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Calibration of Low Cost Inertial Measurement Units without Laboratory Equipment

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Abstract

The popularization of MEMS sensors has enabled the development of low-cost data acquisition technologies. Among the most varied types of sensors, such as accelerometers, microphones and barometers, one of the devices that has stood out is the Inertial Measurement Unit (IMU), which commonly combines accelerometers and gyroscopes in a single package. This makes it possible for the IMU to measure the dynamic behavior of rigid bodies through sensor fusion. One of the main obstacles of these low-cost sensors is an adequate calibration, since the mass production process makes this procedure unfeasible in the production chain. Several authors have committed themselves to proposing a methodology for sensor calibration, although most of these studies still make use of some specific bench-top equipment, such as a rotary table or a 6-axis controlled platform. The present work proposes the elaboration of a static/quasi-static calibration procedure using only a simple template part, which can be manufactured through 3D printing. For this, the values of average acceleration measured in static condition are compared to the acceleration of gravity for the two directions and each direction that the IMU is able to measure. In the gyroscope calibration process, the sensor, coupled to the template, is subjected to a predetermined rotation by the template geometry. Then, the angular velocity values obtained from the MEMS gyroscope are cumulatively integrated and compared to the value of the rotation applied to each sensor axis.

Keywords: Calibration; MEMS; IMU.

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1. INTRODUCTION

The increasing popularization of MEMS sensors has enabled the development of low-cost data acquisition technologies. Among the most varied types of sensors, such as accelerometers, microphones and barometers, one of the devices that has stood out is the Inertial Measurement Unit (IMU), which commonly combines accelerometers and gyroscopes in a single package [1]. One of the essential processes for using IMU for a measurement system is calibration, unlike when used for simpler applications such as screen orientation on smartphones. A well-executed calibration allows the elimination of systematic errors, which does not occur from the factory with low-cost sensors for economic reasons [2].

Several authors, as well as Fong, have developed methodologies for low-cost IMUs calibration. Vargas-Valencia [3] performed the calibration of sensors to capture human gait, while Zhao [4] proposed a continuous self-calibration, assisted by ultrasonic positioning sensors and magnetometers. In an attempt to keep the cost of using the systems low, we have Skog [5], Lv [6] and Qureshi [7] using sensor positioning relative to gravity and a controlled rotary table, while Tedaldi [8] used cameras to calibrate the gyros.

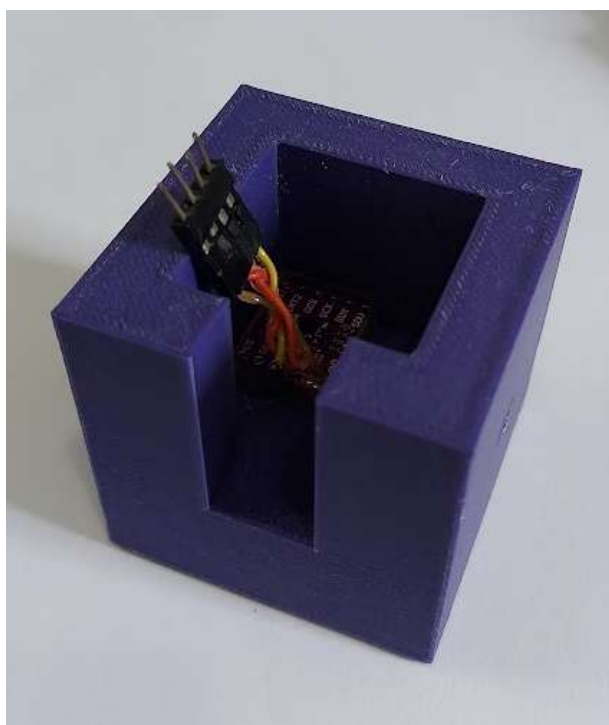


Figure 1: Calibration Cube

In this work, the calibration procedure was performed using a template, seen in Figure 1, manufactured through 3D printing, thus allowing a calibration of the accelerometers with the acceleration of gravity as a reference and the calibration of the gyros through from the integration of the angular velocities obtained during a known rotation of the template.

