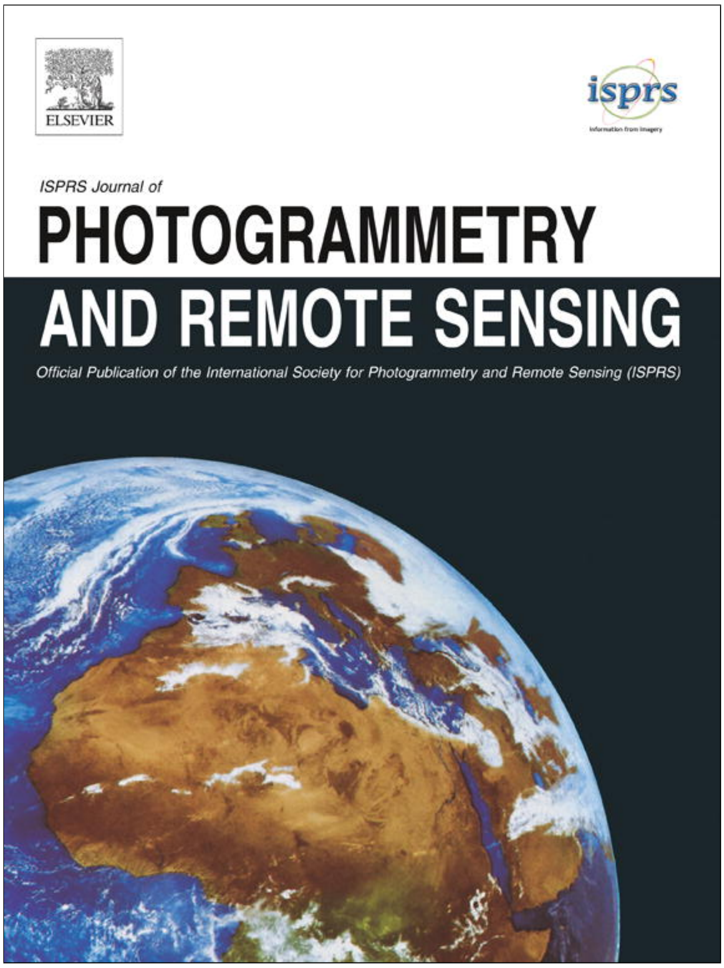
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A simple method to recover the latency time of tactical grade IMU systems

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ABSTRACT

This paper investigates the problem of latency estimation between an IMU (Inertial Measurement 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 IMU–LiDAR latency through a simple procedure. The principle of the method is to put the LiDAR–IMU in rotational motions, thanks to a rotating table. By scanning a spherical target at different angular velocities, we can observe position shifts of the target center from which we derive an estimate the IMU–LiDAR latency. The method we propose works without absolute positioning and is therefore not sensitive to nonmodeled errors coming from GPS geolocated data. We show that in estimating accurately the LiDAR–IMU latency, we can optimize the configuration of a mobile LiDAR survey system in order to enhance its robustness with respect to high motion dynamics of the survey platform.

1. Introduction

Mobile LiDAR (Light Detection And Ranging) is now commonly used in the surveying community. In order to geolocate LiDAR returns, an Inertial Measurement Unit (IMU) which computes navigation data, including attitude angles and a GPS system which provides absolute positioning as well as timing are required. In order to get consistent and accurate survey datasets, all sources of systematic errors have to be minimized. These sources of errors are due to the LiDAR sensor (scan angle errors), the presence of boresight angles between the LiDAR and the IMU (Kumari et al., 2011; Skaloud and Litchi, 2006; Morin and Naser El-Sheimy, 2002 **?**; Schenk, 2001) and GPS time-tagging errors. Timing errors may come from the IMU latency (time difference between the epochs of the physical measurements and the output IMU data is created) and also from the acquisition device configuration. 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 may vary over a large range. These systems must be calibrated for high-precision applications. Typically, the IMU data stream is GPS time-tagged and the latency is estimated. Note that the GPS time-tagging is mainly based on using the PPS (Pulse Per Second) GPS signal.

