INTEGRATION OF A TERRESTRIAL LASER SCANNER WITH GPS/IMU ORIENTATION SENSORS

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ABSTRACT:

Direct orientation of laser systems has been widely used for airborne laser sensors but not with the terrestrial laser systems. The usual way to operate a terrestrial laser is by scanning a scene while the sensor remains static. In order to cover the whole scene, different scans can be combined by matching several common points, finally the orientation of the scene is performed by identifying and providing coordinates for a minimum of 3 points. This procedure is very time consuming leading to a very low productivity. In order to increase productivity the Institut Cartografic de Catalunya (ICC) has integrated a terrestrial laser scanner in a mobile vehicle with the aim to operating the laser while the vehicle is moving.

This paper describes the integration of a terrestrial laser scanner with the GPS/IMU orientation sensors of a Land Based Mobile Mapping System. The laser pulses are synchronized to the GPS time by using a modified PPS signal from a GPS receiver. In order to transfer the reference frame from the GPS/IMU sensors to the laser sensor a number of calibration scans and control points are used and the offset and misalignment between the laser and GPS/IMU sensors is determined. The results of the calibration procedures, as well as accuracies and performance obtained by the integrated GPS/IMU/terrestrial laser system are presented in the paper.

1. INTRODUCTION

During the last years the use of terrestrial laser scanners for 3D modeling has widely been expanded. These systems provide direct measurements of clouds of points that are illuminated by the laser. A terrestrial laser scanner generally collects the data by measuring a complete scene while the sensor remains static. Thereafter, the scene has to be georeferenced by identifying at least 3 points on the laser scanner image and giving them ground coordinates. In order to improve the productivity the ICC decided to directly orient the laser scenes by integrating a terrestrial laser scanner with a GPS/IMU (Inertial Measurement Unit) orientation system in a mobile vehicle with the aim to operate the laser while the vehicle is moving. That integration allowed a direct orientation of the laser scene reducing dramatically the time required to obtain a geocoded scene ready to extract information.

The integration of airborne lasers with GPS/IMU orientation systems has been widely used since mid 90's providing good results and leading to a wide exploit of the airborne lidar technique (Lindenberger 1993). However, terrestrial lasers have not followed the same path and they are seldom directly oriented by a GPS/IMU system.

The integration of the terrestrial laser with the GPS/IMU sensors was done in the frame of the Geomòbil project (Talaya et al. 2004), the mobile mapping system developed at ICC.

2. GEOMÒBIL

In the first stage, the Geomòbil (see figure 1) integrated two CCD cameras in a van to capture stereoscopic pairs of digital images and all the equipment required to georeference directly the collected images. The van was developed as a modular system that should be easily upgradeable with new sensors. Hence, the Geomòbil is composed of different subsystems: an image subsystem, a synchronization subsystem, an orientation subsystem, a power supply subsystem, a data storage subsystem and a climatization subsystem.

Figure 1: Geomòbil system developed at ICC

The orientation subsystem is mainly based on the integration of a GPS receiver and an IMU sensor. However, due to the large number of GPS outages that occur in a terrestrial campaign, it also includes the integration of a DMI sensor (Distance Measurement Indicator), which is used to reduce IMU drifts during these outages. The orientation subsystem is completed with a GAMS system (GPS Azimuth Measurement System), an approach from Applanix based on the heading determination using two GPS antennas mounted on the top of the van, which allows a rapid heading correction after GPS outages.

In order to correctly transfer the reference frame from the orientation subsystem to the CCD cameras, a rigid structure was designed (Figure 2). The reaction of the structure under different forces was modeled and the latest design showed deformations of less than 1 mm in distance and less than 70 arcseconds in angle. The structure acted as a platform for integrating the sensors used for the orientation and any other sensor mounted on it. In particular, the integration of the digital cameras and the GPS/IMU orientation subsystem lead to very good results, photogrammetric points are determined with accuracies better than 5 cm in across track directions and 13 cm in along track direction at an average distance of 18 m (Alamús et al, 2004).