To start the sensor calibration routine, it is essential to determine the error model to be used, aiming to correct the scale, trend and non-orthogonality of the values collected directly from the IMUs [9].

The present work proposes the elaboration of a static/quasi-static calibration procedure using only a simple template part, which can be manufactured through 3D additive manufacturing. For this, the values of average acceleration measured in static condition are compared to the acceleration of gravity for the two directions and each direction that the IMU is able to measure. In the gyroscope calibration process, the sensor, coupled to the template, is subjected to a predetermined rotation by the template geometry. Then, the angular velocity values obtained from the MEMS gyroscope are cumulatively integrated and compared to the value of the rotation applied to each sensor axis.

2. CALIBRATION OF INERTIAL MEASUREMENT UNITS

The calibration of an IMU is a procedure that consists of the determination of the parameters that describe the sensitivity of the sensors and their response to the environment. The calibration of an IMU is generally performed through a static calibration, in which the sensor is placed in static conditions and the bias of the sensors is measured. The calibration of the accelerometer is generally performed through the measurement of the acceleration of gravity in the three directions of the sensor. For this, the sensor is placed in static conditions and the values of the acceleration for each direction are averaged.

The calibration of the gyroscope is generally performed through the estimation of the bias of the sensor. For this, the sensor is placed in static conditions and the average of the angular velocity

values measured by the sensor is considered.

3. CALIBRATION PROCEDURE

The calibration procedure proposed in this work consists of the static/quasi-static calibration of the IMU. For this, the values of the acceleration of gravity in each direction of the sensor are measured, and then the values of the gyroscope are cumulatively integrated and compared to the values of the predetermined rotations.

3.1 Accelerometer Calibration

The calibration of the accelerometer is performed through the measurement of the acceleration of gravity in the direction of the axis of the sensor. For this, the sensor is placed in static conditions and the values of the acceleration measured by the sensor are averaged.

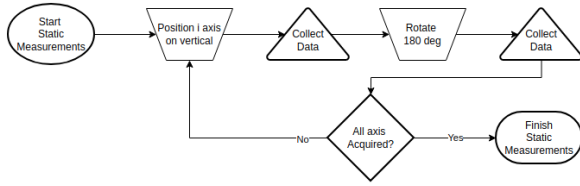


Figure 2: Flowchart of Accelerometer Calibration

The calibration procedure proposed in this work consists of the measurement of the acceleration of gravity in the two directions of the sensor, as shown in Figure 3.

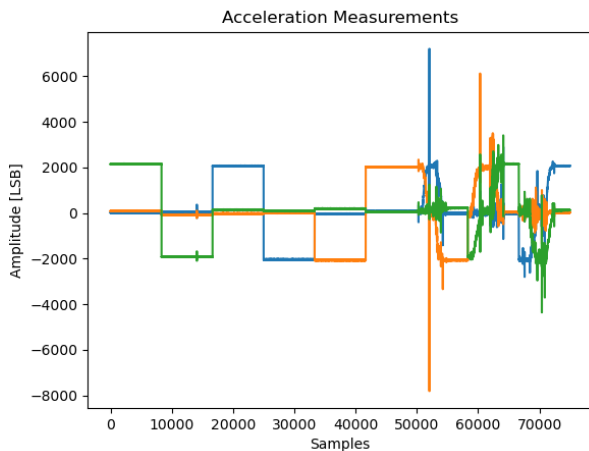


Figure 3: Raw measurements of the Accelerometer

The measured acceleration values are then compared to the acceleration of gravity in each di-

rection. The acceleration of gravity is defined as:

$${}^a b_i = \frac{\overline{u_i} \uparrow + \overline{u_i} \downarrow}{2}, i = x, y, z \quad (1)$$

Equation 2 shows the mathematical model used to represent the sensor, which takes into account for measurements obtained $u[LSB]$ the trend correction $b[LSB]$, the sensitivity $K[un./LSB]$ and the orthogonality correction $S[un./un.]$, thus obtaining the expected value $\mu[un.]$ [10].

