A Novel Auto-calibration Method of the Vector Magnetometer

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Abstract *–Many types of magnetometers have been used to measure the magnetic field vector in a wide range of commercial and military applications. Measured value of magnetometer is corrupted by various errors. In general, magnetometer output errors are caused by random instrument noise, constant biases, scale factor deviations, nonorthogonality of the sensor axes. The high accuracy measurement of magnetic field requires calibrating precisely the magnetometer and compensating measured error of magnetic field. In this paper a novel auto-calibration method of the vector magnetometer is presented. The auto-calibration method can be separated into two steps: fitting ellipsoid to the 3D measured data and solving the model parameters of magnetometer from the fitting ellipsoid. According to the model parameters the measured data is corrected to improve the precision of magnetometer. The ellipsoid fitting algorithm and the model parameter solution are all linear to avoid the nonlinear calculation and the complex iteration. To evaluate the performance of the auto-calibration method, the simulation experiments were performed. The results show that the new method is more convenient the conventional methods, and have many advantages such as: quick, stable, high precision and insensitive to small errors in the data.*

Keywords *– vector magnetometer, auto-calibration, ellipsoid fitting, magnetometer modeling*

Ⅰ. INTRODUCTION

Magnetic fields are vectors, that is, at any point in space a magnetic field has a magnitude and a direction. A magnetic field vector can be separated into three component vectors (X, Y, Z) which are at right angles to one another and are called the rectangular components of the vector. A vector may also be described in terms of its magnitude R and angles D and I. These are called its polar coordinate components. The rectangular and polar components of the vector are related to one another.

Many types of magnetometers have been used to measure the magnetic field vector in a wide range of commercial and military applications. The magnetic compass has been used in navigation for centuries. Today, there are several types of electronic compasses to be chosen from: fluxgate, magneto-resistive, magneto-inductive, and others. Electronic compasses offer many advantages over conventional needle type compasses such as: shock and vibration resistance, electronic compensation for stray field effects, and direct interface to electronic navigation systems. A common type of magnetic compass for navigation systems is the fluxgate vector magnetometer, which consists of a set of coils around a core with excitation circuitry that is capable of measuring magnetic fields with less than 1 nT resolution.

Measured value of magnetometer is corrupted by various errors, so magnetometers are normally calibrated before they are used. In general, magnetometer output errors are caused by random instrument noise, constant biases, scale factor deviations, nonorthogonality of the sensor axes. In the calibration process the parameters of magnetometer error models are estimated by means of experimentations and output data processing, and magnetometer measurements are adjusted using these estimated parameters. The high accuracy measurement of magnetic field requires calibrating precisely the magnetometer and compensating measured error of magnetic field.

The conventional calibration is taken in the standard magnetic field environment. The error parameters are estimated applied the Least-Squares solution by comparing the difference between magnetometer output and the standard magnetic vector value. The calibration precision depends on the standard magnetic field and the attitude measurement of magnetometer. In order to calibrate magnetometer, it need spends a lot of time and cost. Some convenience methods are presented that use Earth's magnetic field vector as a constraint, and estimate the error parameters applied an iterative least-squares algorithm. These methods have some shortages such as: the long computing time [1]. The work in this paper is concerned with developing a novel auto-calibration method for magnetometer triads for precise determination of the magnetic field vector.

This paper is organized in the following manner: First, a model for vector magnetometer output errors is presented. Then a novel auto-calibration method based on ellipsoid fitting is provided. The locus of magnetic field measurements from a triad of magnetometers is constrained to lie on an ellipsoid and how various magnetometer output errors affect this locus. This is followed by a discussion of the results from a series of simulations studies assessing the performance of the algorithm. In the end of this paper, Conclusions are introduced.

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Ⅱ. VECTOR MAGNETOMETER ERROR ANALYSES

Nearly all vector measurements in space are made with ring core fluxgate magnetometers because of high accurate performance, small size and simplicity of signal processing circuitry. So we use the fluxgate magnetometer as the example to build the errors model.