Most survey data acquisition software can compensate for latency errors, but in practice, the estimation of the latency is mostly left to the end-user. The latency should not be an estimate of the IMU internal latency, but should incorporate the total IMU–LiDAR latency which depends on the acquisition system and software settings. We shall call "total latency" the time difference between the epochs of IMU attitude physical measurement and LiDAR measurement. In Habib et al. (2010) and Skaloud (2006), IMU–LiDAR timing error are identified as a source of error, and a maximum latency accuracy of 0.1 ms is suggested in order to meet high-quality standards of the airborne LiDAR surveys.

In most papers dealing with LiDAR data quality improvement, boresight angles, level arms and ranging error are estimated through calibration procedures, generally in matching geolocated data (surface or targets) produced by several survey lines of the same site. The calibration of a survey system can be done by using two different approaches (Filin and Vosselman, 2004): Through the determination of LiDAR, IMU and GPS sources of errors, or through the identification of calibration parameters by matching of data from overlapping survey lines. Generally, calibration methods use geolocated survey data which are subject to errors in case of improper survey system integration procedures. In particular, time-tagging errors may deteriorate the consistency between LiDAR data and IMU data. In case of high motion dynamics of the

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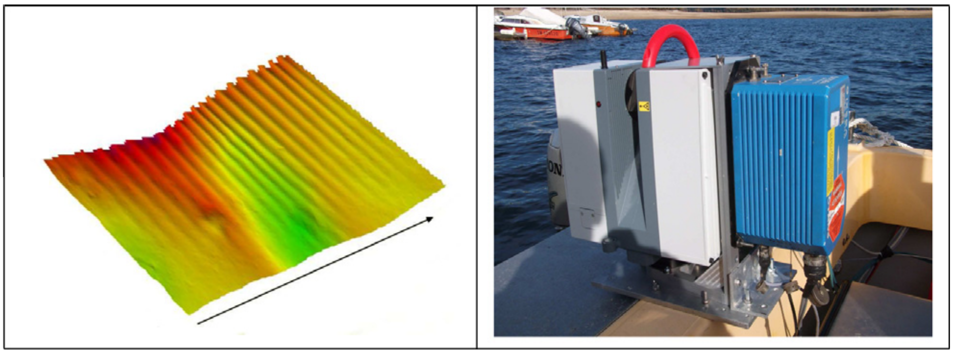

Fig. 1. Example of latency effect on mobile LiDAR data taken from a survey vessel with fast roll motion dynamics. This image shows a beach Digital Elevation Model, produced from survey data corrupted by an IMU–LiDAR latency. The back arrow shows the line followed by the survey vessel (the LiDAR was scanning the port side). In this example, the latency produced a roll error, which effect is amplified with the scanning range. For the sake of clarity a vertical scale factor of 100 has been applied. The maximum amplitude of wavelets is 2 cm at 50 m range.

mobile survey platform, latency induced errors may significantly reduce the calibration parameters accuracy.

A wide variety of platforms are used for mobile LiDAR applications: Aircrafts, helicopters, trucks, and vessels. Some of these platforms (in particular small survey crafts performing harbor inspection or land vehicles used for coastal erosion monitoring) may be affected by fast motion dynamics and therefore, are sensitive to IMU–LiDAR latency. Fig. 1 shows a typical LiDAR survey data set corrupted by IMU–LiDAR latency. LiDAR data was taken from a survey vessel. A tactical grade IMU and a GPS was used for data geolocation purposes. In the presence of IMU–LiDAR latency, the survey vessel was submitted to roll motion dynamics. As a consequence, roll errors we present in the datasets: Small amplitude wavelets at larger ranges can be easily seen in Fig. 1.

This paper will focus on the design of a simple estimation procedure of the latency between a tactical grade IMU and a mobile LiDAR. In Section 2, we review the main sources of latency that may affect LiDAR survey data and propose a simple method for latency estimation. In Section 3, we describe a experimental set-up devoted to latency estimation. In Section 4, we present experimental results and conclude about the latency accuracy that can be reached by this method.

