Research on Ground Calibration Technology for Geomagnetism Sensors

Zhang Hui , Li Chuanjun and Liu Yukuan

School of Aerospace Engineering, Beijing Institute of Technology, Beijing 100081, China

Abstract. The measurements of geomagnetism sensors are often affected by self-factors, install-factors and environment factors, therefore they often exist error and cause measurement accuracy reduction. Focus on these problems, this paper analyse existing ground calibration algorithms and their merits and demerits respectively. Besides, a comprehensive geomagnetism sensor error model is presented. Based on this model, a least square method based ellipsoid fitting calibration and compensation algorithm is presented. The experiment results show that this novel calibration algorithm can effectively restrain and compensate geomagnetism signal measurement error.

1 Introduction

Geomagnetism filed is elementary physical field of earth, it has characteristics such as all-time, all-weather, all-region etc. Therefore geomagnetism filed has abundant parameter information. Particularly, geomagnetism total filed, three components of geomagnetism, magnetism inclination, magnetism declination and geomagnetism gradient can be used for magnetism navigation [1]. Geomagnetism sensors have many advantages such as small volume, low cost, high precision and so on. Furthermore, they have high ability to anti-impact or overload. Hence geomagnetism sensors have widely used in commercial and military filed. The purpose of this paper is to calibrate and compensate of geomagnetism sensors and finally implement geomagnetism navigation through calibrated geomagnetism information [2].

Existing ground calibration algorithms include follows: 1) Ellipsoid fitting method, this method is based on one assumption. That is, under the impact of magnetic sensor measurement error, the measurement trajectory of magnetic field can be approximate to an ellipse trajectory. The essence of Least Squares ellipsoid fitting method algorithm is to find a group of elliptic parameter, which can minimize the distance between the measurement data and the fitting data in a sense. The advantage of this method is easy to calculate, but the compensation effect for three-axis magnetic sensors is limited [3]. 2) Magnetic variation calibration method, this method trying to calculate rotate, stretch and translation factors to correction ellipsoid trajectory into circle trajectory. Then using this model to filter the abnormal signal. This method is also easy to perform, but the precision of compensation calibration is also limited [4]. 3) Kalman filter method. Kalman filter is a common parameter estimation method for linear system. Extend Kalman filter (EKF) and Unscented Kalman filter (UKF) can be used to estimate and compensate model parameters in real time, but these methods need higher precision reference to be standard [5]. 4) Neural network calibration method. Using the magnetometer's output as independent variable, with the taylor expansion of objective function, this algorithm deduce the optimized objective function. Then using this function as network node to build network, and perform functional approximation for magnetometer's signal. This method can calibrate three-axis magnetic sensors error simultaneously, which can enhance performance of magnetic sensors. However, this method also needs higher precision reference to be standard [6]. 5) Ellipsoid fitting method. Within the region that magnetic field strength is constant and know, the measurement data under ideal situation should be a standard sphere. While because of measurement error, the standard sphere is aberration and becomes an ellipsoid. And using the property of ellipsoid, the algorithm can estimate error correction parameters of magnetic sensors, and performing calibration compensation. Ellipsoid fitting method usually using iteration method or least square method to calculate. However, iteration based ellipsoid fitting is vulnerable to initial value and noise, it's easy to divergence and the computation burden is increase [7]. On the other hand, tradition least square based ellipsoid fitting method gets higher precision error compensation, but it also turn into unstable when constraint matrix is singular [8].

2 Geomagnetic sensor error model

In an invariable measure system and constant testing environment, the measurements of earth magnetic field exist error. Generally speaking, the measurement data are often constituted by random error and system error. The former error are normally distributed, which can be noted as $e \sim N(0,\sigma_e^2)$. The latter error are fixed(or changed at a certain regular), and it often include instrument error, installation error and environment error. We analyze these error respectively, and finally build geomagnetic sensor system composition error mathematical model.

Owing to the wide frequency bandwidth of geomagnetic signal, the measurement signal is easy to interference by other magnetism signal. Besides, be limited in machinery manufacturing equipment, production technology level and material characteristics, magnetic sensor exist measurement error, which can be classified as bias error, sensitivity error and non-orthogonal error [9]. The definition of these error are shown as follows.

