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Published in:
The Institute of Navigation

Publication date:
2010

Document version
Early version, also known as pre-print

Citation for published version (APA):
In-Field Practical Calibration of Three-Axis Magnetometers

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BIOGRAPHY

Junping Cai received her B.Sc in Automatic Control from Nanjing University of Aeronautics & Astronautics, China, M.Sc in Mechatronics from University of Southern Denmark (SDU), PhD in Control Engineering from Aalborg University of Denmark. She has been a leading development engineer at Danfoss A/S, and is currently R&D engineer at Center for Product Development (CPD), Mads Clausen Institute (MCI), SDU. Her research interests include control, signal processing, navigation, acoustics and refrigeration systems.

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Cristian Malureanu owns a B.Sc in Data-Electronics from the University of Southern Denmark and M.Sc in Mechatronics from the same university. He is a leading Researching Engineer at The Mads Clausen Institute, University of Southern Denmark. His main interests include Intelligent Sensing, Robotics, Navigation, Acoustics, Algorithms, RF/RFID and Smart System Integration.

ABSTRACT

Magnetometers measure the intensity of the Earth magnetic field, and are widely used in connection with vehicle navigation systems and many other engineering applications. Together with inertial navigation systems consisting of three-axis accelerometers and three-axis rate gyros, an extended application, such as human and animal body motion tracking can be realized. Unfortunately the data from low cost sensors is overlapped with drifts which accumulate in time, and they are also sensitive to the environmental parameters, which often make it necessary to perform the sensor calibration just before use. One of the ways for calibration of magnetometers is to find various parameters in the laboratory, having the sensors subject to controlled magnetic field intensity. This involves complex equipment, impractical for in-field use. This paper describes one procedure for calibrating three-axis magnetometers; it uses only the Earth’s magnetic field vector in the geographic area where the calibration is being performed, together with a mathematic algorithm. It takes only a few minutes and allows the determination of the bias, the scale factor and non-orthogonality parameters at the same time. An experimental validation of the procedure and the algorithm is presented at the end of the paper.

INTRODUCTION

Low cost sensors normally suffer from time drift and are sensitive to the environment and condition they are in use, which often makes it necessary to perform the calibration every time before use. In heading domain, one traditional method for calibrating modern solid state strapdown magnetometers is called “compass swinging” [7]. It has been used successfully for a long time in the applications, where two perpendicular magnetometers are used for determining the vehicle heading. It involves levering and rotating the vehicle containing the magnetometers through a series of known headings, and estimating the Fourier coefficients which characterize the hard and soft iron effect. In the magnetic field domain, a non-linear, two-step estimation algorithm was proposed by Gebre-Egziabher et al. [3] [6]. The calibration algorithm uses an estimator where the states are various errors such as hard iron error, soft iron error and scale factor errors. It is implemented by two steps: the first step is solved by using the standard batch least squares linear estimation techniques, and the second step is solved algebraically. Another method for calibrating magnetometers in the
Earth’s magnetic field is described by Merayo et al. [2] [8]. By exposing the magnetometers to fields in different directions and by knowing the scalar magnitude of the field, three offsets, three scale factors and three non-orthogonal angles between the sensor mechanical axes and intrinsic reference frame system (IRFS) are estimated. The IRFS has the first axis aligned to the sensor first mechanical axis. The second lies in the plane formed by the first and second mechanical axes, and perpendicular to the first one. The third axis is obtained by the cross product of the first two axes.

This paper focuses on calibration of magnetometers in the applications other than vehicle heading, for example in human body motion tracking. In this application, the magnetic disturbance of the hard and soft iron on the magnetometers can be avoided to some extent, at least in the calibration process. This simplifies the calibration procedure quite much. Very simple mathematic algorithm is used to determine three offsets, three scale factors, and six non-orthogonal angles between the sensor mechanical axes and an arbitrary Cartesian reference system, simultaneously. The external references are the direction of Earth magnetic north and the total magnetic field strength, at the location where the calibration is carried out.

**MODELING OF MAGNETOMETERS**

The output of magnetometers can be written as:

\[
y_m = K_m m_s + d_m + b_m
\]

where

- \( m_s \) is the actual or true magnetic component directed along the sensor sensitivity axis;
- \( d_m \) is the magnetic disturbance or distortion;
- \( b_m \) is the magnetometer bias;
- \( K_m \) is the scale factor.