2. Timing errors estimation

2.1. Orientation vs. ranging sensor latency

In Table 1 we give an example of latency induced errors produced in typical vessel mounted LiDAR survey conditions. From this table we see that IMU–LiDAR latency contribution to the total propagated error is significant, and that latency must be accurately estimated in case of fast motion dynamics of the surveying platform, in order to avoid the presence of undesirable artifacts as shown in Fig. 1.

Table 1
Example a latency induced errors, in a typical survey situation: a mobile LiDAR scanning a beach profile of 10° at a range of 50 m, with a roll velocity of 10°/s (case of the horizontal beam only).

Latency (ms)	0.1	1	5	10	15	20	25
Vertical error (cm)	0.09	0.9	4.4	8.8	13.3	17.8	22.4
Horizontal error (cm)	0.5	4.9	24.9	49.9	75.3	100.9	126.8

Since the introduction of GPS, data time-tagging is possible thanks to the PPS (Pulse Per Second) signal. The PPS signal can be used in order to synchronize the acquisition system computer and the survey sensors clocks equipped with a PPS input. However, an accurate time-tagging cannot cancel out the latency due to the sensor itself (e.g. the time difference between the epochs of physical measurement and data output). Most surveying acquisition and processing software require the knowledge of the IMU latency for data geolocation purposes. Generally, this latency value is set to the one given by IMU manufacturers,[1] but it should be set to the time difference between the epochs of attitude (i.e. pitch, roll and yaw) measurements and LiDAR returns. Main sources of total latency are:

- IMU time delay between attitude physical measurement and data output.
- IMU to acquisition computer transmission delay (significant is a serial link is used).
- Acquisition computer hardware and software configuration (presence of buffers, time-tagging device, geolocation method, etc.).

Among all sources of total latency, some of them can be known, but some other are not controllable by the user, as for instance, the latency induced by the acquisition computer and software. The aim of this paper is to propose a simple method enabling the user to estimate the total latency of any IMU–LiDAR survey system.

2.2. Principle of the method

The IMU–LiDAR total latency can be determined by comparing a reference target point to the same target point scanned while the IMU–LiDAR system is submitted to a known rotational motion.[2]

Let us denote by $n = (N, E, D)$ the navigation frame with origin at the rotating table center of rotation, by (bS) the LiDAR body frame, and by (bI) the IMU frame.

Let us denote by M a target reference point[3] coordinated in frame (bS), O the LiDAR optical center, and $\mathbf{x}_f = \overrightarrow{OM}_f$ in a frame f. In the navigation frame, we have

$$\mathbf{x}_n = R^n_{bI} R^{bI}_{bS} \mathbf{x}_{bS} \tag{1}$$

where R^n_{bI} and R^{bI}_{bS} are direction cosine matrix from frame (bI) to (n) and (bS) to (bI). We now consider the same target, but seen from the mobile LiDAR submitted to a rotational motion. The principle of the method is to observe that in the presence of an IMU–LiDAR latency

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[1] Most IMU manufacturers determine the latency by operating the unit on high precision synchronized rotating tables. Correlation between the rotating table and the IMU attitude data is used in order to estimate the IMU latency.

[2] Which can be achieved by a rotating table.

[3] The target reference point can be determined by processing LiDAR returns of a given target. We shall see that a spherical target shape is well adapted.

dt, the point M, detected by the LiDAR with rotational motion, is shifted to a point that we shall denote by M'. Denoting by $\mathbf{x}'_f = \overrightarrow{OM'_f}$, we can write

$$\mathbf{x}'_n = R^n_{bI}(t-dt)R^{bI}_{bS}\mathbf{x}_{bS} \tag{2}$$

We deduce from (1) and (2) that

$$\mathbf{x}_n = R^n_{bI}R^{bI}_n(t-dt)\mathbf{x}'_n$$

Assuming a rotational motion with constant angular velocity, we can write

$$R^{bI}_n(t-dt) = R^{bI}_n - \frac{d}{dt}\left(R^{bI}_n\right)dt = (Id + dt\,\Omega^{bI}_{n/bI})R^{bI}_n$$

where $\Omega^{bI}_{n/bI}$ denotes the angular velocity of frame (bI) with respect to frame (n), coordinated in the (bI) frame. We deduce that

$$\mathbf{x}_n = R^n_{bI}(Id + dt\,\Omega^{bI}_{n/bI})R^{bI}_n\mathbf{x}'_n = \mathbf{x}'_n + dt\,\Omega^n_{n/bI}\mathbf{x}'_n$$

