CALIBRATION OF AN INERTIAL MEASUREMENT UNIT

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***Abstract*—This paper presents a way to calibrate different inertial measurement sensors. In particular we present the calibration of an accelerometer and a gyroscope using least square. A model of the sensors is presented based on the main errors that MEMS devices present, a calibration method is proposed for the static parameters of the model. Finally a temperature adjust is made.**

I. INTRODUCTION

The development of the Microelectromechanical Systems(MEMS) technology has allowed to manufacture many low-cost chip-sensors, such as accelerometers, gyroscopes and magnetometeres. Those chips have been adopted in many applications, for instance Inertial Navigation Systems (INS) [**?**]. However this sensors have many error sources, thus they must be calibrated before being used and they should be re-calibrated peridoically for any precission application. The different sources of error will be analysed in more detail in section II and the implications of those errors will be derived.

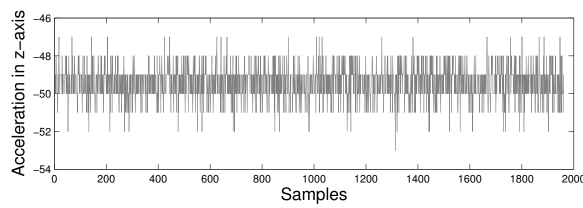
The calibration proposed in this paper is tested on a 3-axis accelerometer ADXL345 of Analog Devices and a 3-axis gyroscope ITG-3200 of InvenSense, yet the model developed and the methodology can be used in other devices because the model is based on comun characteristics of MEMS sensors. The sensors named before are included in a Inertial Measurment Unit(IMU): The Mongoose(figure **??**).

The first step of the calibration is to obtain the static parameters of the devices for the ambience temperautre. This step is based on knowing the exact orientation of the IMU for the calibration of both sensors and the exact angular speed for the gyroscope calibration. Other related works waive this requirement [1] and [2] and uses the fact that in any position angular speed(for the gyroscope calibration) and gravity vector (for the accelerometer calibration) are constant.

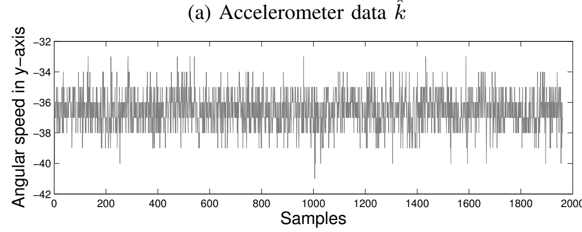
It can be observed(figure **??**) that the measures given by this sensors are not independant of the temperature. Many devices that uses MEMS sensors need to work properly in a wide temperature range. In other cases, the temperature in operation of the system is different(for instance due to Joule Effect of the wires near the sensors) than the ambiance temperature in which the sensor was calibrated. Therefore a temperature adjust must be made.

II. MODEL OF THE SENSORS

As it was stated before, there exist many error sources in MEMS devices. In [1] two of this sources are mentioned: the nonlinear response of the sensors and the non-orthogonality of the axis of the sensor. In addition we can observe also that it exist an electric noise in the measures (figure **??**) and a dependance of the temperature.



(a) Accelerometer data $\hat{k}$



(b) Gyroscope data $\hat{j}$

Fig. 1: Measures from accelerometer and gyroscope in static equilibrium

In the datasheets of the considered sensors([3] and [4]) the effect of nonlinearityis negligible since it represents the $\pm 0.5.\%$ of the full scale for the accelerometer and the $\pm 0.2\%$ for the gyroscope. Therefore we will not consider this effect and after the calibration we must verify that the error due to the nonlinear response is negligeable.

In figure **??** we can observe that the electrical noise of the devices is typically 2 bits, this error (according to the datashets [3] and [4])correspond to $7.8mg$ and $0.14°/s$. The error is not biased, thus we not need to consider it, because several samples are used in any real application and the effect

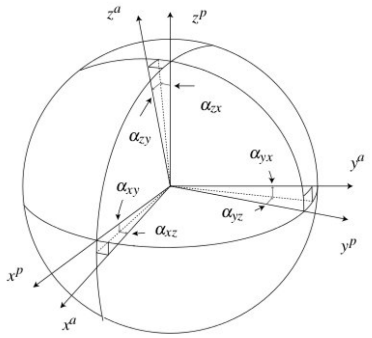


Fig. 2: **Rotations of the sensitivity axis of the accelerometer over the axis of the platform system.**

vanishes.

Based on the asumption that both sensors have a linear response and considering the non-orthogonality of the axis of the devices we are going to present a standard model for both sensors(see [1], [2], [**?**]).