The precise orientation computed by the orientation subsystem (GPS/IMU) can be transferred to any sensor (in particular to the terrestrial laser) mounted on the platform. Thus, the laser data can be directly oriented applying the same principle used for airborne lasers.

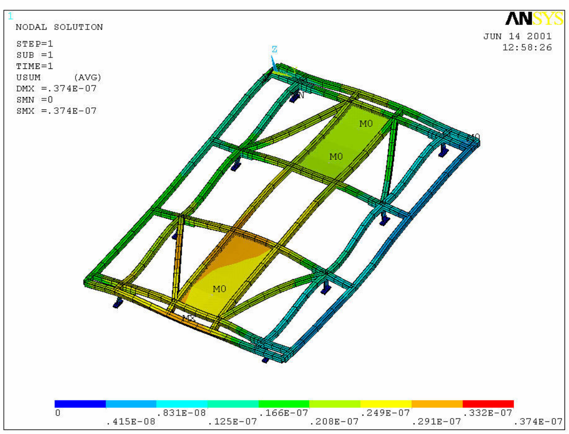

Figure 2: Geomòbil integration platform (response to stress)

3. INTEGRATION OF A LASER SCANNING

The laser selected for the integration was a Riegl Z-210 that is able to collect up to 10000 points per second. For each point a distance measurement, an intensity value and RGB data is collected. The laser has a rotating mirror that allows taking vertical profiles while a servomotor rotates horizontally the whole laser for scanning a static scene (see figures 3 and 4). For each laser point also the angle readings of the mirror and the scan encoders are obtained. These angular values, together with the distance measurement, are used to locate the measured point in a local laser reference frame. The raw data collected by a terrestrial laser are usually parameterized in a spherical coordinates frame, denoting r the distance measured by the laser, ϕ the rotation angle of the mirror and φ the laser position angle during the scanning (see figure 3).

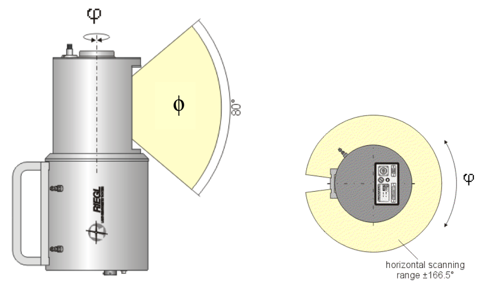

Figure 3: Terrestrial laser spherical coordinate frame (courtesy of Riegl LMS GmbH)

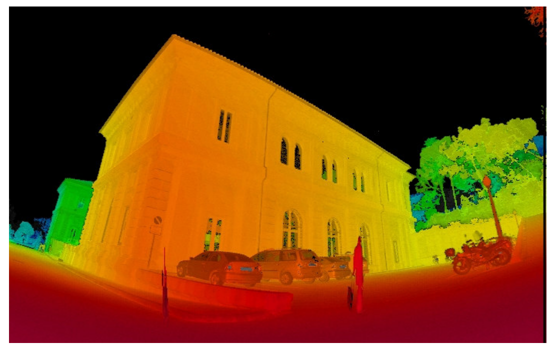

Figure 4: Static terrestrial laser scene coded with a combination of intensity and distance. The rotating mirror scans the scene in vertical lines while the laser rotates around a vertical axis covering the scene in the horizontal direction

The transformation from the laser spherical coordinate frame to a laser cartesian coordinate frame is given by following equation:

$$x = r \cdot \sin\phi \cdot \cos\varphi$$
$$y = r \cdot \sin\phi \cdot \sin\varphi$$
$$z = r \cdot \cos\phi$$

Equation 1: Preliminary transformation from the laser spherical coordinate frame to a laser cartesian coordinate frame