Bias error: This kind of error means when the external magnetic field is zero, the output measurement data is not zero. Bias error can be modeled by a fixed matrix such as $b_o = \begin{bmatrix} b_{ox} & b_{oy} & b_{oz} \end{bmatrix}^T$.

Sensitivity error: Sensitivity error are often caused by the different sensitivity or amplification gain between three-axis sensors. Sensitivity error can be modeled as follow:

$$K_s = \begin{bmatrix} s_x & 0 & 0 \\ 0 & s_y & 0 \\ 0 & 0 & s_z \end{bmatrix} \tag{1}$$

Non-orthogonal error: When the three-axis are set non-orthogonal, just like figure 1, it often cause measurement error, that is, non-orthogonal error. Non-orthogonal also can be modeled as:

$$K_p = \begin{bmatrix} \sqrt{1-\cos^2\beta-\cos^2\gamma} & \cos\beta & \cos\gamma \\ 0 & \cos\alpha & \sin\alpha \\ 0 & 0 & 1 \end{bmatrix} \tag{2}$$

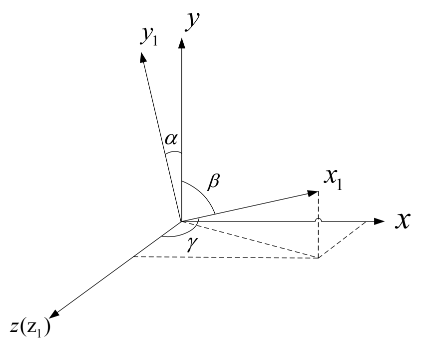

Figure 1. The non-orthogonal error model of geomagnetic sensor

Installation error: Installation error is caused by the misalignment between actual installation position and ideal installation position. Installation error is shown as figure 2 and its mathematic model can be expressed as:

$$K_n = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\varepsilon_3 & \sin\varepsilon_3 \\ 0 & -\sin\varepsilon_3 & \cos\varepsilon_3 \end{bmatrix} \begin{bmatrix} \cos\varepsilon_2 & \sin\varepsilon_2 & 0 \\ -\sin\varepsilon_2 & \cos\varepsilon_2 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\varepsilon_1 & 0 & -\sin\varepsilon_1 \\ 0 & 1 & 0 \\ \sin\varepsilon_1 & 0 & \cos\varepsilon_1 \end{bmatrix}$$

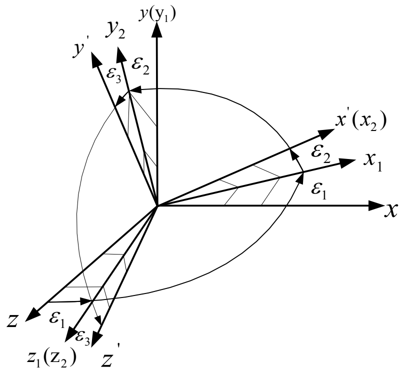

Figure 2. Installation non-orthogonal error

Environment error means when using magnetic sensors in iron-magnetism environment, the error is caused by these magnetic materials. It can also be classified as hard magnetic error and soft magnetic error. Just as their name imply, the hard magnetic error is caused by hard magnetic materials' magnetic field, or interfered by electronic equipment. Hard magnetic error can be expressed as $b_h = \begin{bmatrix} b_{hx} & b_{hy} & b_{hz} \end{bmatrix}^T$. The soft magnetic error is caused by soft magnetic materials' induced magnetic field when they setting in geomagnetic field. Soft magnetic error can be expressed as

$$K_m = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \tag{3}$$

As described previously, if we assume the original magnetic field is B, and the measurement magnetic field with various error is B_m, then we can deduce system error mathematic model as follow:

$$B_m = K_n K_p K_s (K_m B + b_h) + b_o + e \tag{4}$$

It can also be simplified as:

$$B_m = KB + b + e \tag{5}$$

Where $K = K_n K_p K_s K_m B$ is total transformation matrix, $b = K_n K_p K_s b_h$ is total offset vector. K is invertible matrix, hence the sensor error mathematic model can be deduced from equation (5) as follow:

$$B = K^{-1}(B_m - b - e) \tag{6}$$

Where random error can be compensated by hardware, hence e can be ignored, and sensor error mathematic model is:

$$B = K^{-1}(B_m - b) \tag{7}$$

3 The Principle of ellipsoid fitting and error compensation

If the position of geomagnetic sensor is fixed, the measurement data of magnetic sensor should be one constant value theoretically. That is, no matter what direction the vehicle heading to, the measurement data is same. Hence the magnetic data can be modeled as a standard sphere in space. However, because of the existence of various error, the standard sphere is distortion to ellipsoid. The principle of ellipsoid fitting is to using ellipsoid fitting to actual testing data, and estimating the central and shape parameters of ellipsoid. Finally, the parameters of sensors error model can be calculated.