A. Accelerometer

Due to construction issues the sensitivity axis of the device are generaly not orthogonals. Lets define a platform system as shown in figure **??**. Let $\mathbf{a}^a$ be the true acceleration expressed in the sensitivity axis of the accelerometer and let $\mathbf{a}^p$ be the true acceleration expressed in the platform system. We model this fact by the following linear transformation between the two acceleration vectors:

$$\mathbf{a}^p = \mathbf{T}_a^p \mathbf{a}^a,\ \mathbf{T}_a^p = \begin{pmatrix} 1 & -\alpha_{yz} & \alpha_{zy} \\ \alpha_{xz} & 1 & -\alpha_{zx} \\ -\alpha_{xy} & \alpha_{yx} & 1 \end{pmatrix} \tag{1}$$

In equation 1, scalars α_{ij} represents the rotation of the $i-th$ sensitivity axis of the acelerometer over the $j-th$ axis of the platform system. In figure 2 this relation can be observed graphically. Since those errors are due to the manufacturing process we will assume that they will remain constant long enough.

As it was stated befor, we are considering a linear model between the accleration measured in the sensitivity axis and the true acceleration in the same system. Thus we have:

$$\tilde{\mathbf{a}}^a = \mathbf{K}_a \mathbf{a}^a + \mathbf{b}_a \tag{2}$$

In equation 2, $\tilde{\mathbf{a}}^a$ is the measure obtained by the accelerometer, $\mathbf{K}_a$ is a diagonal matrix that represents the sensitivity of each axis and $\mathbf{b}_a$ is a vector that represent the bias of each axis. Those parameters may variate as the temperature changes. However, in this stage we are going to consider them constant. Using equations 1 and 2 we can stablish a model of the acelerometer:

$$\tilde{\mathbf{a}}^a = \mathbf{K}_a \mathbf{T}_p^a \mathbf{a}^p + \mathbf{b}_a = \mathbf{K}_a (\mathbf{T}_a^p)^{-1} \mathbf{a}^p + \mathbf{b}_a \tag{3}$$

B. Gyroscope

The error sources consider in the case of the gyroscope are the same that we developed for the acclerometer. Thus, we are going to consider the same model:

$$\tilde{\omega}_a = \mathbf{K}_\omega (\mathbf{T}_\omega^p)^{-1} \omega^p + \mathbf{b}_\omega \tag{4}$$

III. Calibration method proposed

The problem of calibration is to establish the values for the unkwnown parameters of the model that adjust "the better" a certain set of data. This criterium will be defined in section III-A. For each sensor we want to estimate 12 parameters. We choose to make 27 different measures of accleration and angular speed (this actually means that we have 81 different values) and use 14 of this measures as a training set and the other 13 as a test set.

A. Static Parameter Calibration

Let θ_s (where the subindex s refers to a sensor) be the parameter vector of a certain sensor. We can define this vector as:

$$\theta = [k_{sx}, k_{sy}, k_{sy}, b_{sx}, b_{sy}, b_{sy}, \alpha_{sxy}, \alpha_{sxz}, \alpha_{syx}, \alpha_{syz}, \alpha_{szx}, \alpha_{szy}]^T \tag{5}$$

In equation 5, k_{si}, with $i = 1, 2, 3$ are the diagonal elements of the matrix $\mathbf{K}_s$, b_{si}, with $i = 1, 2, 3$ are the elements of vector $\mathbf{b}_s$ and α_{sij}, with $i = 1, 2, 3$, $j = 1, 2, 3$ and $i \neq j$ are the elements outside the diagonal of the matrix $\mathbf{T}_s^p$.

As adjust criterium we choose to minimize the sum of the squares of the norms of the diferences between true accleracion and measured acceleration. This problem can be written as follows:

$$\min_\theta \sum_{i=1}^{M} ||\mathbf{s}_i^p - \mathbf{T}_s^p (\mathbf{K_s})^{-1} (\tilde{\mathbf{s}}_i^s - \mathbf{b}_s)||^2 \tag{6}$$

In equation 6, M is the cardinal of the training set, $\mathbf{s}_i^p$ is the true magnitude (acceleration or angular speed) and $\tilde{\mathbf{s}}_i$ are the values given by the sensor.

It is important to consider that the function that we want to minimize will generally have more than one local minimum. Thus, we can only assure that the optimum found by algorithms is a local optimum. To ensure that the solution obtained is the desired one, we need to choose carefully the seed for the algorithm. Tipically we will choose a vector θ_0 that is close to the values of the unknow parameters.

1) Accelerometer:

2) Gyroscope:

B. Temperature adjust

IV. Results and analysis

V. Conclusion

References

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