CALIBRATION OF TRIAXIAL ACCELEROMETER BY DETERMINING SENSITIVITY MATRIX AND OFFSETS SIMULTANEOUSLY

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Abstract

In this work, we present a novel approach for calibration of triaxial accelerometers. Acceleration is considered as a vector quantity of three components. Both sensitivity matrix and offsets are estimated simultaneously in least squares sense from a set of measurements with known accelerations. An easy calibration procedure is presented for situations where no calibration devices are accessible.

Introduction

- Accelerometers have been widely used for capturing human movements during last years. Applications of accelerometry cover both monitoring and classification of different types of movements including gait, postural sway and falls [1].
- Traditionally, calibration of the Triaxial accelerometer (TA) has been carried out as a calibration of the three independent, orthogonal uniaxial accelerometers [2].
- This approach does not, however, take into account the transverse or cross-axis sensitivities, which can introduce significant amount of error [3].
- The sensor calibration is an important part of the measurements. The accuracy of the calibration method enhances the validity of the measurements, which makes easier to utilize the results for clinical or scientific purposes.
- In this work, the sensitivity matrix and offsets of a TA are formulated in such a way that they can be estimated simultaneously.

Methods

- In the general case, orientation and skewness of the sensing axes (input axes) of the TA are unknown with respect to geometry of the TA capsule, Fig 1.

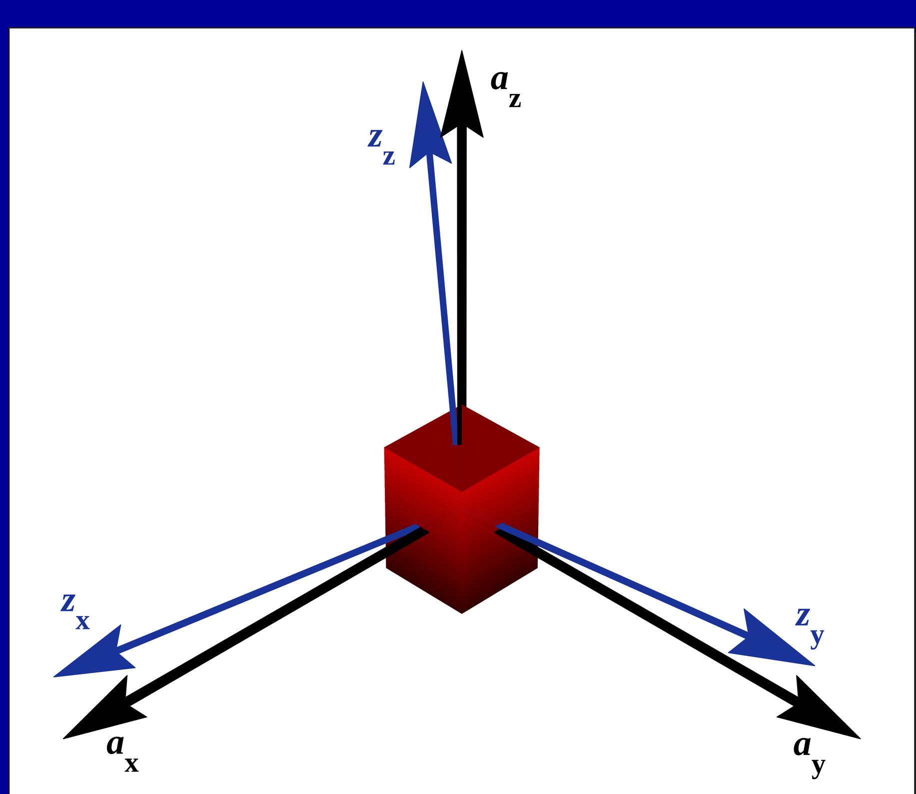

Fig. 1. A known acceleration a (black) and the input axes z (blue) of a TA (red) whose orientation with respect to a is unknown.

- Assuming a known acceleration vector, $\vec{a} = [a_x, a_y, a_z]^T$ (superscript T denotes transpose), the observed acceleration values $z = [z_x, z_y, z_z]^T$ after analog to digital conversion (ADC) can be written in the matrix form

$$z = Ka + O + v, \qquad (1)$$

where K is a sensitivity matrix and O is the offset

$$K = \begin{pmatrix} k_{11} & k_{12} & k_{13} \\ k_{21} & k_{22} & k_{23} \\ k_{31} & k_{32} & k_{33} \end{pmatrix}, \qquad O = \begin{pmatrix} o_x \\ o_y \\ o_z \end{pmatrix}$$

and v is the measurement noise.