Ellipsoid is one kind of quadric surface, the equation of ellipsoid is:

$$\begin{aligned} F(\xi,v) &= \xi^T v \\ &= ax^2+by^2+cz^2 \\ &\quad +2fxy+2gxz+2hyz \\ &\quad +2px+2qy+2rz+d \\ &= 0 \end{aligned} \tag{8}$$

Where $\xi=[a,b,c,f,g,h,p,q,r,d]^T$ is shape parameters of quadric surface, $v=[x^2,y^2,z^2,2xy,2xz,2yz,x,y,z,1]^T$ is measurement data vector. Now if measurement is performed for n times, we can define $D=[v_1 \quad v_2 \quad \dots \quad v_n]^T$ as measurement batch measurement data. Secondly, using fitting ellipsoid to minimize the sum of squared distances from measurement data to fitting ellipsoid. This process can be expressed as follow:

$$\min\left|F(\xi,v)\right|^2 = \min(\xi^T D^T D\xi) \tag{9}$$

Now we build function

$I=a+b+c, J=ab+bc+ac-f^2-g^2-h^2$, then the least square solution under the constraint equation $\alpha J - I^2 > 0$ is $\min(\xi^T D^T D\xi)$. When $\alpha=4$, the shape parameters of fitting ellipsoid is obtained.

The error model of geomagnetic sensor can be rewritten as follow:

$$B^2-(B_m-b)^T(K^{-1})^T K^{-1}(B_m-b)=0 \tag{10}$$

Let $A=(K^{-1})^T K^{-1}$, the equation (7) can be written as:

$$(B_m-b)^T A(B_m-b)=B^2 \tag{11}$$

Besides, equation (8) can be also written as:

$$(B_m-B_0)^T R(B_m-B_0)=1 \tag{12}$$

Expand the above equation, we can get next equation:

$$B_m^T RB_m - 2B_0{}^T RB_m + B_0{}^T B_0 = 1 \tag{13}$$

Where $B_m=[x \quad y \quad z]^T$, $B_0=-R^{-1}\left[p \quad q \quad r\right]^T$ is the coordinate of optimal fitting ellipsoid's center point. The shape parameters matrix of fitting ellipsoid notes as R

$$R=\begin{bmatrix} a & f & g \\ f & b & h \\ g & h & c \end{bmatrix} \tag{14}$$

From all above equations, we can get

$$b=B_0, A=RB^2$$

The singular value decomposition (SVD) of A is

$$A=U\Sigma U^T$$

Now set

$$Q=U\sqrt{\Sigma}U^T$$

then $A=U\Sigma U^T=U\sqrt{\Sigma}U^T U\sqrt{\Sigma}U^T=Q^T Q$. Besides, $A=(K^{-1})^T K^{-1}$, hence $B=U\sqrt{\Sigma}U^T(B_m-b)$.

4 Experiments and Results

To verify the precision of Ellipsoid fitting method, a rotation experiment has been performed. Just like figure 3. Three axis geomagnetic sensor system is put on a rotary table. The frame of rotation system is constructed by aluminum material, which can decrease magnetic interference. The geomagnetic sensor system is constructed by three axis TMR linear sensor—TMR2305 and three axis magneto-resistive sensor HMC1043.

Figure 3. The rotary table used in experiment.

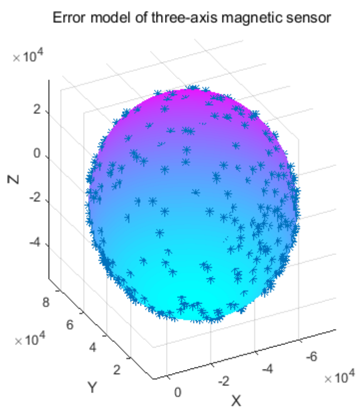

Figure 4. Measurement results for HMC1043.