A. Vector Magnetometer Model

In theory, the fluxgate vector magnetometer is composed of three mutually orthogonal ring core fluxgates, and the output voltages of each sensing axis is in direct proportion to the external magnetic field., but the ideal magnetometer is difficult to exact implementation actually. There are three main errors in the magnetic field measurement using the vector magnetometer: the magnetic bias, the sensitivity factor mismatch, the nonorthogonal error of axis-by-axis.

First, let us analyze the ith axis magnetic sensor. Its output signal can be written as:

$$H_{m,i} = k_i H_{e,i} + H_{0,i}; i = x, y, z \tag{1}$$

where $H_{m,i}$ is the measured value of the ith single axis magnetic sensor, $H_{e,i}$ is the component of the external magnetic field vector $\boldsymbol{H_e}$ resolved along the ith axes of the magnetometer, k_i and $H_{0,i}$ are the sensitivity factor and the offset of the sensor separately. Further, if only the sensitivity mismatch is considered for the magnetometer triad, then the measured vector is

$$\boldsymbol{H}'_m = K_1 \boldsymbol{H}_e \tag{2}$$

where $K_1 = \mathrm{diag}(k_x, k_y, k_z)$ is the sensitivity factor matrix, yet k_x, k_y, k_z are not equal each other.

Three sensing axes of the ideal magnetometer are mutually orthogonal, but the complete perpendicularity of axis-by-axis is impossible in fact because of the install technology limitation. On the assumption that the z_1-axis of magnetometer is coincidence with the normal z-axis, a small angle α exists between the x_1-axis and the normal x-axis in xOz plane because the x_1-axis is not perpendicular to the z_1-axis. The angle β is between the projection of y_1-axis and the y-axis in xOy plane, and the y_1-axis makes an angle γ with the xOy plane, see Fig. 1. So the effect on the magnetic field measurement can be described as:

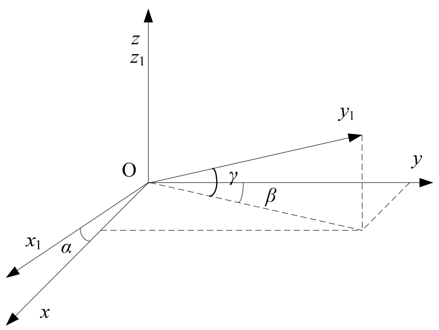

Fig. 1 the nonorthogonal angle of magnetometer

$$\boldsymbol{H}_m = K_2 \boldsymbol{H}_e$$

$$K_2 = \begin{bmatrix} \cos\alpha & 0 & \sin\alpha \\ \sin\beta\cos\gamma & \cos\beta\cos\gamma & \sin\gamma \\ 0 & 0 & 1 \end{bmatrix} \tag{3}$$

Because the nonorthogonal angle α, β and γ are all very small, the matrix K_2 is written as Eq.(4):

$$K_2 \approx \begin{bmatrix} 1 & 0 & \alpha \\ \beta & 1 & \gamma \\ 0 & 0 & 1 \end{bmatrix} \tag{4}$$

In general, considering the synthetical effect of three main error sources: the magnetic bias, the sensitivity mismatch, the nonorthogonal angles, the measured magnetic field vector $\boldsymbol{H_m}$ is

$$\boldsymbol{H}_m = K_1 K_2 \boldsymbol{H}_e + \boldsymbol{H}_0 = K\boldsymbol{H}_e + \boldsymbol{H}_0$$

$$\begin{bmatrix} H_{m,x1} \\ H_{m,y1} \\ H_{m,z1} \end{bmatrix} = \begin{bmatrix} k_{x1} & 0 & \alpha k_{x1} \\ \beta k_{y1} & k_{y1} & \gamma k_{y1} \\ 0 & 0 & k_{z1} \end{bmatrix} \begin{bmatrix} H_{e,x} \\ H_{e,y} \\ H_{e,y} \end{bmatrix} + \begin{bmatrix} H_{0,x} \\ H_{0,y} \\ H_{0,z} \end{bmatrix} \tag{5}$$

where K=K_1K_2 is the scale matrix, $\boldsymbol{H}_0$ is the offset vector of magnetometer triad. If the error parameters K and $\boldsymbol{H}_0$ are known, the external magnetic field can be adjust using Eq.(6).

