Estimation of Synchronization Errors of Kinematic Mapping Systems

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Abstract

Kinematic LIDAR (Light Detection and Ranging) is now a widely used technology in land and hydrographic surveying. A limiting factor in kinematic LIDAR data accuracy is calibration parameters, for both boresight angles and inertial motion unit orientation latency. In this paper, we investigate a method allowing to assess the total latency between the LIDAR attitude angles and the LIDAR ranging information, due to inertial motion unit delays, and acquisition system induced latency. Our method does not require any positioning device, therefore it is independent of unmodelled errors which may corrupt geolocalized data used to calibrate latency. As a consequence, our method can estimate any surveying acquisition and inertial motion unit latency, as well as the latency induced by data buffering with the acquisition system. We show by experimental results, that our latency estimation resolution is compatible with any type of LIDAR or SONAR survey application.

Keywords: LIDAR, Inertial motion unit, time stamping, Latency, Calibration

Introduction

In the framework of surveying, kinematic LIDAR (Light Detection And Ranging) are commonly used in order to accurately model topographic information. These ranging systems return detection points in the sensor frame which are geolocalized thanks to orientation angles given by an inertial motion unit (IMU) and GPS information. In order to get coherent and accurate datasets, all sources of systematic errors have to be minimized. Among these systematic errors, the most sensitive ones are misalignment errors (boresight angles between the ranging sensor and the motion sensor), and timing errors. Timing errors come from the desynchronization of physical measurements between the sensors processing unit clocks, and the acquisition system clock. Both position and orientation measurement of ranging sensors may be affected by timing errors, leading to undesirable systematic errors in the data geolocalization.
Most of the literature aiming at improving data quality from airborne LIDAR, ground based or vessel mounted LIDAR focus on boresight angles calibration \cite{11, 5, 7, 3, 1, 15}. We can distinguish two classes of methods: target methods, which use artificial landmarks and check the spatial coherence of the geolocalised data from several points of view. Other methods use surface matching (i.e. digital elevation models matching) in order to detect and compensate for misalignment angles. In most of these works, latency between the orientation data from the IMU and detection point from the ranging system is not taken into account. However, this latency plays a crucial role in the georeferenced data quality. In \cite{14} synchronization issues, as well as boresight angle lever-arms determination are identified as sources of errors. For meeting high-quality standards in the airborne LIDAR framework, \cite{14} gives a maximum latency accuracy of 0.1ms between orientation and ranging data.

As mentioned in \cite{6}, elimination of the systematic errors from survey data can be done by two different approaches: The first lies in analyzing each component of a survey system (ranging system, inertial motion unit, positioning system, acquisition software), and characterizing individual errors from all sensors.

Another approach is to identify systematic errors from geolocalized data, which happens to be corrupted by a coupled and non linear combination of sensors errors. These methods aim at retrieving systematic errors by inversion methods. However, errors may be highly dependent on the orientation dynamics of the platform. If it is actually the case, non corrected time synchronization errors may contribute significantly to the unobservability of systematic errors.

This paper will focus on the timing error between the inertial motion unit and a ranging system, which can be a kinematic LIDAR, or a multibeam echosounder. In some cases, this error can be minimized if the motion sensor is equipped with a PPS input, but as inertial motion units outputs are produced by time integration and estimation of accelerometer and gyros data, the physical measurement may be not fully synchronized with the output data. In practice, this timing error is ignored, or set to an arbitrary value, advised by the inertial motion unit manufacturer. However, it is quite common to see latency errors in survey datasets, which produces distortions on outerbeams outputs, as shown in figure (1) which shows a multibeam echosounder data set corrupted by an orientation latency.

![Figure 1: Example of latency effect on multibeam echosounder data. The phase difference between the actual roll value and the sensed roll value produces wavelets, which height is amplified by the beam lever arm: no distortion is seen at the Nadir, but high distortion can be observed on outerbeams data.](Image)

Despite the fact that timing error is a major problem for calibrating properly a survey system, a quite small amount of work has been devoted to its determination. In \cite{4} the author analyses...
the possible source of ondulations of outerbeams data for multibeam echosounders, including time delays between motion sensors and multibeam systems. This effect can be enhanced by the fact that for deep water surveys, the time of flight of the acoustic return may be very different from outerbeams and from nadir beams. This implies that time stamping of the attitude value for a complete swath is not a unique time stamp but would depend on the time of arrival of the acoustic return. An analysis of wavelet presence, correlated with roll value of the motion is presented in order to help the hydrographer to identify a possible time delay problem in its datasets.