Figure 4. shows the ellipsoid fitting result for HMC1043, as what we discussed before, the measurement results is distortion to ellipsoid. Figure 5 shows the residuals error of ellipsoid fitting.

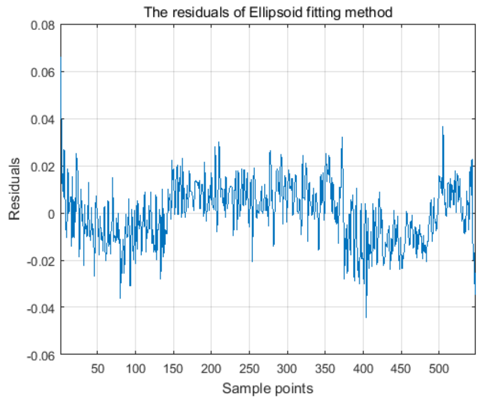

Figure 5. The residuals error of ellipsoid fitting.

Based on these data, the shape parameters of fitting ellipsoid and sensor error calibration model can be expressed as follows:

$$R=\begin{bmatrix} a & f & g \\ f & b & h \\ g & h & c \end{bmatrix}$$
$$=10^{-9}\begin{bmatrix} 0.5897 & 0.0050 & 0.0059 \\ 0.0050 & 0.5103 & -0.0133 \\ 0.0059 & -0.0133 & 0.4934 \end{bmatrix}$$

$$K^{-1}=\begin{bmatrix} 1.3220 & 0.0059 & 0.0069 \\ 0.0059 & 1.2287 & -0.0162 \\ 0.0069 & -0.0162 & 1.2083 \end{bmatrix}$$

$$b=\begin{bmatrix} -35318.1397 & 45038.2748 & -9220.9663 \end{bmatrix}^T$$

Figure 6 shows the calibration results for HMC1043 magnetic sensor.

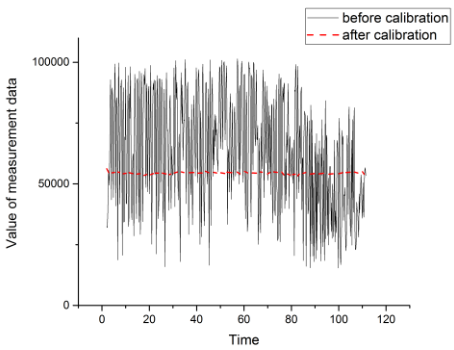

Figure 6. The measurement data and calibration data.

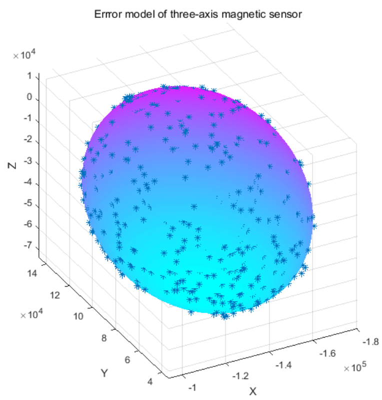

Figure 7. The measurement results for TMR2305

Similarly, figure 7 shows the measurement results for TMR2305 magnetic sensor.

Figure 8 shows the residuals of ellipsoid fitting. Based on these testing data, the shape parameters of fitting ellipsoid and sensor error calibration model can also be calculated. Finally, figure 9 shows the measurement data after calibration.

$$R=\begin{bmatrix} a & f & g \\ f & b & h \\ g & h & c \end{bmatrix}$$
$$=10^{-9}\begin{bmatrix} 0.5353 & -0.0147 & -0.0189 \\ --0.0147 & 0.3320 & -0.0219 \\ 0.0189 & -0.0219 & 0.5329 \end{bmatrix}$$

$$K^{-1}=\begin{bmatrix} 1.2583 & -0.0196 & -0.0225 \\ -0.0196 & 0.9915 & -0.0290 \\ -0.0225 & -0.0290 & 1.2553 \end{bmatrix}$$

$$b=\begin{bmatrix} -136987.0139 & 90713.6502 & -29807.8842 \end{bmatrix}^T$$

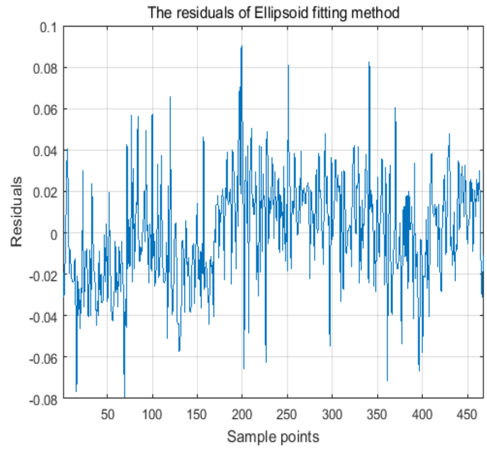

Figure 8. The residuals of ellipsoid fitting.