$$\boldsymbol{H}_e = K^{-1}(\boldsymbol{H}_m - \boldsymbol{H}_0)$$

$$\begin{bmatrix} H_{e,x}^m \\ H_{e,y}^m \\ H_{e,z}^m \end{bmatrix} = \begin{bmatrix} 1/k_{x1} & 0 & -\alpha/k_{z1} \\ -\beta/k_{x1} & 1/k_{y1} & -\gamma/k_{z1} \\ 0 & 0 & 1/k_{z1} \end{bmatrix} \left(\begin{bmatrix} H_{m,x1} \\ H_{m,y1} \\ H_{m,z1} \end{bmatrix} - \begin{bmatrix} H_{0,x} \\ H_{0,y} \\ H_{0,z} \end{bmatrix} \right) \tag{6}$$

Ⅲ. VECTOR MAGNETOMETER CALIBRATION

The purpose of calibration is to estimate a set of parameters K and $\boldsymbol{H}_0$, and to adjust the erroneous measured vector $\boldsymbol{H_m}$ using these parameters so that it is equal to the true external magnetic field vector $\boldsymbol{H_e}$.

A. Locus-Constraint Auto-calibration

When geomagnetic field varies slowly with time, the magnitude of geomagnetic field vector $\boldsymbol{H_e}$, can be regarded as a known constant F_e at a given calibration site in the calibration process. That is,

$$\|\boldsymbol{H}_e\|^2 = (\boldsymbol{H}_e)^T \boldsymbol{H}_e = F_e^2 \tag{7}$$

Substituting Eq.(6) into Eq.(7), and then expanding, gives

$$\begin{aligned} &(\boldsymbol{H}_m)^T (K^{-1})^T K^{-1} \boldsymbol{H}_m - 2(\boldsymbol{H}_0)^T (K^{-1})^T (K^{-1}) \boldsymbol{H}_m \\ &\qquad + (\boldsymbol{H}_0)^T (K^{-1})^T (K^{-1}) \boldsymbol{H}_0 = F_e^2 \end{aligned} \tag{8}$$

Especially, the following condition is met for an ideal magnetometer triad.

$$K_1 = K_2 = I_{3\times3}; \boldsymbol{H}_0 = \boldsymbol{0}_{3\times1} \tag{9}$$

Then

$$\left(\boldsymbol{H}_m\right)^T \boldsymbol{H}_m = H_{m,x}^2 + H_{m,z}^2 + H_{m,z}^2 = F_e^2 \tag{10}$$

From Eq.(10), it is obvious that the measured data vector meet a sphere equality whose centre locate the origin, and radius is the intensity of the external magnetic field. When the offset of each sensing axis is not exist, that is the offset vector $\boldsymbol{H}_0$ is equal to **0**, for any vector $\boldsymbol{H_m}$ is not equal to 0, Eq.(8) is simplified as

$$\left(\boldsymbol{H}_m\right)^T \left(K^{-1}\right)^T K^{-1}\boldsymbol{H}_m = \left\|\boldsymbol{H}_e^m\right\|^2 > 0 \tag{11}$$

So the matrix $\left(K^{-1}\right)^T K^{-1}$ is a positive definite matrix. According to the geometry theory, equality (8) expresses an ellipsoid or sphere concerning the three components of the vector $\boldsymbol{H_m}=[H_{m,x}, H_{m,y}, H_{m,z}]^T$. Eq.(8) indicates that the magnetic field measurements are constrained to lie on an ellipsoid that is determined by error parameters. Furthermore, Eq.(8) can be changed to its quadric standard form.

$$\begin{aligned}\left(\boldsymbol{H}_m\right)^T \frac{\left(K^{-1}\right)^T K^{-1}}{F_e^2}\boldsymbol{H}_m - 2\frac{\left(\boldsymbol{H}_0\right)^T \left(K^{-1}\right)^T \left(K^{-1}\right)}{F_e^2}\boldsymbol{H}_m \\ + \left(\boldsymbol{H}_0\right)^T \frac{\left(K^{-1}\right)^T \left(K^{-1}\right)}{F_e^2}\boldsymbol{H}_0 = 1\end{aligned} \tag{12}$$

When errors of magnetometer are very small, the locus ellipsoid is approximate to a sphere.

