Calibration of Vessel Mounted LiDAR

Nicolas Seube, Alan Picard, Thomas Touzé, France
Ecole Nationale Supérieure de Techniques Avancées Bretagne

Jean-Guy Nistad, Mathieu Rondeau, Canada
Centre Interdisciplinaire de Développement en Cartographie des Océans

Topic C : innovations in processing techniques

ABSTRACT

This paper investigates the problem of latency estimation between an IMU (Inertial Motion Unit) and a LiDAR (Light Detection And Ranging). The latency is due to the IMU itself, but also to the acquisition software and hardware configuration, which is generally set-up by survey systems users. We propose a method for latency estimation, and we show that this method meets the accuracy requirements of most LiDAR survey applications. We present test results of our method on various acquisition systems and hardware configuration which demonstrate that it is able to identify very accurately the total latency through a simple procedure. Our method does not require any positioning device, therefore it is independent of non modeled errors which may corrupt geolocalized data. Our method enable the user to estimate any LiDAR-IMU latency, in order to to optimize the configuration of a kinematic survey system and to enhance its robustness features with respect to high motion dynamics.

We also propose a new boresight angle calibration method between LiDAR and IMU, and we estimate its accuracy and precision. As these two methods do not need any positioning data, they avoid the propagation of GPS errors into the calibration procedure.

Key words: LiDAR, Boresight calibration, Latency calibration, Patch test, Marine Infrastructure surveys.

1. INTRODUCTION AND BACKGROUND

Kinematic LiDAR (Light Detection And Ranging) is now commonly used in the surveying community. In order to geolocalize detection points, a LiDAR is generally coupled with an Inertial Motion Unit (IMU) which gives attitude angles, and with a GPS system for both positioning and time stamping.

In order to get coherent and accurate survey datasets, all sources of systematic errors have to be minimized. These errors due may be to the LiDAR itself (range bias, deflection angle bias), to the presence of boresight angles between the LiDAR and the [Kumari et al., 2011, Skaloud and Litchi, 2006, Morin, K., Naser El-Sheimy, N., 2002] and to time-stamping errors. Timing errors may come from the IMU latency (time difference between physical measurements and the IMU output) and also from the acquisition device configuration, which is generally left to the survey system user.

Most tactical grade IMU systems (widely used in surveying and airborne mapping) are coming with an independent clock, not synchronized to GPS, and thus, the implementation of the GPS time-tagging that may vary over a large range. These systems must be calibrated for high-precision application.

Latency error can be minimized if the motion sensor manages time-tagging thanks to the GPS Pulse Per Second (PPS) signal input.

Most survey data acquisition softwares can compensate for such latency errors, but in practice, the latency setting is mostly left for the end-user. This latency should not only represent the IMU latency, but the IMU-LiDAR latency, that we shall call the total latency: It will be defined by the time difference between the instant of IMU attitude physical measurement and the instant of LiDAR measurement. More importantly, the total latency may be affected by user software settings, and by acquisition computer hardware settings, including communication devices. In [Habib et al. 2010], IMU-LiDAR timing error are identified as a source of error, and a maximum latency accuracy of 0.1ms is suggested in order to meet high-quality standards of the airborne LiDAR surveys.

Calibration procedures are based on geolocalized survey data the which may be corrupted by errors from survey sensors, environmental perturbations, and data integration procedures. Time-stamping errors may also affect the temporal coherence between sensor data, and in particular between LiDAR ranging data and IMU orientation data. These errors may become significant in case of undesirable high dynamics of the kinematic survey platform. If it is actually the case, latency errors may contribute significantly to the non observability of calibration parameters. Kinematic LiDAR surveys are performed from a wide variety of platforms (aircrafts, helicopters, trucks, and vessels). Some of these platforms (in particular small survey craft performing harbour inspection or coastal erosion monitoring) may be affected by fast motion dynamics, and thus sensitive to IMU-LiDAR latency.

