necessary to create a geo-referenced point. The second step is the creation of the different kinds of products and databases out of the point cloud.

Calculation of the point cloud:
- The calculation of the position and orientation of the sensor platform. This step is done inside TERRAoffice.
- The laser raw measurements are merged with the positions and (calibrated) orientations to calculate a geo-referenced point cloud. Under very difficult GNSS conditions, a strip adjustment can lead to an improvement of the absolute accuracy.

Creation of final products:
- The dataset is split into project tiles of a size that can be handled by the lidar data analysis software.
- The points in the cloud are classified to be ground points, vegetation, buildings and so forth.
- The geo-referenced and classified point cloud can then be used as the basis of products such as:
  - 3D city models with detailed façade and street level information.
  - Digital terrain models, especially for rapid volume determination for the mining industry.
  - Highway surveying where level, gradient and edge of carriageway information is extracted.
  - Asset Management Databases for highway authorities (for example, sign posts and street furniture) or utilities (for example, heights of wires over the road).
  - Change detection for military and security forces.

System Calibration

The relative position of the different sensors to the IMU can be measured directly at the sensor assembly. The relative orientation, or misalignment, has to be determined from the data. For this misalignment calibration, features like street marking or house corners are captured in multiple paths. Certain target structures allow separate determination of the three misalignment angles. Due to the rigid mounting of the laser scanners and the IMU, the misalignment calibration does not change noticeably between different missions.

SYSTEM ACCURACY

For a Mobile Mapping vehicle like the StreetMapper, the accuracy of the results has to be quoted in two different ways:

Relative Accuracy

The relative accuracy describes the spread of the measurements between two points in the same region, taken in a short time period. This error is dominated by the noise of the single laser scanner measurements. For the StreetMapper the relative accuracy is about 1 cm or less.

It should be noted, that the accuracy of the measurement of the distance between two features in the measured scenery is not equal to this relative accuracy. This accuracy is strongly influenced by the possibility to determine the position of the features in the point cloud. Depending on the shape of the feature and on the point density, this accuracy can better or worse than the given relative accuracy.

For the operation of the StreetMapper, both, the relative accuracy and the accuracy to measure the distance between two features is nearly independent of the short term GNSS conditions. In periods of missing GNSS, only the absolute accuracy is decreasing!

This behavior can be exploited in applications where only the relative position of features is of interest, and not the absolute position in a mapping coordinate system. These could be applications like distance measurement inside tunnels (see Figure 4), or in the planning of driving routes for large and heavy loads.
Absolute Accuracy

The absolute accuracy is the accuracy of laser measurements in a local mapping coordinate system. This absolute accuracy is dominated by the quality of the GNSS solution. Under good conditions this accuracy is about 2cm, under difficult conditions it can be go up to 0.5m.

STREETMAPPER ACCURACY TRIALS

Danish Road Directorate

The Danish Road Directorate manages the Danish national roads, which carry almost 30% of the total transport volume in Denmark. Many of the new projects for the Construction Unit are rebuilding and creating new extensions of existing highways. This demands very accurate road surveys, especially with regards to elevation. Current traditional methods, such as manual surveying of points using total stations, make this task very difficult, not to mention dangerous, especially on an existing highway with flowing traffic.

3D Laser Mapping was asked to provide a demonstration of the StreetMapper system by scanning Frederikssundmotorvejen, a 3km dual carriageway just outside Copenhagen. The results from StreetMapper were compared against control points gathered by the Danish Road Directorate.

Data Capture. The StreetMapper was driven at an average speed of 45kph down each lane of the highway. A configuration with 4 laser scanners was used, with 1 pointing down at 20 degrees, 1 up at 20 degrees, and 1 to either side at 45 degrees. This arrangement allowed StreetMapper to achieve an average density of 200 points per square meter on each of the driving lanes. Figure 5 shows a plan view of the point data on the highway surface.

The GNSS conditions were good with 8 satellites were visible at the start of the survey, rising to 10 at the end of the survey. There were trees and bridges along the route that obscured visibility of satellites during the survey.
Estimated Accuracy. In the TERRAOffice software the GNSS/INS trajectory is calculated in the forward and reverse directions. The final result is the average of the two results, however the difference between the two solutions gives a good measure of estimated accuracy of the survey. The average INS position RMS (the difference between the forward and reverse TERRAoffice trajectory calculations) was 20mm in elevation and 15mm and 10mm for northing and easting respectively.
In Figures 6 and 7, the estimated accuracy can be seen varying with mission time (which can be plotted as position when necessary). Two characteristics of the data can be seen. Firstly, the points where the GNSS signals are obscured by trees and bridges can be seen as downward spikes in Figure 6 (indicating where fewer satellites are visible or none at all). In Figure 7, corresponding times can be seen with spikes in the accuracy graph, where the positional error is higher. Secondly, a trend can be seen, where as the number of satellites in view increases over time, the corresponding average accuracy improves. This highlights the need to plan missions requiring the highest accuracy at times where most satellites are visible.

**Measured Accuracy.** Accurately surveyed control points were located every 200m in the emergency lane. The main control network was surveyed using static GNSS followed by a free network adjustment and then levelled with precision alignment levelling. Each control point was then surveyed using RTK-GNSS over two sessions (with one initialisation per session and different satellite configurations). The positional accuracy of each control point was between 5 and 10mm in plan and elevation.