Consequently, the auto-calibration process of magnetometer can be separated into two steps [1,2,3]. In the first step, a set of parameters of the optimal ellipsoid is obtained by fitting the measured vector data that is collected from the magnetometer executing a few attitude maneuvers: heading angle, pitch angle or roll angle changes. In the second step, the error parameters are extracted from the optimal ellipsoid parameters determined in the first step.

B. Ellipsoid Fitting

Fitting algebraic curved surface with scatter 3D points has been discussed widely and some excellent work has been done. However, a few of these fitting techniques are ellipsoid specific. In analytic geometry, the conditions that ensure a quadratic surface to be an ellipsoid have been researched in detail. When its leading form is positive definite, the solution of a quadratic equation represents an ellipsoid. Ellipsoid fitting can be performed in several ways by applying some known bounded surface fitting techniques. However, these techniques involve a highly nonlinear optimization procedure, which often stops at a local minimum and can not guarantee an optimal solution. A new ellipsoid fitting algorithm is proposed using the direct least square method in [4]. The fitting algorithm is quick, stable and insensitive to small errors in the data. Because the locus ellipsoid is similar to a sphere, a simplified form of the ellipsoid fitting algorithm is applied in this paper.

According to the analytic geometry theory, a quadric surface is defined as the locus of points such that their coordinates satisfy the most general equation of the second degree in three variables, namely

$$\begin{aligned}F(\boldsymbol{\xi}, \boldsymbol{z}) = \boldsymbol{\xi}^T \boldsymbol{z} = ax^2 + by^2 + cz^2 + 2dxy \\ + 2exz + 2fyz + 2px + 2qy + 2rz + g = 0\end{aligned} \tag{13}$$

where $\boldsymbol{\xi} = [a, b, c, d, e, f, p, q, r, g]^T$ and $\boldsymbol{z} = [x^2, y^2, z^2, 2xy, 2xz, 2yz, 2x, 2y, 2z, 1]^T$. $F(\boldsymbol{\xi}; \boldsymbol{z_i})$ is the algebraic distance of a point P_i (x_i, y_i, z_i) to the quadric surface F(a; x) = 0. A way of Fitting ellipsoid is to minimize the algebraic distance over the set of N data points in the least square sense, namely

$$\hat{\boldsymbol{\xi}} = \arg\min_{\xi\in R^6} \sum_{i=1}^{N} F(\boldsymbol{\xi}, \boldsymbol{z}_i)^2 = \arg\min_{\xi\in R^6} \boldsymbol{\xi}^T D^T D\boldsymbol{\xi}; \tag{14}$$

where $D=[\boldsymbol{z}_1, \boldsymbol{z}_2, \ldots, \boldsymbol{z}_n]^T$; zi=$[x_i^2, y_i^2, z_i^2, 2x_iy_i, 2x_iz_i, 2y_iz_i, 2x_i, 2y_i, 2z_i, 1]^T$. Though the optimal parameters $\boldsymbol{\xi}$ can be solved using the least square method, the corresponding quadric surface may not be an ellipsoid.

It is shown in [4] that when $4J - I^2 > 0$, Eq.(13) must represents an ellipsoid. On the other hand, for an ellipsoid, when its short radius is at least half of its major radius, then the inequality $4J - I^2 > 0$ is satisfied. So $4J - I^2 > 0$ is a necessary and sufficient condition for a quadric surface to be an ellipsoid that short radius is at least half of its major radius. Because the locus ellipsoid is similar to a sphere, and satisfies the limitation that its short radius is at least half of its major radius, $4J - I^2 > 0$ is a constraint condition of Eq.(14) to sure the optimal surface is an ellipsoid approximate to a sphere. So the locus ellipsoid fitting problem is converted to a optimal problem:

$$\hat{\boldsymbol{\xi}} = \arg\min_{\xi\in R^6} \boldsymbol{\xi}^T D^T D\boldsymbol{\xi} \quad \text{subject to } 4J - I^2 = 1 \tag{15}$$