$$\mu = M(u - b) = S \cdot K(u - b) \quad (2)$$

where

$$\mu = \begin{Bmatrix} \mu_x \\ \mu_y \\ \mu_z \end{Bmatrix}, S = \begin{bmatrix} 1 & s_{xy} & s_{xz} \\ s_{yx} & 1 & s_{yz} \\ s_{zx} & s_{zy} & 1 \end{bmatrix},$$

$$K = \begin{bmatrix} k_x & 0 & 0 \\ 0 & k_y & 0 \\ 0 & 0 & k_z \end{bmatrix}, u = \begin{Bmatrix} u_x \\ u_y \\ u_z \end{Bmatrix}, b = \begin{Bmatrix} b_x \\ b_y \\ b_z \end{Bmatrix}$$

Once the bias values are subtracted, a single transformation matrix ${}^a M = {}^a S \cdot {}^a K$ can be obtained relating the values obtained for the 6 calibration positions with their respective ideal values, the value of gravity itself.

$$[{}^a \mu] = [{}^a M] \cdot [{}^a u]$$

$$[{}^a M] = [{}^a \mu] \cdot [{}^a u]^\dagger \quad (3)$$

being,

$$[{}^a \mu] = \begin{bmatrix} g & -g & 0 & 0 & 0 & 0 \\ 0 & 0 & g & -g & 0 & 0 \\ 0 & 0 & 0 & 0 & g & -g \end{bmatrix} \quad (4)$$

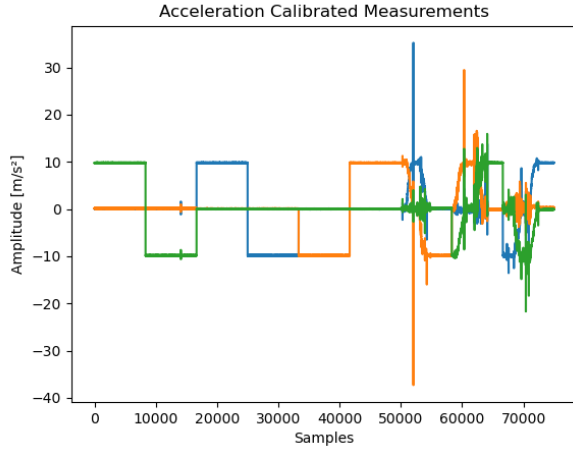


Figure 4: Calibrated Accelerometer Measurements

$$[{}^a u] = \begin{bmatrix} \overline{u_x} \uparrow & \overline{u_x} \downarrow & \overline{u_x} & \overline{u_x} & \overline{u_x} & \overline{u_x} \\ \overline{u_y} & \overline{u_y} & \overline{u_y} \uparrow & \overline{u_y} \downarrow & \overline{u_y} & \overline{u_y} \\ \overline{u_z} & \overline{u_z} & \overline{u_z} & \overline{u_z} & \overline{u_z} \uparrow & \overline{u_z} \downarrow \end{bmatrix} - \begin{Bmatrix} {}^a b_x \\ {}^a b_y \\ {}^a b_z \end{Bmatrix} \quad (5)$$

The calibrated values resulting from plugging the Equation 2 with the calibration parameters, $[{}^a M]$ and ${}^a b$, and the raw measurements from the accelerometer are shown in Figure 4.

3.2 Gyroscope Calibration

For gyroscope calibration, the proposed process is similar, however, due to the difficulty of implying a controlled angular velocity to the sensor and known as a reference for calibration without advanced instruments such as an instrumented and calibrated rotary table, some more steps are necessary.

Figure 5 shows the process involved in measuring rotation during the dynamic step for gyroscope calibration.