- The diagonal elements of the sensitivity matrix K contain information about calibration gains and the off-diagonal elements describe transverse sensitivity due to misalignment of input axis.
- For an ideal TA, the off-diagonal terms of K should be zero and the diagonal terms should be equal.
- Calibration of the TA can be defined as the derivation of all components of K and the offset O simultaneously.
- The twelve parameters to be estimated can be expressed as a parameter vector, $\theta = [k_{11}, k_{21}, \ldots, k_{33}, o_x, o_y, o_z]^T$.
- Then, equation (1) for i'th calibration measurement can be written in the form

$$z^{(i)} = H^{(i)}\theta + v, \qquad (2)$$

where the observation matrix $H^{(i)}$ for i'th measurement is given by

$$H^{(i)} = \begin{pmatrix} a_x^{(i)} & 0 & 0 & a_y^{(i)} & 0 & 0 & a_z^{(i)} & 0 & 0 & 1 & 0 & 0 \\ 0 & a_x^{(i)} & 0 & 0 & a_y^{(i)} & 0 & 0 & a_z^{(i)} & 0 & 0 & 1 & 0 \\ 0 & 0 & a_x^{(i)} & 0 & 0 & a_y^{(i)} & 0 & 0 & a_z^{(i)} & 0 & 0 & 1 \end{pmatrix}$$

- When N independent calibration measurements have been performed, the problem can be formulated in stacked form

$$\begin{pmatrix} z^{(1)} \\ \vdots \\ z^{(N)} \end{pmatrix} = \begin{pmatrix} H^{(1)} \\ \vdots \\ H^{(N)} \end{pmatrix} \theta + v. \qquad (3)$$

- When $N \geq 4$, the problem can be solved in least squares (LS) sense as

$$\hat{\theta} = \left(H^T H\right)^{-1} H^T z. \qquad (4)$$

- The sensitivity matrix $\hat{K}$ and the offset $\hat{O}$ can be separated from $\hat{\theta}$, and the calibrated acceleration values $\hat{a}$ can now be estimated from the equation (1)

$$\hat{a} = \hat{K}^{-1}\left(z - \hat{O}\right). \qquad (5)$$

- This method allows an easy procedure to calibrate the TA when no special calibration devices are present.
- Complete calibration can be done in six measurements by making use of gravitational acceleration, i.e., by placing each of the TA faces perpendicular to gravitational acceleration in turn. One case is shown in Fig. 1 ($a_z = 1\,g$ and $a_x = a_y = 0$). If the unit of acceleration is expressed as g (≈ 9.81 m/s^2), the matrix H then consists of values 0, -1 and 1.

Results

- The usability of the proposed method is studied in this section. A TA, *Meac-x*, was connected to a datalogger *ME6000*, both manufactured by Mega Electronics Ltd, Finland.
- The calibration measurements were performed by making use of gravitational acceleration with help of a carefully positioned worksurface and a block perpendicular to it.
- The calibration measurements were carried out by holding the TA steadily several seconds in six different possible orientations. A marker was applied in the middle of each steady state. The measurements are shown in Fig. 2.

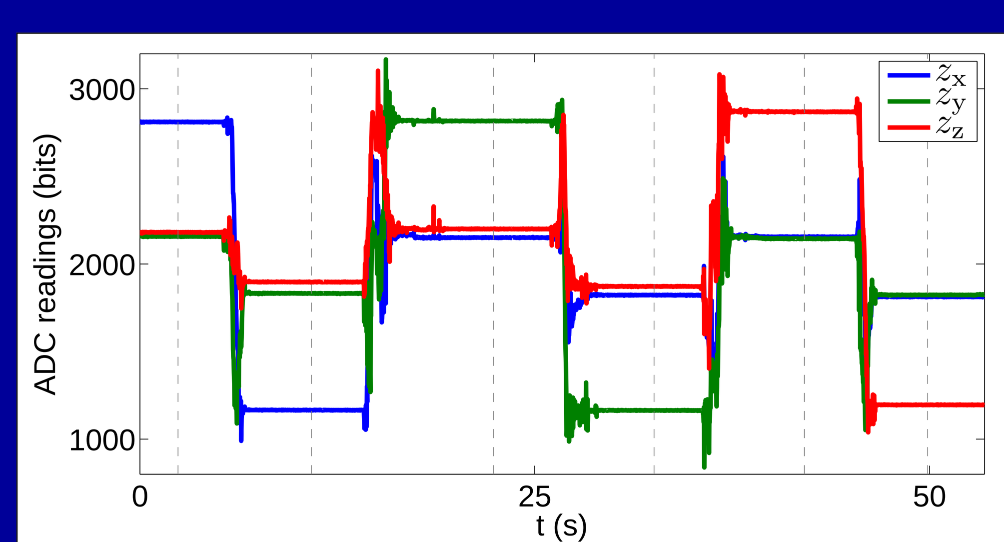

Fig. 2. The calibration measurements. The unit of vertical axis is ADC readings. The dashed lines indicate occurrences of markers in the middle of each steady TA orientation.