**Planimetric Accuracy.** In order to test the planimetric accuracy of the StreetMapper data, the edge of the highway was digitized from the lidar point using Microstation and TerraScan software. The surveyed points were projected orthogonal to the digitized lines and the difference between the surveyed point and the corresponding projected point was measured. The results are presented in Table 1.

<table>
<thead>
<tr>
<th>XY</th>
<th>X (Easting)</th>
<th>Y (Northing)</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of points</td>
<td>794</td>
<td></td>
</tr>
<tr>
<td>Mean difference (m)</td>
<td>0.023</td>
<td>0.004</td>
</tr>
<tr>
<td>Max. +difference (m)</td>
<td>0.125</td>
<td>0.039</td>
</tr>
<tr>
<td>Max. -difference (m)</td>
<td>-</td>
<td>-0.040</td>
</tr>
<tr>
<td>RMS (m)</td>
<td>0.029</td>
<td>0.010</td>
</tr>
</tbody>
</table>

Table 1. Planimetric accuracy results.
The key result is the mean difference between the lidar points and the control is 23mm in XY.

![Figure 8: Distribution of errors in Easting and Northing](image)

**Elevation Accuracy.** To test height accuracy of the StreetMapper data, the elevation of the control points were compared to the elevation of the lidar points in the immediate neighborhood. Both sets of data were transformed in height to the local geoid, and a planimetric transformation was made to local reference system of KP2000 (Sealand). This is the reference used for all the road projects in Denmark and is a local transformation based on ETRS89 with a small scale correction. The result is presented in Table 2.

<table>
<thead>
<tr>
<th># of points</th>
<th>1020</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean value (m)</td>
<td>-0.0013</td>
</tr>
<tr>
<td>max. Value (m)</td>
<td>0.075</td>
</tr>
<tr>
<td>min. Value (m)</td>
<td>-0.060</td>
</tr>
<tr>
<td>RMS (m)</td>
<td>0.0124</td>
</tr>
<tr>
<td>std.dev. (reduce to mean)</td>
<td>0.0123</td>
</tr>
</tbody>
</table>

Table 2. Elevation Accuracy results.

The key result is the RMS of the height difference is 12mm between StreetMapper data and a total of 1020 control points.
Stuttgart City Models

An accuracy trial took place in Stuttgart, Germany on November 18th, 2007. A distance of 13 km was covered in about 35 minutes within an area in the city centre with a size of 1.5 km x 2km.

A 3D visualisation of this data set is depicted together with the measured trajectory in 9. This 3D city model is maintained by the City Surveying Office of Stuttgart. The roof geometry of the respective buildings was modelled based on photogrammetric stereo measurement, while the walls trace back to given building footprints. These outlines were originally collected by terrestrial surveying for applications in a map scale of 1:500. Thus, the horizontal position accuracy of façade segments are at the centimetre level since were generated by extrusion of this ground plan. Despite the fact that the façade geometry is limited to planar polygons, they can very well be used for the purposes of assessing StreetMapper accuracy.

Figure 9: 3D city model used as reference data with overlaid trajectory

Figure 10: Estimated horizontal accuracy of the trajectory after GNSS/IMU post processing.
Various buildings were compared in areas of good and poor GNSS, and at different ranges from the laser scanner. As an example, for the building depicted in Figure 11 which is in an area of very poor GNSS, rather large differences between the reference façade and an estimated plane can occur; the standard deviation of the estimated planes is still 5cm. In general, the collected façade point cloud can still be used for applications requiring precise distance measurements. Furthermore, the absolute accuracy of the geo-referencing process can be improved, if the existing building model is used as control point information. Over the whole survey area, accuracy levels of better than 30mm in good GNSS conditions make the StreetMapper system practical for many mapping applications. Good point coverage makes this a very suitable tool for geometric enrichment of building facades.

Measurement of Overhead Telephone Cables

Because of the full field of view and the high relative accuracy the StreetMapper can be used to measure overhead cables quickly and accurately. In October 2005, the minimal distance of overhead telephone cables to the ground was measured by the StreetMapper and a total station survey instrument. Measurements were taken at the same time to ensure the same atmospheric conditions. To find minimum distance in the lidar data set, a catenary curve was fitted to the points that were classified as wire points. Then the distance from the lowest point of this curve to a plane fitted to a cluster of points on the ground below was measured. For the total station measurement the lowest point of the cables was selected visually and then the vertical distance to the ground was measured.

The comparison of the results of 25 wires from 9 different sites showed standard deviation of 59 mm. The maximum difference was 104 mm.
Compared to the relative accuracy of the StreetMapper and of the total station measurement, the accuracy looks relatively poor, but Figures 12 and 13 show the reason for these values. The difficulty is not to define the catenary curve of the wire, but the position of the minimum distance to ground. The ground is not a nicely defined plane, but a real street with deformations, with curb and with slope.

Besides the greater operating speed and better accuracy, the StreetMapper measurements have the advantage, that they are not biased to measure a longer minimum distance rather than a shorter one. This is the case for the traditional way of checking the wire height (Figure 14). If the minimum point is not exactly found, or if the pole is not really vertical, the measurements are always over-estimating the free space over the road.
CONCLUSION
Accuracy levels of better than 30mm in good GPS conditions make the StreetMapper system practical for many mapping applications, such as for highway surveying and for making exact measurements of clearances under overhead wires. The projects illustrated here show that the expected accuracy can be achieved in a variety of real world projects. With the accuracy results shown here, we have demonstrated that this technology is ready for widespread adoption for a variety of surveying and mapping tasks.

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