Let us denote by $\mathbf{\Delta}_n = \mathbf{x}_n - \mathbf{x}'_n$, the target point M shift point due to the latency dt.

$$\mathbf{\Delta}_n = dt\,\Omega^n_{n/bI}\mathbf{x}'_n = dt\,\omega^n_{n/bI}\wedge\mathbf{x}'_n = dt\,R^n_{bI}\,\omega^{bI}_{n/bI}\wedge\mathbf{x}'_n \tag{3}$$

Both $\mathbf{\Delta}_n$ and $\mathbf{x}'_n$ can be computed by data post-processing. Note that in Eq. (3), the angular velocity $\omega^{bI}_{bI/n}$ should be given by the rotating table itself, as the IMU data are submitted to latency. By taking the norm of Eq. (3), we finally have

$$dt = \frac{\|\mathbf{\Delta}_n\|}{\left\|\omega^{bI}_{n/bI}\wedge\mathbf{x}'_n\right\|} \tag{4}$$

Let us note that this equation does not depend on the boresight rotation matrix between the IMU and the LiDAR R^{bI}_{bS}, which means that latency calibration can be performed priorly to boresight angle calibration.

2.3. Estimation of a sphere center reference point

First, let us mention that it is not possible to accurately estimate the IMU–LiDAR latency in scanning a target containing sharp edges (a road sign for instance) at different angular velocities with a resolution lower than the repetition frequency of the LiDAR. Indeed the repetition frequency induces a space uncertainty $\delta x = (\omega_2 - \omega_1)R\delta T$, which combined with Eq. (3) proves that the maximum latency uncertainty would be actually δT.

A good candidate as a target reference point is the center of a sphere, which can be determined very accurately from LiDAR point cloud (Grejner-Brzezinska et al., 2011). Indeed, by using an iterative least square fitting method, one can estimate the sphere center position from LiDAR returns, through the following sphere radius observation equation:

$$r(x,y,z) = \sqrt{(x-x_i)^2 + (y-y_i)^2 + (z-z_i)^2}$$

where (x, y, z) are the coordinates of the sphere center, and (x_i, y_i, z_i) are LiDAR returns from the sphere surface. This observation equation can be linearized at a point (x', y', z') lying in a neighborhood of (x, y, z) by:

$$r(x',y',z') = r(x,y,z) + \begin{pmatrix} \frac{\partial r}{\partial x}(x,y,z) & \frac{\partial r}{\partial y}(x,y,z) & \frac{\partial r}{\partial z}(x,y,z) \end{pmatrix}\begin{pmatrix} x'-x \\ y'-y \\ z'-z \end{pmatrix}$$

Starting from a barycentric estimate (x_0, y_0, z_0) of the sphere center, the following iterative least square algorithm estimates the sphere center: from the current estimate (x_0, y_0, z_0), we compute a new estimate (x_1, y_1, z_1) by solving the following $(N, 3)$ least square system, N being the number of the sphere LiDAR echoes:

$$\left[\frac{(X_0 - X_i)^T(X_1 - X_0)}{r(x_0,y_0,z_0)} = r(X_0) - r(X_1)\right]_{i=1,N} \tag{5}$$

where $X_i = (x_i, y_i, z_i)$.

3. Experimental set-up

3.1. Mobilized equipment

The method we propose has been tested in coupling a Leica HDS6200 LiDAR, to an IxSea OCTANS4 attitude sensor.

The OCTANS4 is a strap-down attitude sensor which is widely used in the hydrographic surveying community. It is equipped with three fiber optic gyroscopes (0.05°/h/bias stability) and three accelerometers (with accuracy of 1000 μg) and outputs pitch, roll, heading, and heave motion estimates. Attitude data are computed by estimating the inertial rotation, without the help of magnetic sensor or GPS baseline. According to the manufacturer, the roll/pitch/yaw accuracy of the OCTANS4 is 0.01° RMS for 68% of the data, and the heading accuracy is 0.1°/s latitude. The latency between the physical measurement of the unit and its output on the serial link lies in the range [2.15,2.55] ms.