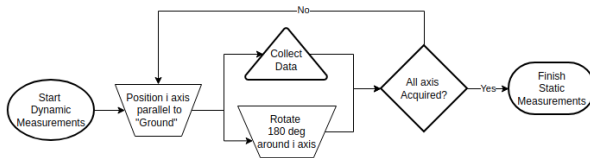


Figure 5: Flowchart of Gyroscope Calibration

First, the trend values can be obtained during the static measurements performed for the accelerometers by averaging the recorded values, see Figure 6.

$$\{{}^g b\} = \begin{Bmatrix} {}^g b_x \\ {}^g b_y \\ {}^g b_z \end{Bmatrix} = \begin{Bmatrix} \overline{{}^g u_x} \\ \overline{{}^g u_y} \\ \overline{{}^g u_z} \end{Bmatrix} \quad (6)$$

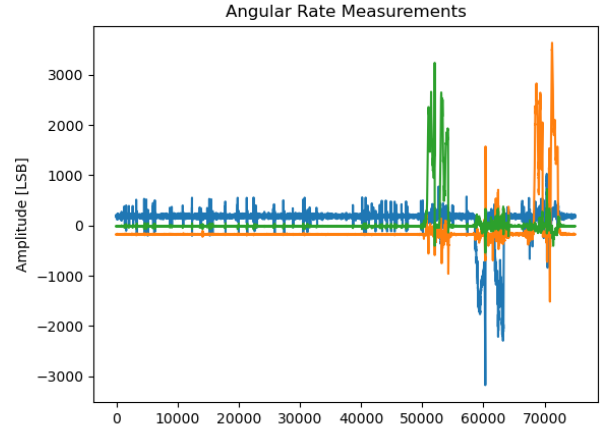


Figure 6: Raw Measurements of the Gyroscope

It is therefore essential to integrate the values obtained, obtaining the angular displacement for a given time interval $[t_i, t_{i+1}]$, during which a given rotation will be manually applied to the calibration cube, $\pi[rad]$, for example.

$$\{{}^s \theta\} = \begin{Bmatrix} {}^s \theta_x \\ {}^s \theta_y \\ {}^s \theta_z \end{Bmatrix} = \int_{t_i}^{t_{i+1}} \left(\begin{Bmatrix} {}^g u_x \\ {}^g u_y \\ {}^g u_z \end{Bmatrix} - \begin{Bmatrix} {}^g b_x \\ {}^g b_y \\ {}^g b_z \end{Bmatrix} \right) dt \quad (7)$$

After performing 3 rotations, one for each axis, it is then possible to set up a matrix equality similar to the one used in Equation 3, obtaining the Matrix ${}^g M$ which together with ${}^g b$ allows the conversion of the digital values arising from data acquisition in sensors for angular velocity values.

$$[{}^o \theta] = [{}^g M] \cdot [{}^s \theta]$$

$$[{}^g M] = [{}^o \theta] \cdot [{}^s \theta]^\dagger \quad (8)$$

Being,

$$[{}^o \theta] = \begin{bmatrix} \pi & 0 & 0 \\ 0 & \pi & 0 \\ 0 & 0 & \pi \end{bmatrix} \quad (9)$$

$$[{}^s \theta] = \begin{bmatrix} {}^s \theta_x \curvearrowright & {}^s \theta_x & {}^s \theta_x \\ {}^s \theta_y & {}^s \theta_y \curvearrowright & {}^s \theta_y \\ {}^s \theta_z & {}^s \theta_z & {}^s \theta_z \curvearrowright \end{bmatrix} \quad (10)$$

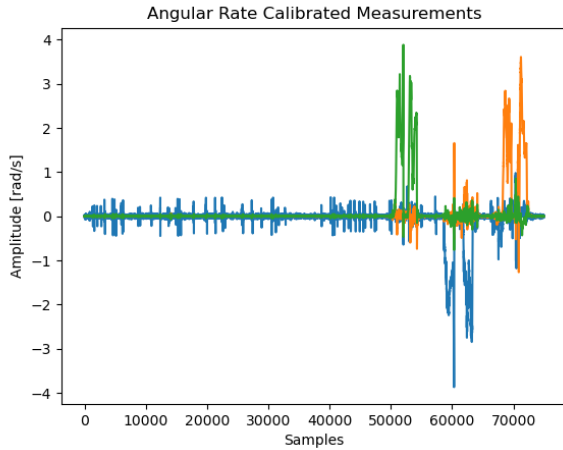


Figure 7: Calibrated Measurements of the Gyroscope

4. VALIDATION

In order to validate the use of IMU sensors, two experimental procedures were performed to compare commercial piezoelectric sensors and accelerometers and gyroscopes, respectively.