2. LIDAR-IMU LATENCY CALIBRATION PROCEDURE

In this section, we propose a method that can be used for estimating the inertial motion unit latency with respect to a ranging system, connected to a acquisition software. Latency between a ranging system and an IMU can be determined by applying a controlled rotational motion to the ranging system and by estimating the position shift of a spherical target induced by a rotational motion. Hereafter, we shall describe a possible set-up in the case of a LiDAR coupled to a motion sensor. For doing so, it is required to get the following data:

- Position of the ranging system optical center through time;
- Orientation of the inertial motion unit frame with respect to the navigationframe. It is to be mentioned that the orientation bias between the motion sensor frame and the LIDAR is not required at this stage, and will be investigated later;
- Scan lines (e.g. set of detection points) from the LIDAR;
- Angular velocities of the LIDAR-IMU system.

Angular velocities provided from the IMU are submitted to the same latency that we would like to estimate. Therefore, it is preferable to use an external source of angular velocity. We chose to use a 3D motion simulator capable of measuring angles with high accuracy, and to control very precisely angular velocities. In the following, we suppose that angular velocities are available with very high accuracy.

Let us denote by $n = (N, E, D)$ the navigation frame with origin at the motion simulator center of rotation, by bS the kinematic LiDAR body frame, and by bI the inertial motion unit frame. Let us first observe that latency estimation is not affected by orientation bias from the IMU frame and the kinematic LiDAR frame. Let us denote by M a LiDAR detection point, referenced from its optical center O in its own frame S , and $x_f = OM_f$ in a frame f . In the navigation frame, we can write for a static (or quasi static) kinematic LiDAR detection point

$$x_n = R_{bI}^n R_{bS}^{bI} x_S \quad (1)$$

where R_{bI}^n and R_{bS}^{bI} are direction cosine matrix from frame (bI) to (n) and (bS) to (bI).

Now consider the same scene, but seen from the kinematic LiDAR in rotational motion. The principle of the method is to consider that point M has been detected by the LiDAR, but shifted in the navigation frame. Let M' be the image of point M , the kinematic LiDAR being in rotational motion. Denoting by $x'_f = OM'_f$, we can write

$$x'_n = R_{bI}^n (t - dt) R_{bS}^{bI} x_S \quad (2)$$

From (1) and (2), we deduce that

$$x_n = R_{bS}^{bI} R_{bI}^n (t - dt) x'_n$$

Assuming that the rotational motion is with a constant angular velocity, and after some manipulations, we obtain the relationship between latency and the displacement vector $\Delta_n = x_n - x'_n$ due to the rotational motion:

$$dt = \frac{\|\Delta_n\|}{\|\omega_{bI/n}^{bI} \wedge x'_n\|}$$

where $\omega_{bI/n}^{bI}$ denotes the angular velocity of the LiDAR-IMU with respect to the (n) frame, expressed in the IMU coordinate system.

3. EXPERIMENTAL RESULTS OF THE LATENCY CALIBRATION METHOD

The problem is now to define a reference point M that can be defined from a LiDAR scan. A good candidate for such a point is the center of a spherical target. Indeed, this center can easily be fitted by LiDAR returns from the sphere surface with a very high accuracy. By an iterative least-square procedure, one can accurately estimate a sphere center from surface points [Grejner-Brzezinska, 2011]. In figure 2, we plotted LiDAR return from a spherical target used in our experimental set-up.

Figure 1: Spherical targets scans. Right side 7 deg/sec scans, left side -7deg/sec scans. Position shift of the centers has been estimated with a precision of 0,04 mm.

Our method aims at being a laboratory test and will not require any positioning device, which will therefore not propagate positioning errors in the calibration itself. The experimental set-up that we realized is formed by a Leica HDS6200 Laser scanner, coupled with an OCTANS 4 Attitude sensor (they are mounted in the same mechanical bracket). The IMU and the LiDAR have been installed on an IX-Motion TRI30 motion simulator, capable of achieving rotational motions with a high precision and accuracy (about 0.001 deg/sec).