By construction the laser axes are not perfectly aligned, the mirror rotation axis (ϕ angle) and the laser scanning axis (φ angle) do not intersect, so this difference has to be corrected in order to transfer the initial laser spherical coordinates to a local laser cartesian coordinates frame. In equation 2 the formulas used by the laser software (Riegl, 2001) to perform the transformation are described. Assuming that the origin of the laser cartesian frame lies on the axis defined by the rotating mirror (ϕ angle), r_o is an offset on the distance measurement and φ_d is the misalignment of the scanner rotation axis:

$$x_e = r_o \cdot \cos\varphi_d$$
$$y_e = r_o \cdot \sin\varphi_d$$

$$X_l = r \cdot \sin\phi \cdot \cos\varphi + x_e \cdot \cos\varphi + y_e \cdot \sin\varphi$$
$$Y_l = r \cdot \sin\phi \cdot \sin\varphi + x_e \cdot \sin\varphi - y_e \cdot \cos\varphi$$
$$Z_l = r \cdot \cos\phi$$

Equation 2: Final transformation from the laser spherical coordinate frame to a laser cartesian coordinate frame

If the laser remains static while collecting a scene it would be easy to determine the transformation to a mapping reference frame by measuring some control points. Once a global translation (X_T,Y_T,Z_T) and a rotation matrix M_l^m are determined every laser point (X_l,Y_l,Z_l) on the scene can be transformed by applying the same function (see equation 3).

$$\begin{pmatrix} X_m \\ Y_m \\ Z_m \end{pmatrix} = \begin{pmatrix} X_T \\ Y_T \\ Z_T \end{pmatrix}_{translation} + M_l^m \begin{pmatrix} X_l \\ Y_l \\ Z_l \end{pmatrix}$$

Equation 3: Transformation between the laser cartesian coordinate frame to a mapping cartesian coordinate frame (static case)

This transformation can also be determined directly by the GPS/IMU subsystem using the formulas described in equation 4.

According to the explanations in the previous paragraphs, the laser was rigidly mounted on the integration platform (figure 5). Assuming that the GPS/IMU systems are capable to determine the orientation of the integration platform at any moment, the transfer of the reference frame from the GPS/IMU to the laser can be done as long as the laser data is synchronized with the GPS/IMU observations and the spatial transformation between the GPS/IMU frame and the laser frame is known, i.e. determined in a calibration procedure.

Figure 5: Terrestrial Laser integrated in the Geomòbil

The laser labels the beginning of each line with a precise internal clock. The synchronization is performed by relating the laser time system to the GPS time system. The laser internal clock can be reset by an external TTL signal. By using this possibility a modified PPS signal is pseudorandomly sent to the laser. After the survey, at the office, a software synchronizes the laser internal time system to a global GPS time system by comparing the pseudorandomly resets of the laser internal clock to the previously stored time at which the TTL signals were generated. Knowing the GPS time at the start of each line, the GPS time of every laser point is computed by adding the laser repetition period to the time of the previous laser point.

The orientation subsystem of the Geomòbil allows a continuous determination of the transformation between the IMU reference frame to the mapping reference frame. Once every laser point is time labeled in GPS time the transformation between the laser reference frame to the mapping reference frame (e.g. WGS84) can be done according to equation 4 in two steps: a) transformation from the laser to the IMU reference frame and b) transformation from the IMU to the mapping reference frame. The first step comprises the offset determination between the laser and the IMU reference frame (V_l^b in equation 4) and the misalignment matrix between laser and the IMU reference frame (M_l^b in equation 4). The offset and the misalignment matrix (V_l^b and M_l^b) remain constant as long as both systems (IMU and laser) are rigidly mounted on the integration platform and the platform does not have any distortion due to the stress. As explained in the next section these constant values are determined in a calibration survey. In a second step the rotation matrix (M_b^m in equation 4) and the translation vector ($X_{GPS/IMU}$, $Y_{GPS/IMU}$, $Z_{GPS/IMU}$ in equation 4) are determined using the integration of the GPS/IMU observations. Notice that the rotation and translation matrix applied in the second step are not constant and keep varying during the survey. Therefore, for each laser point a different translation and rotation matrix will be derived from the computed trajectory.