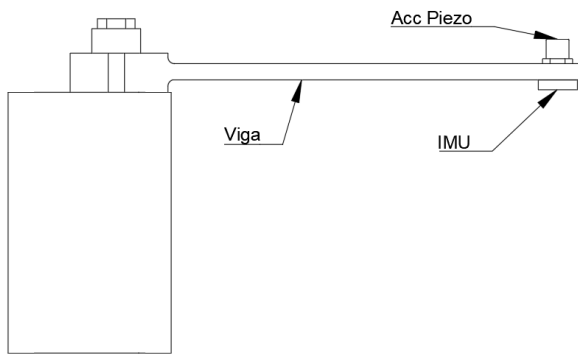


Figure 8: Beam Schema

To validate the accelerometers, the sensors were positioned as illustrated in Figure 8 on a small cantilevered beam, which was impacted with an impact hammer. The values measured by both sensors were compared with each other, both in the time domain and in the frequency domain, as seen in Figure 9

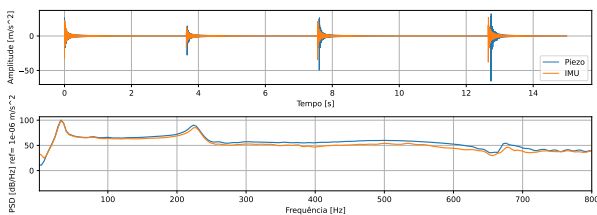


Figure 9: Comparison between piezoelectric accelerometer and MEMS

The validation of the gyroscopes was done by comparing the acceleration values obtained through the piezoelectric

sensors and the angular velocity obtained through the IMU converted into linear acceleration, combining the Equations 11 and 12, according to the configuration shown in Figure 10.

$$a_t = \alpha \times r \quad (11)$$

$$\alpha = \frac{d\omega}{dt} \quad (12)$$

$$a_c = \omega \times (\omega \times r) \quad (13)$$

With the IMU positioned at the center of the rotation and the piezoelectric sensors fixed at a distance of $r = 50mm$, the values obtained can be compared

$$a_p = a_o + a_c + a_t \quad (14)$$

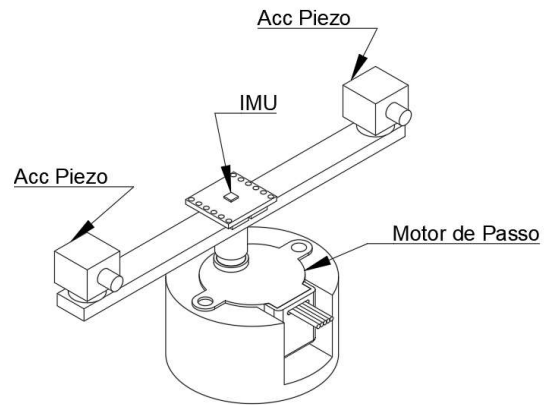


Figure 10: Gyroscope Validation Experiment Setup

Several different angular movements were tested and the signals in the time and frequency domains were compared. Figure 11 illustrates one of these comparisons.

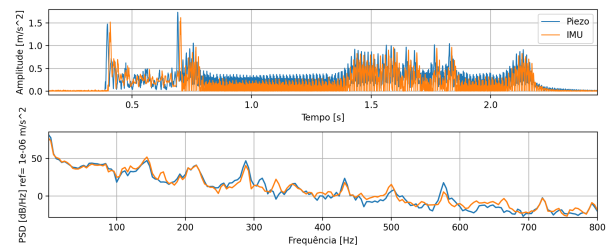


Figure 11: Comparisons between the IMU and piezoelectric sensors



5. CONCLUSION

This paper proposes a new simple routine for calibration of Inertial Measurement Units aided only by a template part, designed to be easily manufactured through 3D printing techniques. The proposed method can be effortlessly implemented as long as there is a flat surface nearly orthogonal to the gravity vector, not requiring any fancy bench equipment, making it cheaper simpler and laboratory independent.

Further research and modeling can and should be developed to alleviate the effects of significant temperature change around the sensor in question. Also improvements on the acquisition circuitry can render better signal quality by reducing noise over the data transmission lines.

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