The Leica HDS6200 is a terrestrial laser scanner that can also be used as a mobile LiDAR. Accuracy of a single measurement at low range (less that 25 m) is 5 mm on position, 2 mm on distance. Its scanning optics is a vertically rotating mirror, with scan rate of up to 1 million points per second. The time delay between two measurements is about 0.5 μs, so we can consider that the latency due to the assimilation of LiDAR data is essentially due to the acquisition computer.

The two systems have been rigidly mounted on the same mechanical bracket, fixed on a IXMotion TRI-30 3D rotating table with control facilities of the rotational motion. For our purposes, one axis has been used, the other ones being leveled and fixed. The TRI-30 angle measurement precision is 0.005°, and the accuracy of angular velocity regulation is about 0.01°/s. The principle of the experimental setup is shown in Fig. 2.

3.2. Tests methodology

It is to be mentioned that latency calibration using GPS positioning for the purpose of data geolocation suffers from inaccuracy. Indeed, GPS positioning errors may be significant with regards to target geolocation accuracy that should be reached in order to estimate the IMU–LiDAR latency. Our objective is to estimate the latency of a complete data acquisition system (LiDAR, IMU, acquisition computer, acquisition software) with a resolution of 0.1 ms, which requires an accuracy in the target reference point (e.g. the center of a sphere) of about 0.02 mm. This objective is clearly not compatible with GPS positioning errors, even in applying IMU-GPS data hybridization post-processing filters and smoothers.

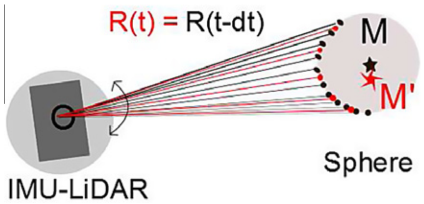

Fig. 2. Schematic view of the experimental set up. The sphere center is viewed at point M', due to the fact that the orientation at t is actually the orientation at $t + dt$. LiDAR echoes from the sphere are be used to determine the sphere center viewed with an angular velocity, and to determine dt by Eq. (4).

Following (Filin, 2003) who mentions the presence of nonmodeled positioning errors in calibration datasets, we designed a positioning free latency calibration method. To do so, we used the following methodology:

- The IMU/LiDAR common bracket was fixed on the rotating table horizontally, and the rotating table was leveled with an accuracy of less than 15 arcsec.
- The rotational motion applied to the IMU–LiDAR was a pure yaw velocity $\omega_{bl/n}^{bl} = (0, 0, \omega_D)^T$ as shown in Fig. 2.
- The LiDAR optical center was fixed above the vertical of the rotating table center of rotation with an accuracy of less than 0.5 mm, in order to cancel out any translation due to the yaw rotation.
- The angular velocity ω_D was not measured from the IMU, but from the rotating table in order to avoid the use of time delayed yaw velocity data from the IMU.

Let us now describe the acquisition set-up that has been used for testing our method. The OCTANS4 attitude output was connected to the acquisition PC via a serial link at 115,200 bauds. The PPS synchronization from the GPS was not used by the OCTANS4 IMU, and the attitude data time-tagging was performed by the acquisition computer. With this setup, the total latency that we shall estimate will include the IMU latency.

The PPS signal was sent from the GPS receiver to the acquisition PC and the LiDAR. This signal was supplemented with a GPS/ZDA message (which contains date and time), and both ZDA and PPS were sent via a serial link at 115,200 baud. The time uncertainty on the descending front of the PPS input was 0.1 μs, and the ZDA input was sent 15 ms after the descending front. Transmit time of the ZDA message was about 10 ms, which guarantees that the ZDA information was recognized and time-tagged by the acquisition computer and the LiDAR. In such conditions, we consider that these two devices were synchronized on the same clock.