**Misalignment**

Three-axis magnetometers are composed of sensor triples; ideally each triplet is mounted so that the nominal sensitivity axes of the three sensors are mutually orthogonal. Unfortunately the actual axis of each sensor does not exactly match the nominal sensitivity axis; such a difference is referred to as “misalignment” or sometimes “non-orthogonality”. The presence of misalignment makes it necessary to characterize the actual orientation of the sensitivity axis of each sensor [1]. In figure 1, \( \chi \psi \zeta \) define a Cartesian reference system, and the direction of nominal sensitivity axes of sensor triplets. Letter \( s \) refers to sensors, \( s_x, s_y, s_z \) are unit vectors, representing the direction of the actual sensitivity axes of sensor triples. \( s_{xx}, s_{xy}, s_{xz} \) are the projection of the vector \( s_x \) along \( x, y \) and \( z \)-axis respectively, \( \theta_x, \phi_x \) are non-orthogonal angles for \( s_x \).

![Fig. 1. Three-axis magnetometer in a Cartesian reference system, where all sensors are misaligned. \( \chi \psi \zeta \) define the direction of nominal sensitivity axes, and \( s_x, s_y, s_z \) define the direction of actual sensitivity axes. \( s_{xx}, s_{xy}, s_{xz} \) are the projection of the unit vector \( s_x \) along \( x, y \) and \( z \)-axis respectively.](image)

The orientation of each sensor triplet with respect to the reference system (actual sensitivity axes vs. nominal sensitivity axes) can be expressed by the following orientation matrix [1] and [4]:

\[
K_d = \begin{bmatrix}
 s_{xx} & s_{xy} & s_{xz} \\
 s_{yx} & s_{yy} & s_{yz} \\
 s_{zx} & s_{zy} & s_{zz}
\end{bmatrix}
\]

where:

\[
 s_{xx} = s_x \cos \theta_x \\
 s_{xy} = s_x \sin \theta_x \sin \phi_x \\
 s_{xz} = s_x \sin \theta_x \cos \phi_x
\]

Since \( s_x \) is a unit vector, so

\[
 s_{xx}^2 + s_{xy}^2 + s_{xz}^2 = s_x^2 = 1
\]

This property will be used in the determination of scale factor as described later. The components of \( s_y, s_z \) can be written in a similar way. There are 6 non-orthogonal angles in total. In an ideal situation, the orientation
matrix is a 3-by-3 identity matrix, with ones on the diagonal and zeros elsewhere.

Scale Factor

The scale factor matrix of the three sensors in each triplet can be written as the following diagonal matrix:

\[
K_m = \begin{bmatrix}
k_x & 0 & 0 \\
0 & k_y & 0 \\
0 & 0 & k_z \\
\end{bmatrix}
\]  

(5)

Bias

The bias vector of the three sensors in each triplet can be written as:

\[
b_m = \begin{bmatrix}
b_x \\
b_y \\
b_z \\
\end{bmatrix}
\]  

(6)

Magnetic Distortions

The disturbance vector can be written as:

\[
d_m = \begin{bmatrix}
d_x \\
d_y \\
d_z \\
\end{bmatrix}
\]  

(7)

Magnetic distortions can be categorized as two types: “hard iron effects” and “soft iron effects”.

Hard iron distortions arise from permanent magnets and magnetized iron or steel. These distortions will remain constant and in a fixed location relative to the magnetic sensors for all heading orientations. Hard iron effects add a constant magnitude field component along each axis of the sensor output.

The soft iron distortion arises from the interaction of the Earth’s magnetic field and any magnetically soft material surrounding the sensors. The amount of distortion from the soft iron depends on the sensor orientation.

In practice, soft iron effects are usually much weaker, and hard iron effects dominate over soft iron effects provided that the use of ferromagnetic materials near the magnetometer can be avoided [5]. Calibration methods become straightforward, if soft iron effects can be neglected compared to hard iron effects. In this case only the components of a constant interference field have to be measured and compensated.

Taking the sensors orientation into consideration, the general output of magnetometer can be rewritten as:

\[
y_m = K_m K_d m + o_m
\]  

(8)

Where \(d_m\) and \(b_m\) are replaced by one constant \(o_m\), since in the calibration process, both of them are considered to be constant.

From above equation, we can see fifteen coefficients need to be identified in the calibration phase, namely nine orientation components (six non-orthogonal angles), three scale factor components, and three constants covering hard iron effect and bias.