Figure (2) shows the mechanical mounting of the LiDAR-IMU on the motion simulator, the control panel of the acquisition software Qinsy, and the control panel of the 3D motion simulator that have been used during our tests. A spherical target of diameter 20cm was placed at a distance of 2.5 meter from the laser scanner optical center. It should be noted that in our approach, a relatively short distance to the target is not a limiting factor. Indeed, an increase of the distance to the target (denoted by x'_n in the latency estimate equation) would generate a larger position shift of the target when viewed at several angular speeds, but would deteriorate the quality of estimation of the sphere centres from ranging measurements.

A reasonable choice of the target range should be based on ranging precision considerations, in order to get a good estimate of the target center. This choice can be balanced by a relatively high value of the angular velocity which amplifies the target center shift.

Figure 2: Experimental set-up for latency calibration: The Leica HDS6200 and the IxSea Octan4 are mounted on a IxMotion TRI30 motion simulator, scanning a sphere of precision.

Both LiDAR and IMU data were gathered by the Qinsy acquisition software. It should be mentioned that our method estimates the total latency between the IMU, the LiDAR and the acquisition PC. In order to check for the latency induced by the PC acquisition buffer size, we made several tests with different software configurations. Indeed, as the OCTANS4 was not connected to a Pulse per Second signal, and data were transmitted through a serial link, the size of the serial link buffer might impact the total latency. Data from these tests are given in table (1).

The latency of the OCTANS 4, when connected by a serial link, is around 2,35 ms with 0,2ms uncertainty. The latency due to buffering should be added, and the latency due to data assimilation by Qinsy in order to get the total latency. Table (1) gives the results we obtained with several buffer configurations, in order to check the impact of various buffer size and our latency estimate resolution.

One can check that the residual latency (e.g; the latency due to the acquisition software and data assimilation is quite constant, with an accuracy of 0,2ms. Note that figures given in table (1) are averaged values of a serie of runs, which returned the latency estimate with SD values of about 0.01ms. We can conclude from these tests that the method is able to find IMU latency with an accuracy of 0,2ms and a precision of 0,01ms.

It is also very important to mention that this method applies to any IMU connected to an acquisition system, and do not depend of the ranging device (LiDAR or MBES). Therefore, hydrographic survey systems and IMUs latency can be estimated by using this method, which is a positioning error free calibration method.

Table 1: Latency estimation results

FIFO buffer size	Sphere center SD	Total latency	OCTANS 4 latency	Buffer th. latency	Residual latency
0	0.041mm	2.82ms	2.35ms	0	0.47ms
8 bytes	0.044mm	3.31ms	2.35ms	0.69ms	0.27ms
14 bytes	0.042mm	3.97ms	2.35ms	1.22ms	0.40ms

4. LIDAR-IMU BORESIGHT ANGLES CALIBRATION PROCEDURE

The approach we present here is devoted to LiDAR-IMU boresight calibration procedure independent of any positioning data; namely, we do not want positioning errors to corrupt the calibration procedure.

4.1 Principle of the method

The procedure we propose for LiDAR-IMU boresight angle calibration is motivated by the fact that we would like to eliminate the influence of positioning errors on the misalignment angles computation. The procedure we propose can be achieved in a laboratory, and requires to make a serie of static scans of a tripod (see figure (1)) target from several points of views.

Let us suppose that the LiDAR and the IMU are rigidly mounted in a mechanical bracket. We start by a first static scan of the tripod. The major advantage of this type of target lies in the fact that its orientation can be determined only from the knowledge of the intersection points (C_1, C_2, C_3) between the LiDAR scanning plan and the tripod itself. Points (C_1, C_2, C_3) can be determined by fitting the center of the ellipse produced by the intersection of the LiDAR scanning plan and the tripod cylinders. By using notations defined in figure (1), it can be readily shown that for all $i, j \leq 3; i \neq j$ we have

$$d_{ij}^2 = d_{0i}^2 + d_{0j}^2 - 2d_{0i}d_{0j} \cos \theta_{ij}$$

These three non linear equations can be numerically solved for $(d_{0i})_{i=1..3}$, with prior knowledge of the three angles forming the tripod. Then, we can estimate the tripod center O , being the intersection of three spheres of centers (C_1, C_2, C_3) with radius (d_{01}, d_{02}, d_{03}) .