Some other approaches, implemented in hydrographic acquisition softwares propose to the user to correlate the outbeams of the ranging device to the roll and/or pitch time serie. By determining a phase error between the two signals, one can estimate the timing error between the motion sensor and the ranging sensor. The main drawback of this approach lies in the fact that the survey must be conducted over a flat terrain, in order to eliminate the possible effect of terrain ondulations that could be interpreted as timing errors. The other drawback is the accuracy of the latency estimation is relatively poor.

1. Timing errors estimation

1.1. Orientation vs ranging sensor latency

Since the introduction of timestamping by using the Pulse Per Second information from GPS receivers [10], timing error are usually considered as negligible. Indeed, most of GPS receivers deliver a PPS signal which can be used in order to synchronize both acquisition system computer and ranging system (most commercially available equipments are fitted with a PPS input and timestamp their data internally). However, even an accurate time stamping cannot cancel out the latency due to a inertial motion unit. Indeed, these kind of systems output information provided by the integration and filtering of dynamical information.

The type of timing error on which we will focus, lies in the existence of a delay between the physical orientation (i.e pitch, yaw and roll) measurement and the timestamp of detection points from the ranging device (MBES or kinematic LIDAR). This timing error has a quite important effect due to the fact that the survey plateform may have a quite fast orientation dynamics, and that the detection beam have a quite high lever arm. It should be mentionned that no well established methodology has been defined for estimating the orientation vs. ranging latency. It is quite a common practice in the survey community to rely on IMU manufacturers latency data, which is the fixed value from physical measurement time to IMU output time. In most commercial acquisition softwares, latency is oftenly considered as a constant value, which should be entered by the user.

Our approach focus on the residual latency estimation of a complete survey system, including an IMU, a ranging system, a positioning device, and an acquisition computer. Instead of considering that the IMU latency value is sufficient to charaterize the complete sensor suite and acquisition system time delays, we first identify sources of time delays, and try to estimate the total latency of the system. Main sources of latency lies in :

- IMU time delay between physical measurement and data output
- transmission delay between the IMU and the acquisition computer (significant is a serial link is used)
Table 1: Example of latency induced errors, in a typical survey situation: A kinematic LIDAR scanning a beach profile of 10 degrees at a range of 50m, with a roll velocity of 10 degrees/sec (case of the horizontal beam only)

<table>
<thead>
<tr>
<th>Latency (ms)</th>
<th>0.1</th>
<th>1</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>vertical error(cm)</td>
<td>0.09</td>
<td>0.9</td>
<td>4.4</td>
<td>8.8</td>
<td>13.3</td>
<td>17.8</td>
<td>22.4</td>
</tr>
<tr>
<td>horizontal error(cm)</td>
<td>0.5</td>
<td>4.9</td>
<td>24.9</td>
<td>49.9</td>
<td>75.3</td>
<td>100.9</td>
<td>126.8</td>
</tr>
</tbody>
</table>

- size of the acquisition computer buffers (size of the FIFO stack)
- acquisition software time stamping management
- acquisition software orientation, ranging, position data assembling method for final geolocalization

Among all sources of total latency, some can be checked, some other are not controllable by the user, as for instance, latency induced by the software time stamping management.

Another fact is that total latency estimation from field data analysis is relatively unreliable, since the ranging data spatial resolution is generally not compatible with the required accuracy and precision required for latency estimation. In table (1) we give an example of latency induced errors produced in typical ground based lidar, or vessel mounted lidar survey conditions.

1.2. Principle of the method

In this section, we present the principle of a method that can be used for estimating the motion sensor latency with respect to a ranging system, operated by an acquisition software. Latency between a ranging system and the inertial motion unit can be determined by applying a controlled rotational motion to the ranging system and by estimating the position shift of a spherical target due to a relatively fast 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 motion sensor (I) frame with respect to the navigation frame (n). It is to be mentioned that the orientation bias between the motion sensor frame (I) and the LIDAR (S) is not required at this stage, and will be investigated later.
- Scanlines (e.g. set of detection points) from the LIDAR.
- Angular velocities of the LIDAR-IMU system

Angular velocities are provided from the IMU, but they 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 motion\(^1\). In the following, we suppose that angular velocities are available with very high accuracy.