Calibration Algorithm

The magnetic field strength on the earth varies with location and time, covering the range from about 0.3 to 0.6 Gauss. Figure 2 shows the Earth’s magnetic field vector. Magnetic north is in the direction of \(H_{eh}\). \(H_{eh}\) is the horizontal component of Earth’s field, perpendicular to gravity. \(H_{ez}\) is the vertical component of Earth’s field, and in the direction of gravity. Total field vector \(H_e\) lies in the plane defined by the magnetic north and the magnetic down; \(H_e\) is the vector sum of the magnetic north \(H_{eh}\) and magnetic down \(H_{ez}\).

Fig. 2. Earth magnetic field vector, \(H_{ez}\) is the vertical component of the magnetic field, \(H_{eh}\) is the horizontal component of the field, and \(H_e\) is the total magnetic field.

For example in Copenhagen, the capital of Denmark, according to the geomagnetic field calculation model by the U.S. Geological Service (USGS) [9], in the year of 2005, \(H_e\) is approximately 49,915.12 nT, \(H_{eh}\) is about
17,076.73 nT, and $H_e$ is 46,903.14 nT. It is slowly varying from year to year. Geographic (or true) north differs from the magnetic north by an inclination angle.

Imagine we align the three-axis magnetometer arbitrary in the Earth’s magnetic field, we would get three outputs from each axis of the sensors, and the calibrated vector sum is the total field $H_e$. If we align virtually two axes of the sensor along the plane defined by the magnetic north and down, namely $mz$ plane, and rotate the sensor set around the magnetic east (clock wise 90 degree from the magnetic north) 360 degree, theoretically, two axes of the sensor will have corresponding changed output, and expose once to maximum field strength $+$ $|H_e|$ and once to minimum $-$ $|H_e|$ respectively. The third axis of the sensor align with magnetic east will output only the zero-field reading.

This ideal situation will happen only when three axes of the sensor are perfect mutual orthogonal. So if one sensor axis is aligned with the magnetic east, the other two axes of the sensor will lie precisely inside the $mz$ plane. In the real life, with presence of the misalignment, a cross-axis effect will introduce extra output to the sensor triplet even when its axis is aligned with magnetic east, thus extra consideration need to be taken.

**Bias and Magnetic Disturbance**

Rotating around the magnetic east, and if we record the maximum and minimum value for each sensor axis inside the $mz$ plane, and taking the misalignment into the consideration, the offset can be obtained by the following average:

$$y_{m1} = K_n K_d |H_e| + o_m$$
$$y_{m2} = K_n K_d (-|H_e|) + o_m$$
$$o_m = \frac{y_{m1} + y_{m2}}{2} \quad (9)$$

Two extreme conditions can occur here: first, if the sensitivity axis is approximately perpendicular to the total field vector $H_e$, the measured value will be very small, and the nonlinearity is probably negligible, but there will be a large normal field which gives a significant cross-axis effect. Second, if the sensitivity axis is approximately along the total field vector $H_e$, the measured value will be very large, and the effect of nonlinearity is probably significant and non-negligible, but the cross-axis effect can be neglect. Following the procedure as in [1], a manipulated matrix form of the mathematic expression is adapted.

$$Y_{m+} = K_n K_d |H_e| + O_m$$
$$Y_{m-} = K_n K_d (-|H_e|) + O_m$$
$$Y_{mS} = Y_{m+} + Y_{m-}$$
$$O_m = \frac{1}{2} Y_{mS} \quad (10)$$

Where

$$Y_{m+} = \begin{bmatrix} y_{x,max} & y_{x+} & y_{x+} \\ y_{y+} & y_{y,max} & y_{y+} \\ y_{z+} & y_{z+} & y_{z,max} \end{bmatrix}$$
$$Y_{m-} = \begin{bmatrix} y_{x,min} & y_{x-} & y_{x-} \\ y_{y-} & y_{y,min} & y_{y-} \\ y_{z-} & y_{z-} & y_{z,min} \end{bmatrix} \quad (11)$$

The elements lying on the diagonal of $O_m$ are determined in the presence of large magnetic value and affected mainly by the nonlinearity, off-diagonal elements are affected mainly by the cross-axis effect.