$$\begin{pmatrix} X_m \\ Y_m \\ Z_m \end{pmatrix} = \begin{pmatrix} X_{GPS/IMU} \\ Y_{GPS/IMU} \\ Z_{GPS/IMU} \end{pmatrix} + M_b^m M_l^b \left(\begin{pmatrix} X_l \\ Y_l \\ Z_l \end{pmatrix} + V_l^b \right)$$

Equation 4: Transformation between the laser cartesian coordinate frame to a mapping cartesian coordinate frame (kinematic case)

The use of integrated GPS/IMU data to directly orient laser data has the advantage that the transformation between the local laser reference frame and the mapping reference frame is known at any moment (as far as the laser is synchronized), independently if the laser is collecting data in a static mode or in kinematic mode. Therefore, the laser can be used as a pushbroom sensor while fixing the scan angle and sweeping the scene with profiles while the vehicle is in movement.

3.1 Calibration

The offset and the misalignment matrix are determined by applying equation 4 to a set of static laser scenes where several ground control points have been observed and by a final adjustment.

A number of previously surveyed points were signalised with reflecting material, which allows a good identification of the ground control points in the laser intensity image (see second image on figure 6). Several scenes were captured while the van was stationary and the GPS/IMU sensors were collecting data. Afterwards, an adjustment was done for computing the offset and the misalignment matrix. The translation and rotation matrix ($X_{GPS/IMU}$, $Y_{GPS/IMU}$, $Z_{GPS/IMU}$) and M_l^b were derived form the GPS/IMU trajectory and used as observations in the adjustment. The measurements of the signalised points in the intensity image were also used as observations. In order to improve the determination of the parameters and to decouple their correlation four scenes taken with different azimuth angles were used in the adjustment. Figure 7 shows the distribution of the adjustment with the red ellipses indicating the position and formal error of the IMU orientation, the blue ellipses indicating the position and formal error of the laser orientation and the very small black ellipses showing the position and formal error of the 15 signalised points used (notice that some of the points differ only in the vertical coordinates and therefore, are shown superimposed in figure 7). The black lines link the laser position with the ground control points and symbolise the laser image measurements of the signalised points.

The results and the formal accuracies of the adjustment are presented in table 1.

		value	σ
offset	X	-2.169 m	0.006 m
	Y	0.007 m	0.006 m
	Z	0.462 m	0.006 m
Misalignment	ω	-89° 59' 3"	34 "
	φ	0° 1' 32"	12 "
	κ	-89° 59' 49"	12 "

Table 1: Determination of the offset and misalignment matrix in the adjustment

4. DYNAMIC LASER SCANNING

Once the laser was synchronized to GPS time and the constant offset and misalignment matrix computed by using the method described in the previous section, it was possible to use the terrestrial laser as a pushbroom sensor by fixing the scan angle and sweeping the scene with profiles while the vehicle is in movement. Every single point measured by the laser is transformed to the mapping reference frame by using its corresponding orientation and applying the formulas described in equation 4.