\(^1\)This 3D simulator, a TRI-30 table from IX-motion is used for motion sensor calibration checks, and investigation of motion sensor errors.
Let us denote by $n = (N, E, D)$ the navigation frame with origin at the motion simulator center of rotation, by $bl$ the kinematic LIDAR body frame, and by $bS$ the inertial motion unit frame. Let us first observe that latency estimation is not affect 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 $x_f = O M_f$ in a frame $f$. In the navigation frame, we can write for a static (or quasi static) kinematic LIDAR detection point

$$x_n = R_{bS}^n R_{bl}^{bS} x_S$$

where $R_{bS}^n$ and $R_{bl}^{bS}$ are direction cosine matrix from frame $bl$ to $n$ and $bS$ to $bl$.

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

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

in assuming that at time $t$, the direction cosine matrix is shifted in time of the latency $dt$. We deduce that

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

Assuming that the rotational motion is at constant angular velocity, we have

$$R_{bl}^b (t - dt) = R_{bl}^b - dt \dot{R}_{bl}^b = (Id + dt \Omega_{bl/n}^b) R_{bl}^b$$

thus, we deduce that

$$x_n = R_{bl}^b (Id + dt \Omega_{bl/n}^b) R_{bl}^b x'_n = x'_n + dt R_{bl}^b \Omega_{bl/n}^b R_{bl}^b x'_n = x'_n + dt \Omega_n^b R_{bl}^b x'_n$$

Let us denote by $\Delta = x - x'$, the shift of a detection point due to the latency $dt$.

$$\Delta_n = dt \Omega_n^b x'_n = dt \omega_n^{bl/n} \wedge x'_n$$

which express nothing else than the fact that $M'$ has been shifted from $M$ at the angular velocity $\omega_n^{bl/n}$ with lever arm $x_n$. Note that equation (1) provides 3 estimates of the latency $dt$, that can be averaged in order to get its least-square estimate.

For practical estimation, equation (1) can be rewritten in taking into accounts the angular velocity of the motion sensor body frame ($bl$) with respect to the navigation frame, coordinatized in the inertial motion sensor body frame ($bl$):

$$\Delta_n = dt R_{bl}^b \omega_n^{bl/n} \wedge x'_n$$

The displacement vector $\Delta_n$ due to the latency and the vector $x'_n$ can be both computed by data postprocessing. Note that the angular velocity $\omega_n^{bl/n}$ should be determined independently of the motion sensor, or to select data only when $\omega_n^{bl/n}$ is constant, in order to cancel out the latency effect. By taking the norm of equation (2), we have

$$dt = \frac{\| M'M_n \|}{\| \omega_n^{bl/n} \wedge O M'_n \|}$$

for which the knowledge of $R_{bl}^{bI}$ is not required.
1.3. Estimation of a sphere center reference point

The idea is to apply different rotational motion to a LIDAR coupled with an inertial motion unit, while scanning a given target. The rotation motion will give to the beam detection point two different radial motions \( v_i = R\omega_i \), which will cause a target position variation due to latency. Let’s emphasize that it is not possible to accurately estimate the latency in scanning a target containing sharp edges (a road sign for instance) at different beam detection point speeds 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 equation (2) proves that the maximum latency uncertainty is actually \( \delta T \).

Therefore, instead of detecting a latency by using a target containing an edge, it seems better to use a target for which a reference point can be easily computed from scanlines subject to latency induced position shift. A good candidate for such target is the sphere, which center can be computed from any set of surface detection point \[8\]. Indeed, by using an iterative least square fitting method (the so-called variation of coordinate method \[2\]), one can quite easily estimate the sphere center position from detection points, through the following 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 detection points 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

\[
r(x', y', z') = r(x, y, z) + \left( \frac{\partial r}{\partial x}(x, y, z) \frac{\partial r}{\partial y}(x, y, z) \frac{\partial r}{\partial z}(x, y, z) \right) \begin{pmatrix} x' - x \\ y' - y \\ z' - z \end{pmatrix}
\]