- The ADC readings occurring around the markers were averaged to minimize the effect of measurement noise and were accumulated into vector z.
- Then the observation matrix H was constructed and K and O were estimated as above, eq. (2)-(4).
- The validity of calibration was tested with a very simple experiment: The TA was rolled along the worksurface so that the direction of TA z-axis was parallel to the earth's surface. In such a measurement the x- and y- channel accelerations should vary within the $-1\,g$ to $+1\,g$ and the z-channel reading should be zero.
- The measured accelerations are shown in Fig. 3. The upper part of the figure shows the uncalibrated ADC-readings in the raw ADC-data and the lower part the signals calibrated with the K and O obtained before.

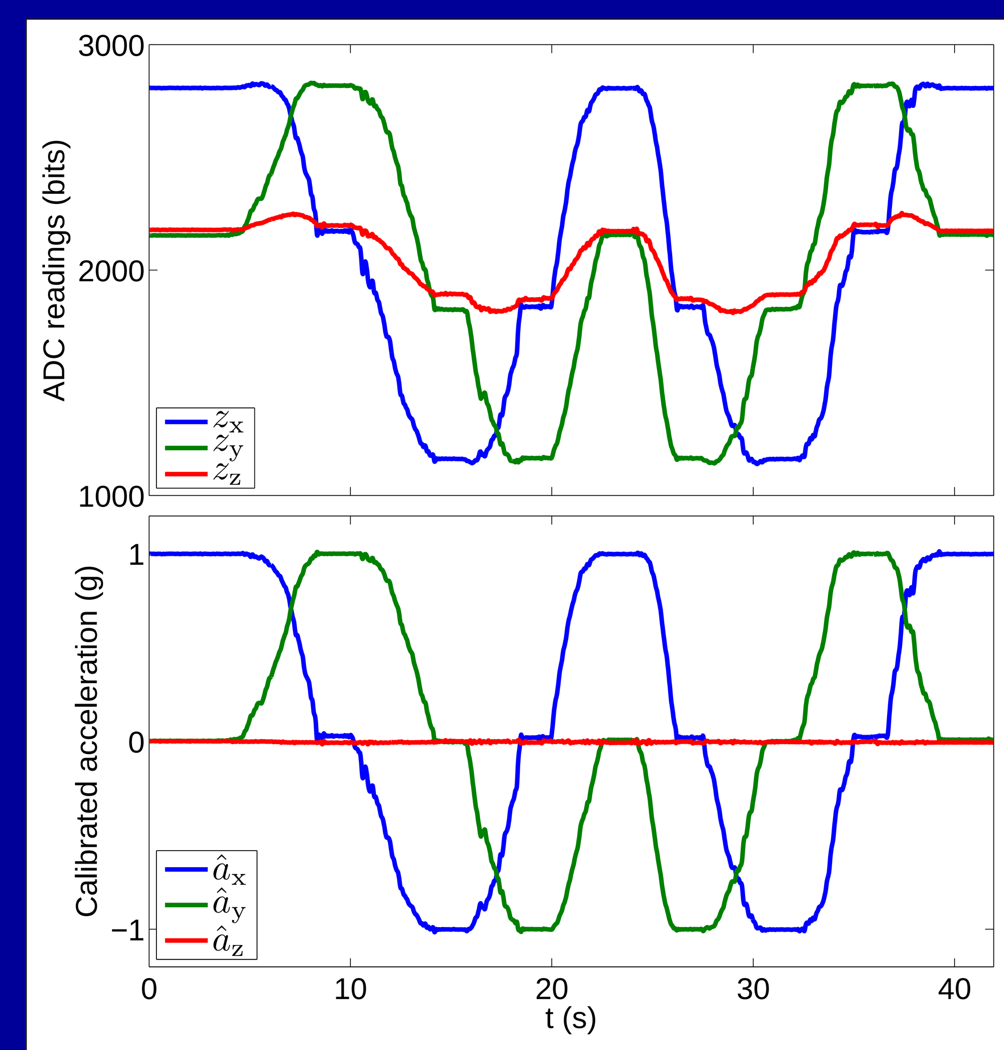

Fig. 3. The measured uncalibrated signals when a TA is rolled so that the z-axis is parallel to earth's surface (upper) and the signals after calibration (lower).

- Due to skewness of the input axes of the TA the z-channel reading fluctuates in the raw ADC-data, whereas after calibration it is very close to zero. The zero-level of calibrated signal is rectified in x- and y-channels as well.

Conclusions

- By applying the method presented in this work, the sensitivity matrix and offsets of the TA can be determined simultaneously. Many commercially available TA's have been constructed from uni- or biaxial acceleration sensors.
- Misalignment of those sensors inside the TA capsule can cause transverse sensitivity with relative magnitude of several percents and, thus, the transverse sensitivities should be included in the model.
- An advanced calibration method can enable the use of cost-effective TA's by compensating the imprecision of manufactoring process, i.e. the skewness of sensing axes.
- It should be noted that this method does not take into account the non-linearities in the TA sensitivities.
- The calibration can be accomplished without any special calibration devices by utilizing the gravitational acceleration.
- However, better calibration precision could be achieved if such a calibration device is utilized which covers the whole dynamics of the TA, a programmable robotic arm for example.

References

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