Having an estimate of the IMU latency (2.35 ms) is very useful in order to validate our approach. The total latency that we should estimate incorporates the IMU latency, transmission time, buffering time, and acquisition software induced latency. IMU and LiDAR data has been acquired under the Qinsy software, which time-tags the LiDAR data by using the PPS information. The PC communication board configuration have been carefully checked. Indeed, as mentioned in (QPS, 2007), latency due to bad configuration of the reception buffer mode may significantly impact the hardware latency, depending on the communication board used and the size of the buffer FIFO stack.

We chose to first disable the buffer FIFO stack in order to minimize latency, and then, we performed tests with another value of the FIFO stack, in order to check the accuracy of our estimate, as the induced latency due to this stack size can be easily estimated.

3.3. Description of the experimental procedure

Fig. 3 shows the LiDAR–IMU mechanical installation on the rotating table. A 20 cm diameter spherical target was placed at 1.5 m away from the LiDAR optical center. It should be noticed that a relatively short distance to the target is not a limiting factor. Indeed, the target position shift induced by the yaw rotation of the rotating table increases with the distance to the target (denoted by $\mathbf{x}_n'$ in Eq. (4)), but the larger the LiDAR range is, the fewer LiDAR echoes from the spherical target are. A reasonable choice of the target range should be based on ranging precision considerations, in order to get a good estimate of the spherical target center. This choice can be balanced by a relatively high value of ω_D (the angular velocity) which amplifies the target center shift.

Fig. 3. The system used for latency estimation: a common bracket is used in order to assemble the IMU and the LiDAR. The bracket is mounted on the rotating table. A precision sphere located at 1.5 m away from the LiDAR optical center is used as a target.

The procedure we used consists in scanning the target clockwise and counter clockwise, in order to increase the angular velocity difference, and therefore the latency estimation resolution. We use the two angular velocities $(0, 0, \omega_D)^T$ and $(0, 0, -\omega_D)^T$ in the latency estimate given by Eq. (4). We mention that this equation is relevant in 3D, since the rotational motion applied to the LiDAR and the IMU may be not a pure rotation around the IMU vertical axis, in case of misalignment between the rotating table and the IMU frame.

4. Experimental results

We present experimental results obtained at various angular speeds of the IMU–LiDAR system, which illustrate the accuracy and the precision of our latency estimation method. Several angular velocities (denoted by ω_{Di} and $-\omega_{Di}$) have been used, from 2°/s to 18°/s. After 30 alternate scans, LiDAR data (geolocated by the software Qinsy thanks to the attitude data returned by the IMU) were split in two separate datasets: one for the angular velocity ω_{Di}, and another one for velocity $-\omega_{Di}$. From these two datasets, an estimation of the sphere center was performed thanks to the iterative least square method described in Section 2.3. Then, the latency dt was estimated thanks to Eq. (4).

In Fig. 4, one can check that the amount of collected data through 15 LiDAR scans for each angular velocity (around 30,000 points), enables to finely estimate the spherical target center. The spherical target center position standard deviation (STD) we obtained with a yaw velocity of 6°/s was 0.04 mm (see Table 2). One should notice that under these conditions, the latency precision is about 0.25 ms which is the precision of the latency estimate given by the IMU manufacturer.

4.1. Latency estimation for various angular velocities

A series of six runs of 30 alternate scans has been performed at several angular speeds, in order to study the influence of the scanning speed on the latency estimation process. Indeed, at high angular speeds, the sphere center shift is high, but the number of LiDAR echoes from the sphere is low. Therefore, the latency resolution should be higher, but the sphere center estimation may be less accurate. In fact, one can check in Table 2 that the sphere center STD growth ratio with respect to the angular velocity is lower that one, which means that the faster the rotational motion is, the bet-