Starting from a barycentric estimate \((x_0, y_0, z_0)\) of the sphere center, the following iterative least square algorithm enables, whenever it converges, to accurately estimate the sphere center: From the current estimate \((x_0, y_0, z_0)\), we compute the new estimate \((x_1, y_1, z_1)\) by solving the following \((N, 3)\) least square system, \(N\) being the number of the sphere measurement points:

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

where \(X_i = (x_i, y_i, z_i)\)

2. Experimental set-up

2.1. Mobilized equipment

In order to test this approach, we used a Leica HDS6200 laser scanner, coupled with an IxSea OCTANS4 attitude sensor.

The OCTANS 4 is a strapdown attitude sensor which is widely used in the hydrographic surveying community. It is equipped with three fiber optic gyroscopes (0.05 deg/hour/ bias stability) and three accelerometers (with accuracy of 1000 \(\mu\)g) and outputs pitch, roll, heading, and heave motion estimates. Orientation is 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 deg RMS for 68% of the data, and the heading accuracy is 0.1 deg× secant
The latency between the physical measurement of the unit and its output on the serial link lies in the interval [2.4, 2.6] ms.

The LeicaHDS6200 is a TLS that can be also used in 2D kinematic mode. Accuracy of a single measurement at low range (less than 25m) is 5mm on position, 2mm 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 ranging 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 motion simulator. This simulator enables to very accurately control the rotational motion of the laser scanner and the IMU. Its angle measurement precision is 0.005 degrees for the three axis. The accuracy of angular velocity regulation is about 0.01 deg/s. The experimental set-up is shown in picture (2).

2.2. Tests Methodology

It is to be mentionned that outdoor calibration suffers from inaccuracy due to positioning issues. Indeed, either in target or surface calibration procedures, the positioning errors may be significant at the level of accuracy that is to be reached for latency estimation. Our objective was to estimate the latency of a complete data acquisition system (2D kinematic laser scanner, IMU, acquisition PC and operating system, 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 0.02 mm. This objective is clearly not compatible with GPS positioning errors, even in PPK mode.

Following [5] who mentions the presence of unmodeled positioning errors in calibration datasets, we designed an indoor test procedure, which works without positioning. To do so, we used the following methodology:

- The IMU/Laser scanner common bracket was fixed on the 3D simulator horizontally, and the simulator was levelled with an accuracy of less than 15 arcsec.
- The rotational motion was a pure yaw velocity (see figure (2)): \( \omega_{bI/n} = (0, 0, \omega_D) \)
- The Laser scanner optical center was fixed on the vertical of the 3D simulator center of rotation with an accuracy of less than 0.5mm, in order to cancel out any translational motion due to the yaw rotation.
- The angular velocity \( \omega_D \) was not measured from the motion sensor itself, but from the 3D motion simulator.

Let us now describe the acquisition set-up that has been used for our tests. The Octans4 attitude output was connected to the acquisition PC via a serial link at 115200 bauds. The PPS synchronization from the GPS was not used by the Octans4 IMU. As a consequence, the attitude data timestamping was performed by the acquisition computer, at the data time of arrival via the serial link. The PPS signal was shared by the acquisition PC and the laser scanner, so we can consider that these two devices are synchronized on the same clock. It should be mentionned that even if a PPS input would have been used by the Octans IMU, it would not cancel out the orientation latency with the laser scanner, but only cancel out the acquisition PC and transmission time induced latency.

Having an estimate of the physical latency of the IMU under study is very useful in order to validate our approach. Both orientation and scanner data were acquired by the commercial
software Qinsy, which time stamps the Leica scanner data, on the PPS time base. It should be mentioned that the configuration of the PC communication board have to be carefully checked. Indeed, as mentioned in [12], internal 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.

In our case, we chose to first disable the buffer FIFO stack in order to reduce the latency as close as possible to the IXsea manufacturer latency estimate. In a second stage, we performed tests with two different values of the FIFO stack, in order to check the coherence of our estimate, as the induced latency due to this stack size can be easily computed.