**Scale Factor and Orientation Matrix**

Scale factor and orientation matrix can be calculated from the same measurement data set as follows:

$$Y_{m+} = K_m K_d |H_e| + O_m$$
$$Y_{m-} = K_m K_d (-|H_e|) + O_m$$
$$Y_{mD} = Y_{m+} - Y_{m-}$$
$$Y_{mD} = 2|H_e| K_m K_d$$
$$K_m K_d = \frac{1}{2|H_e|} Y_{mD} \quad (12)$$

Since the rows of the orientation matrix $K_d$ are unit vectors, scale factor matrix components can be determined by the following equation:

$$k_{x}^2 = \text{diag}(K_m K_d) \times (K_m K_d)^T$$
$$k_{y}^2 = \text{diag}(K_m K_d) \times (K_m K_d)^T$$
$$k_{z}^2 = \text{diag}(K_m K_d) \times (K_m K_d)^T \quad (13)$$
The orientation matrix $K_d$ can be afterwards easily determined from the following equation:

$$K_m K_d = \frac{1}{2|H_e|} Y_{mD}$$

$$(15)$$

$$K_d = \frac{1}{2|H_e|} K_m^{-1} Y_{mD}$$

**IMPLEMENTATION OF THE CALIBRATION PROCEDURE**

The requirement for the calibration process is quite simple; we fix the three-axis magnetometer in a rectangular plastic case, a Cartesian reference system $xyz$ is normal to three of case sides. A horizontal plane surface and a reference block are used as the supporting base. Align the reference block in the direction of magnetic north, align $x, y, z$ axis with magnetic east, and rotate the sensor case around $x, y, z$ axis 360 degree respectively, record the data and group them into the matrix as defined in equation (12).

Fig. 3. Calibration platform, a three-axis magnetometer is placed inside the sensor case; supporting base is placed horizontally, with a reference block pointing in the direction of magnetic north.

To find the magnetic north and local magnetic field strength, a digital magnetometer HMR2300 from Honeywell is used, which has high accuracy, less than 0.5% full scale over ±1 gauss.

In order to avoid the magnetic interference, ferromagnetic material in the neighborhood should be removed.

**EXPERIMENTAL RESULTS**

**Hardware Specification**

The magnetic sensing elements, for the three dimensions, are based here on a HMC1043 three-axis magnetic sensor from Honeywell.

Each axis extends differential analog outputs, coming directly from $3 \times 4$-elements Wheatstone bridges. Their level is around the half of the applied bridge voltage ($V_b$) in close-to-zero magnetic field environments. The $V_b$ here is 3V.

An about ~200 gain differential amplifier is used, a low-pass filter, then the outputs of the three axis feeds to a multiplexed 3-channel 10b ADC and a microcontroller. The reading time, temperature and virtual reference for each of the readings are also stored. The data is sent to a SD Card and transferred to a mainframe computer at a rate of 160 datasets/sec 3D at once.

Additionally filtering is done in software, both at microcontroller level, before storage, and at mainframe level. Different types of algorithms are examined in order to pick the interesting parameters out of the raw signal data.

**Testing Results**

Figure 4 shows the calibration data from a three-axis magnetic sensor. From the figure we can see that the first rotation is carried out when the $x$-axis is aligned with the magnetic east, the second rotation is carried out when the $y$-axis is aligned with the magnetic east, and the last one is when the $z$-axis is aligned with the magnetic east. Figure 5 shows the filtered data for the calibration.

Once the gain $K_m$, misalignment $K_d$ and offset $o_m$ are obtained from the calibration data, the true magnetic field value $m_T$ can be calculated by the measurement $y_m$ according to the following formula.

$$m_T = (K_m K_d)^{-1} (y_m - o_m)$$

$$(16)$$

Figure 6 shows a new set of filtered data from one random testing. Figure 7 shows the true data after calibration, and the total field strength is calculated by the following equation.

$$m_{tot} = \sqrt{m_{xT}^2 + m_{yT}^2 + m_{zT}^2}$$

$$(17)$$

Ideally, the total field strength at one location is a constant.
Fig. 4. Raw calibration data reading in count from a three-axis magnetometer, when rotating around the magnetic east.

Fig. 5. Filtered calibration data in volt from the three-axis magnetometer, when rotating around the magnetic east.

Fig. 6. One new set of random testing data in volt from the three-axis magnetometer, filtered

CONCLUSIONS AND DISCUSSION

This paper describes an in-field practical calibration method for three-axis magnetometers. It is implemented in the magnetic field domain, and focuses on the application as body motion tracking. Fifteen parameters are determined by three rotations and simple mathematic calculation, and simultaneously. The referential Cartesian coordinate can be selected arbitrary, and there is no need to pre-align the sensor set precisely with any of the reference axis. The only external reference needed for the calibration is the direction of the magnetic north and the total field strength, at the location where the calibration is carried out. It takes only a few minutes, and can be repeated easily and whenever needed.

Hard and soft iron interference as well as time drifting issue for magnetometers, together with inertial navigation systems, in the body motion tracking process, will be the topic of further investigation.

REFERENCES