Figure 3: Geometric view of the bore-sight calibration target

Let us denote by (x_0, y_0, z_0) the coordinates of point O in a frame attached to the Lidar scanning plan, and $(x_i, 0, z_i)$ the coordinates of points C_i . Then, we have

$$(x_0 - x_i)^2 + y_0^2 + (z_0 - z_i)^2 = d_{0i}^2, i = 1..3$$

this last system being explicitly solved for (x_0, y_0, z_0) by

$$(x_0 - x_1)^2 + y_0^2 + (z_0 - z_1)^2 = d_{01}^2$$

$$2x_0(x_2 - x_1) + 2z_0(z_2 - z_1) = d_{01}^2 - d_{02}^2 + x_2^2 - x_1^2 + z_2^2 - z_1^2$$

$$2x_0(x_3 - x_1) + 2z_0(z_3 - z_1) = d_{01}^2 - d_{03}^2 + x_3^2 - x_1^2 + z_3^2 - z_1^2$$

We observe that y_0 has two solutions, which express the fact that the tripod center may be located in the two half space separated by the Lidar scanning plane. Knowing the coordinates of point O , we can reconstruct the directions OC_i of each tripod foot in the Lidar scanning plane.

Let us now suppose that two different static scans of the tripod have been performed, for two different Lidar orientations. For a given orientation i let us denote by $X_{bsi} = OC_i$ the tripod foot vectors coordinatized in the LiDAR frame bS. Note that each of these vectors can be uniquely attached to a given footprint whenever the diameters of the foot tube are different.

4.2 Derivation of the bore-sight calibration equations

Consider now two different foot vectors, X_{bs1}, X_{bs2} obtained from two orientations of the LiDAR scanning plan towards the tripod. Let us denote by

- $R_{bs}^{bl}(\varphi, \theta, \psi) = \begin{pmatrix} c\psi c\theta & c\psi s\theta\varphi + s\psi c\varphi & -c\psi s\theta c\varphi + s\psi s\varphi \\ -s\psi c\theta & -s\psi s\theta\varphi + c\psi c\varphi & s\psi s\theta c\varphi + c\psi s\varphi \\ s\theta & -c\theta\varphi & c\theta c\varphi \end{pmatrix}$ the direction cosine matrix defining the rotation from the LiDAR frame bs to the IMU frame, namely, the boresight angle direction cosine matrix parametrized by Euler angles (φ, θ, ψ) ;
- $(\varphi_0, \theta_0, \psi_0)$ an a priori estimate of the boresight angles;
- R_{bli}^n , the direction cosine matrix from the IMU frame to the navigation frame n (e.g; the local geodetic frame (North, East, Down)) a from the point of view i .

The basic principle of our method is to express that in the navigation frame n , the tripod foot vectors $R_{bli}^n X_{bli} = R_{bli}^n R_{bs}^{bl} X_{bsi}$, coordinatized in the navigation frame are invariant for each LiDAR static scan. Therefore, the fundamental equation for this calibration method is

$$R_{bli1}^n X_{bli1} = R_{bli2}^n X_{bli2},$$

We start with

$X_{bli} = R_{bs}^{bl} X_{bsi} := g(\varphi_0, \theta_0, \psi_0)$. In considering a linear approximation of this equation, we obtain: $g(\varphi, \theta, \psi) = g(\varphi_0, \theta_0, \psi_0) + g'(\varphi_0, \theta_0, \psi_0) \cdot (\varphi - \varphi_0, \theta - \theta_0, \psi - \psi_0)^T$, which leads to the following linear system

$$R_{bli1}^n g(\varphi_0, \theta_0, \psi_0)_1 - R_{bli2}^n g(\varphi_0, \theta_0, \psi_0)_2 = (R_{bli1}^n g'(\varphi_0, \theta_0, \psi_0)_1 - R_{bli2}^n g'(\varphi_0, \theta_0, \psi_0)_2)(\Delta\varphi, \Delta\theta, \Delta\psi)^T$$