2.3. Description of the experimental procedure

Figure (3) shows the mechanical mounting of the IMU and laser scanner on the motion simulator. 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 as short distance to the target is not a limiting factor in our approach. Indeed, an increase of the distance to the target ($\overrightarrow{OM_n}$ in equation (3)) 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 centers 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), which implies a relatively short range. This choice can be balanced by a relatively high value of $\omega_D$ (the angular velocity) which will produce a relatively high shift of the target center.

The procedure we used consists in scanning the target clock-wise and counter clock-wise, in order to increase the angular velocity difference, without decreasing the sampling rate of the sphere which could alterate the quality of the center estimation. In fact, we use two angular velocities $\omega_D$ and $-\omega_D$. In this situation, the estimate (3) rewrites as:

$$dt = \frac{\|\overrightarrow{M'M_n}\|}{\|2\omega_D \wedge \overrightarrow{OM_n}\|}$$

As this equation does not depend on $R_{bI}^l$, we deduce that even in the case of boresight angles between the IMU and laser scanner, the latency estimation will not be affected. This means that latency calibration can be performed prior to any boresight angle calibration.
3. Experimental results

In this section, we show that we can estimate the latency of a global acquisition system with a quite high accuracy and precision.

In order to estimate the latency $dt$, the simulator was tasked to rotate around its vertical axis along a 20 degrees sector at $\omega_{D1} = -7\text{deg/sec}$ and $\omega_{D2} = 7 \text{deg/sec}$. The angular velocity was controlled very accurately by the motion simulator with an uncertainty of 0.01 deg/sec. After a serie of 30 alternate scans, laser scanner data (georeferenced by the acquisition software qinsy, based on the orientation value given by the IMU) were merged in two separate datasets, one for angular velocity $\omega_{D1}$, and another one for velocity $\omega_{D1}$.

For these two datasets, an estimation of the sphere center was performed thanks to the iterative least square method described in section 1.3. Then, using equation (5), were $\omega_{D} = 7 \text{deg/sec} (\text{assumed to be constant thanks to the motion simulation performances}), dt$ can be estimated.

The following table summerizes the results that we obtained in three different configuration, that we were able to compare with reference data.

<table>
<thead>
<tr>
<th>FIFO buffer size</th>
<th>Sphere center SD</th>
<th>Total latency</th>
<th>IMU latency</th>
<th>Latency due to buffer</th>
<th>Residual latency</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.04 mm</td>
<td>2.8 ms</td>
<td>2.5 ms</td>
<td>0</td>
<td>0.3 ms</td>
</tr>
<tr>
<td>8 bytes</td>
<td>0.04 mm</td>
<td>3.4 ms</td>
<td>2.5 ms</td>
<td>0.69 ms</td>
<td>0.21 ms</td>
</tr>
<tr>
<td>14 bytes</td>
<td>0.04 mm</td>
<td>4.0 ms</td>
<td>2.5 ms</td>
<td>1.21 ms</td>
<td>0.29 ms</td>
</tr>
</tbody>
</table>
From this table we see that the total latency is well estimated, and that the resolution of our method is such that we are able to estimate the acquisition latency with a quite good stability. The latency induced by the buffer size is clearly identified, and this table shows that the knowledge of the IMU latency is not sufficient at all to characterize the total latency of the system.

Figure 4: A view of the spheres viewed at -7 deg/sec (left), and +7 deg/sec (right). One can check that both spheres are well sampled and fitted.

In figure (4), we can see that because of the large amount of data collected through 15 scans for each angular velocity (around 30,000 points), both spheres are well fitted, which is confirmed by the very low value of the center estimate standard deviation (0.04 mm).

4. Conclusion

In this paper, we derived a method for the determination of the total latency of an inertial motion unit (including the time delay induced by the acquisition software) and a kinematic 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 the latency estimation is less than 0.1 ms, which is within the range of uncertainty given by the manufacturer. It is also important to mention that the total latency is the one that should be considered in order to shift the orientation data for georeferencing the kinematic LIDAR detection points. Indeed, this latency includes the buffer induced latency, and the residual latency, essentially due to the acquisition software. Therefore LIDAR (and SONAR) surveys methodology should incorporate this total latency, in order to improve their data quality. We also shown that the total latency, which is a very sensitive information for setting-up a survey system, can be estimated by an experimental method taking into account the global parametrization of a realistic survey system.

References