It can be seen that the transfer matrix of these two kinds of geomagnetic sensor is similarity, while the bias vector of TMR2305 is bigger than HMC1043. When performing least squares based ellipsoid fitting, the measurement data of all two kinds of sensors have been compensated effectively.

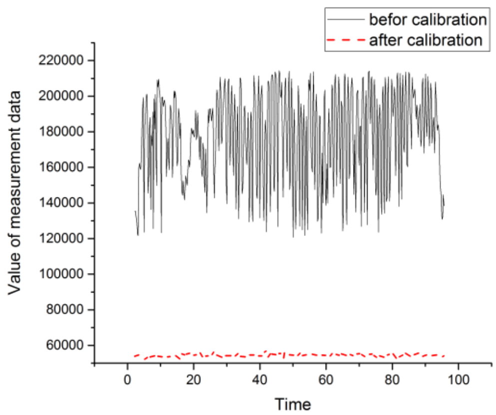

Figure 9. The measurement data and calibration data.

5 Conclusion

This paper summarizes the common methods of geomagnetic sensors' calibration and compensation methods, meanwhile compared their advantages and disadvantages. Besides, this paper presents a novel least squares based ellipsoid fitting calibration and compensation method. The error types and error model have been analysed. Finally, real test experiments have been performed for common sensor HMC1043 and TRM2305 respectively, and the results prove that this method is more accuracy and effective. Of course, because of the influence of various factors in the actual environment, magnetic field compared with an ideal value exists errors. The aim of our further work is to shield the existing magnetic field and to build a certain magnetic field.

Acknowledgment

This paper is supported by National Natural Science Foundation of China (61473039) and the key laboratory of dynamics and control of flight vehicle, Ministry of education, school of aerospace engineering, Beijing Institute of Technology.

References

1. Goldenberg F. Geomagnetic navigation beyond the magnetic compass. *IEEE ION Position, Location and Navigation Symposium*. Coronado, CA. 2006: 684-694.
2. Li, X. P., Fan, J., Ding, J., & Qian, X. B. (2006). Multi-core orthogonal fluxgate sensor. *Journal of Magnetism & Magnetic Materials*, 300(1), e98-e103.
3. Gebreegziabher, D. (2007). Magnetometer autocalibration leveraging measurement locus constraints. *Journal of Aircraft, 44*(4), 1361-1368.
4. Yang, X., & Huang, S. (2004). Magnetic deviation analysis and verification for magnetic compass. *Journal of University of Electronic Science & Technology of China, 33*(5), 547-550.
5. Soken, H. E., & Hajiyev, C. (2011). In flight magnetometer calibration via unscented Kalman filter. *International Conference on Recent Advances in Space Technologies* (pp.885-890). IEEE.
6. Huang, Y., & Hao, Y. (2012). Error correction of magnetic field component gradiometer based on flann and least-squares. *Chinese Journal of Scientific Instrument, 33*(4), 911-917.
7. Wang, M., Wu, Y., Yu, B., & Automation, S. O. (2015). Research on tri-axial magnetic sensor calibration and measurement error compensation based on iterative algorithm. *Ordnance Industry Automation*.
8. Zhang, Q., Pan, M., Chen, D., & Pang, H. (2012). Scalar calibration of tri-axial magnetometer with linearized parameter model. *Chinese Journal of Sensors & Actuators, 25*(2), 215-219.
9. Huang, X. G., & Wang, J. (2011). Error analysis and compensation methods for geomagnetic signal detection system. *Acta Armamentarii,32*(1), 33-36.
10. Yang, X., & Huang, S. (2004). Magnetic deviation analysis and verification for magnetic compass. *Journal of University of Electronic Science & Technology of China, 33*(5), 547-550.