In combining three observation sites, we obtain nine equations, which can be solved by a weighted least square¹ which returns approximated values of (φ, θ, ψ) . Then, by updating $(\varphi_0, \theta_0, \psi_0) \leftarrow (\varphi, \theta, \psi)$, we create a sequence of estimated boresight angles. Convergence of this process is not guaranteed but generally occurs after a few iterations.

5. ANALYSIS OF THE BORESIGHT CALIBRATION METHOD

5.1 Description of the simulation set-up

In order to study the robustness and performance of the boresight calibration method, a simulation of the whole estimation process has been performed for checking the boresight angles values with respect to some uncertainty on the ellipse center estimates. In this set-up, we considered a tripod with a 60 deg angle with respect to its vertical axis, and we generated a sequence of 3 LiDAR scanning plans given by the following rotations in roll, pitch and heading :

$$(\varphi, \theta, \psi) = [-20, 0, 30], [0, 20, 120], [20, -20, 240]$$

¹ The weight matrix depending on the confidence on the estimation of the coordinates of the foot vector (which comes from the ellipse center estimate) and from the precision of the IMU which delivers the direction cosine matrix.

The uncertainty on the ellipse center was estimated by a statistical analysis of the least-square residuals and was set to 1mm and 1cm for a tripod tube of diameter 10cm.

5.2 Performance and Robustness analysis

From figure (4) and (5), it can be seen that our estimation method is unbiased. One should mention that the method presented in [Grejner-Brzezinska, 2011] induced a bias in the boresight matrix estimation since this method is based on a composition of micro-rotators which is no more a true direction cosine matrix representing a rotation matrix.

The following result show frequency distribution graphs of the roll, pitch and yaw errors for several ellipse centre distribution errors. It can be seen figure (5) that for a realistic error distribution on the ellipse centers (about 1mm), the boresight angle errors are less than 0,01 deg on pitch and roll, and 0,05 deg for the heading angle. Our simulation results indicate that this method converges in a few iterations, generally less than five. The robustness of the method can be checked in figure (4): even in the case of 1cm (this error is clearly over estimated) of ellipse center error, boresight angles are quite well estimated, with an error of less than 0,1deg for pitch and roll and less than 0,5 deg for heading.

From these simulation results, we observe that the estimation procedure including ellipse detection uncertainty, geometric reconstruction of the tripod foot vectors, and boresight matrix estimation is unbiased and very accurate, in comparison of classical surface matching methods which cumulate latency errors due to kinematic survey, positioning errors, and surface modeling errors.

Figure 4: Boresight errors with 1cm uncertainty on ellipse centers

Figure 5: Boresight errors with 1mm uncertainty on ellipse centers

6. CONCLUSION

The LiDAR calibration methods we propose offer many advantages in comparison of field calibration methods: they save survey mobilization time, they are free of any positioning errors, which is not the case of surface matching methods and target methods. They also avoid the classical obstruction and loss of accuracy due to calibration on edged targets. The boresight calibration method we propose is also free of inertial measurement errors due to eventual fast dynamics motion, as it only requires a serie of static scans.

The latency calibration approach may be applied to any IMU and acquisition software, independently of the ranging sensor (LiDAR or MBES). The boresight calibration procedure is for the moment limited to LiDAR, but should be also adapted to MBES calibration.

REFERENCES

- [Barber, D., Mills, J., 2006] Geometric validation of ground-based mobile laser scanning system. *ISPRS Journal of Photogrammetry & Remote Sensing* 68, 123-141.
- [Burman, H., 2002] Laserstrip adjustment for data calibration and veri_cation. *International Archives of Photogrammetry and Remote Sensing* 34(3A), 67-72.