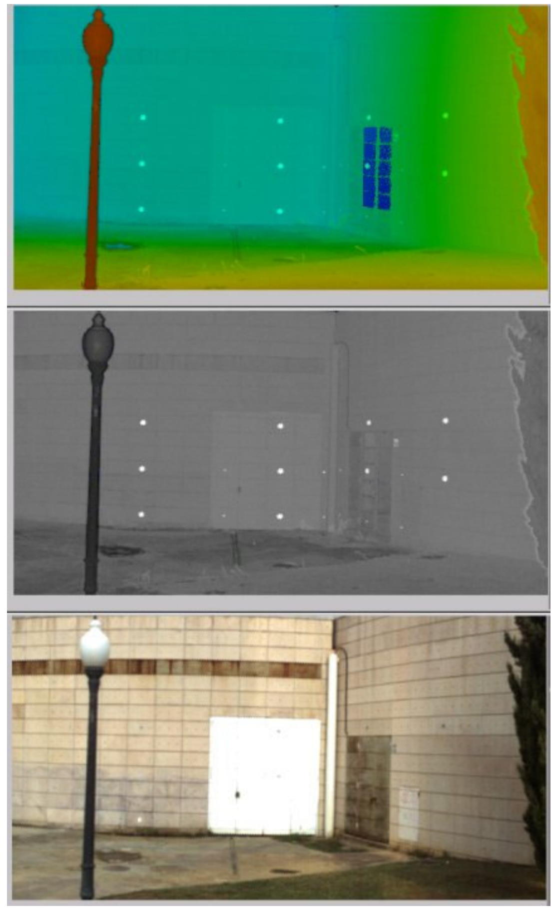

Figure 6: Calibration scene. Combination of intensity and distance image (above), intensity image (centre) and RGB image (below) (signalised points are easily identified in the intensity image)

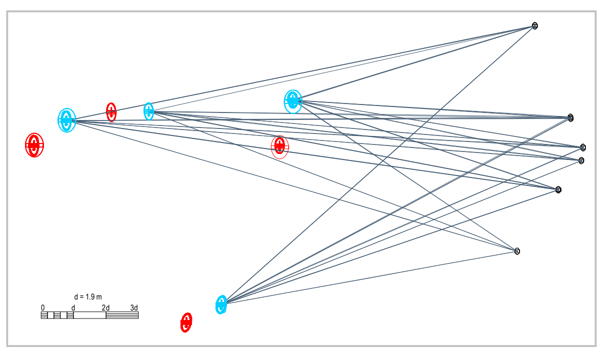

Figure 7: Laser mounting calibration: adjustment of four laser static scenes. Red: position of the GPS/IMU sensors. Blue: position of the terrestrial laser. Black: control point measured in the laser scenes

Figures 8 and 9 show the laser RGB images collected in a kinematic mode. The laser was vertically mounted on the integration platform and the rotating mirror was performing vertical scans looking at the right side of the van while it was moving. In figure 8 the exterior buildings of a roundabout can be observed while in figure 9 some cars can be identified parked on the street. These images show the oriented raw laser data represented in a mapping reference frame. In order to obtain useful information these data have to be filtered and edited e.g. for extracting and modeling the buildings represented in the images.

Figure 8: RGB laser points collected in a kinematic survey (laser looking to the right side of the van)

Figure 9: RGB laser points collected in a kinematic survey (laser looking to the right side of the van)

The laser can also be mounted horizontally. In this configuration the rotation mirror performs horizontal scans perpendicular to the direction of the van. This configuration has two main applications: a) while the scanner is looking down it can be used to model the road surface and b) while the scanner is looking up it can be used to model aerial infrastructures. Figure 10 shows an example of an horizontal scanner. In that case the scanner was looking up while the van was mounted on a train and the train overhead power cable was surveyed.

4.1 Comparison with 1:1000 city map

An urban survey was carried out in kinematic mode with the laser vertically mounted (as shown in figure 5) and performing vertical scans of the buildings façades. After orienting the laser points using the method described in this paper, the point clouds were plotted together with the available city map that have an accuracy of 20 cm (1.64 σ) per component.