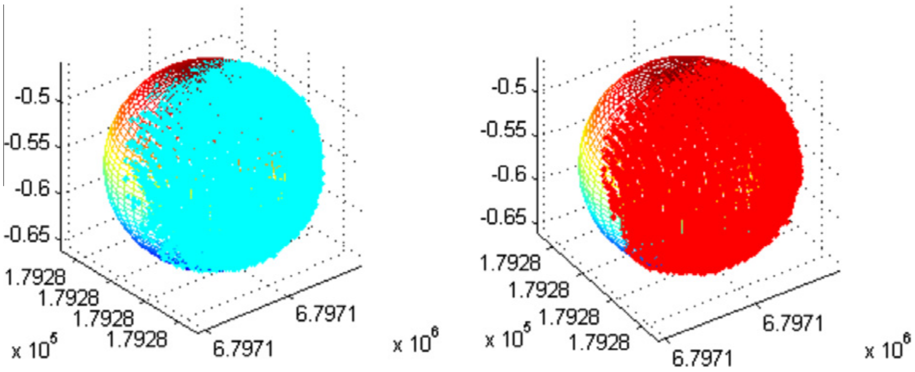

Fig. 4. The spherical target viewed at −6°/s (left), and +6°/s (right). One can check that both spheres are well sampled and fitted.

Table 2
Latency estimates for various angular speeds. Latency standard deviation decreases with the angular speed value. In these results, the OCTANS4 IMU time-tags in taking into account its known latency of 2.35 ms. So the total latency estimate is 4.21 ms.

ω_D (°/s)	2	4	6	10	14	18
Latency estimate (ms)	1.31	1.47	1.56	1.87	1.86	1.86
Sphere center STD (10^{-5} m)	2.33	3.12	4.04	5.22	6.14	7.03
Latency STD (ms)	0.49	0.33	0.25	0.19	0.12	0.09

ter the latency estimate will be. Indeed, one can check that estimated latency values stabilize around 1.86 ms for angular velocities greater than 10°/s. The minimum latency STD is obtained with an angular velocity of 18°/s, and is 0.09 ms, which is acceptable for most LiDAR applications.

4.2. Influence of the FIFO stack size

We present here some results that shows the influence of the acquisition PC buffer size on the latency value. We performed these tests with another acquisition PC, for which it appears that the total latency estimation is 2.82 ms instead of 1.86 ms with the previous PC configuration. In order to check the influence of the serial link buffer size, we did some trials in setting its size to 14 bytes. The theoretical added latency due to the presence of this buffer is 1.22 ms. Thus the total latency should be close to 4.04 ms. Our estimate of the total latency is 3.97 ms, which represents an error of 0.07 ms and is consistent with the latency STD presented in Table 2. The latency induced by the buffer size is clearly identified, and this result shows that the knowledge of the IMU latency is not by itself sufficient for setting the IMU–LiDAR latency. From this result, we conclude that the resolution of our latency estimation method is compatible with most of mobile LiDAR application.

4.3. Results from field testing

In order to show the error magnitude that can be reached in case we ignore the total latency of an IMU–LiDAR system, we installed our rotating table outside, and we scanned a parking lot. The LiDAR–IMU bracket was mounted on the rotating table (used in 3D motion), moving at constant yaw velocity (1°/s), while rolling with a sinusoidal motion from −6° to 6° at a frequency of 1 Hz. The LiDAR scanned a sector of 20°, with maximum range of 25 m. This experiment was performed without positioning, in order to cancel out possible errors due to GPS.

First, we processed the LiDAR data in taking into account the IMU total latency that we estimated by our method (4.21 ms). This dataset was considered as the reference data. Then, we set the OCTANS4 manufacturer's latency value of 2.35 ms (ignoring the total latency) and processed again the data. With such a latency error of 1.86 ms, the maximum elevation error at 25 m was 1.4 cm. This result is consistent with the a priori error Table 1. It clearly shows that knowing the total latency may significantly contribute to the minimization of the total propagated error budget.

5. Conclusion

In this paper, we derived a simple method for the determination of the total latency between an IMU and a mobile LiDAR. We have seen that the total latency can be estimated without positioning, by scanning a reference target at several rotational speeds. According to our results, the accuracy of our latency estimate is lower than the uncertainty given by the manufacturer. We also shown that the total latency can be estimated by an experimental method taking into account the global parametrization of a realistic survey system. It is also important to mention that the total latency is the one that should be considered in order to shift the IMU data used for geolocating mobile LiDAR point clouds. Indeed, this latency includes the buffer induced latency, and the residual latency, essentially due to the acquisition software. Therefore LiDAR surveys methodologies should incorporate this total latency, in order to improve mobile LiDAR survey data quality.

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