[Clarke, J. H., 2003] Dynamics motion residuals in swath sonar data: Ironing out the creases. *International Hydrographic Review* 4(1), 6-23.

[Filin, S., 2003] Recovery of systematic biases in laser altimetry data using natural surfaces. *Photogrammetric Engineering & Remote Sensing* 69, 1235-1242.

[Filin, S., Vosselman, G., 2004] Adjustment of airborne laser altimetry strips. In: *ISPRS Congress Istanbul, Proceedings of Commission III*.

[Glennie, C., 2007] Rigorous 3d error analysis of kinematic scanning lidar systems. *Journal of Applied Geodesy* 1, 147-157.

[Grejner-Brzezinska, D. A., Toth, C. K., Sun, H., Wang, X., Rizos, C., Nov 2011] A robust solution to high-accuracy geolocation: Quadruple integration of gps, imu, pseudolite, and terrestrial laser scanner. *IEEE Transactions on instrumentation and measurement* 11, 3694-3708.

[Gruen, A., Beyer, H., 2001] Calibration and Orientations in Computer Vision. Springer, Ch. System Calibration through Self-Calibration., pp. 163-193.

[Habib, A., Bang, K., Kersting, A., Chow, J., 2010] Alternative methodologies for lidar system calibration. *Remote Sensing* 2, 874-907.

[Jaakkola, A., Hyppa, J., Kukko, A., Yu, X., Kaartinen, H., Lehtomaki, M., Lin, Y., 2010] A low-cost multi-sensoral mapping system and its feasibility for tree measurements. *ISPRS Journal of Photogrammetry & Remote Sensing* 65, 514-522.

[Kumari, P., Carter, W. E., Shrestha, R. L., 2011] Adjustment of systematic errors in als data through surface matching. *Advances in Space research* 47, 1851-1864.

[Mettenleiter, M., Oberteiber, N., Hartl, F., Ehm, M., Baur, J., Frohlich, C., 2008] 3d laser scanner as part of kinematic measurement system. In: *International Conference on Machine Control & Guidance*.

[Morin, K., Naser El-Sheimy, N., 2002] Post-mission adjustment methods of airborne laser scanning data. In: *FIG XXII Int. Congress, Washington DC*.

[QPS, 2007] Timing in Qinsy. QPS BV, The Netherlands.

[Schenk, T., 2001] Modeling and analyzing systematic errors of airborne laser scanners. Tech. rep., Department of Civil and Environmental Engineering and Geodetic Science, The Ohio State University, Columbus, OH.

[Skaloud, J., 2006] Reliability of direct georeferencing: Phase 0. Tech. rep., Euro SDR commission 1: sensors, primary data, acquisition and georeferencing.

[Skaloud, J., Litchi, D., 2006] Rigorous approach to boresight self-calibration in airborne laser scanning. ISPRS Journal of Photogrammetry & remote Sensing 61, 47-59.

[Yan, W., Shaker, A., Habib, A., Kersting, A., 2011] Improving classification accuracy of airborne lidar intensity data by geometric calibration and radiometric correction. ISPRS Journal of Photogrammetry & Remote Sensing 67, 35-44.

CONTACTS

Nicolas Seube, Alan Picard, Thomas Touzé
ENSTA Bretagne
2 rue François Verny
Brest
FRANCE
Tel. +33(0)2 98 34 88 88
Fax +33 (0)2 98 34 88 46
Email: nicolas.seube@ensta-bretagne.fr
Web site: <http://www.ensta-bretagne.fr>

Jean-Guy Nistad, Mathieu Rondeau
CIDCO
310, rue des Ursulines, C.P. 3300
Rimouski (Québec) G5L 3A1
CANADA
Tel. +1 418 725 1732 #1722
Fax +1 418 724 1401
Email: nistadj@cidco.ca
Web site: www.cidco.ca