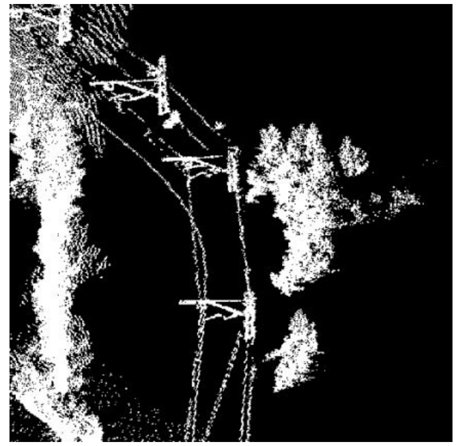

Figure 10: Intensity image from a train overhead power cable (laser looking up)

It is well known that the determination of the trajectory of a van inside a city is very difficult due to the constant GPS outages. Therefore, the comparison was done on those parts of the trajectory where an acceptable orientation was computed. From a laser point cloud plotted together with the 1:1000 line map ten well defined check points were measured. Figure 11 illustrates the selection of one well defined point at a building roof corner. The coordinates of the laser points were compared to the point map coordinates. Table 2 shows the comparison of the ten check points identified in the 1:1000 line map and in the laser point cloud.

Point-ID	dE	dN	dH [m]
1	0.07	-0.11	-0.03
2	-0.24	-0.16	-0.10
3	0.30	-0.75	-0.15
4	0.26	-0.41	0.02
5	-0.07	-0.08	-0.22
6	0.02	-0.24	-0.02
7	-0.04	-0.38	-0.15
8	0.02	-0.31	-0.06
9	-0.27	-0.28	-0.24
10	0.16	-0.25	-0.07

	MIN.	MEAN	MAX.	RANGE	RMS.	σ [m]
dE	-0.27	0.02	0.30	0.57	0.18	0.18
dN	-0.75	-0.30	-0.08	0.67	0.35	0.18
dH	-0.24	-0.10	0.02	0.26	0.13	0.08

Table 2: Differences of coordinates at the 10 check points (laser coordinates – map coordinates)

As can be observed the results are on the level of 0.18 m in Easting, 0.35 m in Northing and 0.13 m in the vertical component. As the path studied is not very long the systematic difference observed in the North direction is assumed to be caused by a remaining error in the trajectory determination.

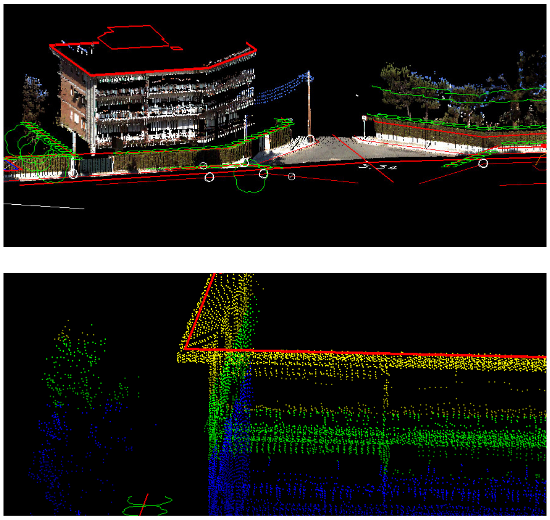

Figure 11: Comparison of 1:1000 map with the laser points. in RGB (above) and colour coded elevation representation (below)

5. SUMMARY

This report describes the integration of a terrestrial laser scanner on the Geomòbil mobile mapping system developed at ICC. The critical points of the integration are described, including the laser synchronization and the system calibration.

The calibration procedure described in the paper allowed the determination of the IMU/laser offset with a formal accuracy of 0.006 m and the determination of the misalignment matrix with a formal accuracy of 12-34 arcseconds.

The direct orientation of a terrestrial laser opens the possibility to use the sensor as a pushbroom sensor that is able to scan crossroad sections and buildings façades while the vehicle is moving. Assuming a good GPS coverage and a good orientation determination, the dynamic laser survey showed RMS differences of 0.18 m in Easting, 0.35 m in Northing and 0.13 m in the vertical component compared to 1:1000 city maps.

In order to fully exploit the integration of a terrestrial laser scanner in a mobile mapping frame further developments are necessary including building reconstruction by processing the laser point cloud and improving the orientation accuracy in urban areas.

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