If we define C as a 10×10 matrix in the following way:

$$C = \left[\begin{array}{c|c} C_1 & \mathbf{0}_{6\times4} \\ \hline \mathbf{0}_{4\times6} & \mathbf{0}_{4\times4}\end{array}\right]; C_1 = \left[\begin{array}{ccc|c} -1 & 1 & 1 & \\ 1 & -1 & 1 & \mathbf{0}_{3\times3} \\ 1 & 1 & -1 & \\ \hline & \mathbf{0}_{3\times3} & & -4\boldsymbol{I}_{3\times3}\end{array}\right] \tag{16}$$

The equality $4J - I^2 = 1$ can be written as $\boldsymbol{\xi}^T C\boldsymbol{\xi} = 1$ and the constraint minimization problem (15) becomes that of solving a set of equations using the Lagrange multiplier method:

$$D^T D\boldsymbol{\xi} = \lambda C\boldsymbol{\xi} \tag{17}$$

$$\boldsymbol{\xi}^T C\boldsymbol{\xi} = 1 \tag{18}$$

The matrix C has the eigenvalues {1, -2, -2, -4, -4, -4, 0, 0, 0}. According to the theorem and corollary in [5], [6], the Eq.(17) has only one solution, which is the general eigenvector associated with the unique positive eigenvalue of the general eigenvalue system $D^T D\boldsymbol{\xi} = \lambda C\boldsymbol{\xi}$. The solution $\hat{\boldsymbol{\xi}}$ is the optimal fitting ellipsoid parameter to the 3D scattered points.

Let $X=[x, y, z]^T$, the optimal ellipsoid equality (13) is written as the quadric standard form

$$\left(X-X_0\right)^T A\left(X-X_0\right)=X^T AX-2X_0^T AX+X_0^T X_0=1;$$
$$A=\begin{bmatrix} a & d & e \\ d & b & f \\ e & f & c \end{bmatrix};X_0=-\frac{1}{2}A^{-1}\begin{bmatrix} p \\ q \\ r \end{bmatrix} \tag{19}$$

where matrix A represents the optimal ellipsoid shape, X_0 represents the centre coordinates of the ellipsoid.

C. Solving the model parameters of magnetometer

Comparing Eq.(19) and Eq.(12), we can get the relationship between the model parameters of vector magnetometer and the parameters of the optimal fitting ellipsoid.

$$\begin{cases} K^T K=\dfrac{1}{F_e^2}A^{-1} \\ \boldsymbol{H}_0=X_0 \end{cases} \tag{20}$$

From Eq.(5), the matrix K^TK is written on the sensitivity factors k_{x1}, k_{y1}, k_{z1}, and the nonorthogonal angles α, β, γ.

$$K^T K=\begin{bmatrix} k_{x1}^2+\beta^2 k_{y1}^2 & \beta k_{y1}^2 & \alpha k_{x1}^2+\beta\gamma k_{y1}^2 \\ \beta k_{y1}^2 & k_{y1}^2 & \gamma k_{y1}^2 \\ \alpha k_{x1}^2+\beta\gamma k_{y1}^2 & \gamma k_{y1}^2 & \alpha^2 k_{x1}^2+\gamma^2 k_{y1}^2+k_{z1}^2 \end{bmatrix} \tag{21}$$

Let the inverse matrix of A is

$$A^{-1}=\begin{bmatrix} a' & d' & e' \\ d' & b' & f' \\ e' & f' & c' \end{bmatrix} \tag{22}$$

Substituting Eqs.(21) and (22) to Eq.(20), we can estimate the model parameters of the vector magnetometer.

$$\begin{aligned} &\hat{\alpha}=\frac{b'e'-d'f'}{a'b'-d'^2} \\ &\hat{\beta}=d'/b' \\ &\hat{\gamma}=f'/b' \\ &\hat{k}_{x1}=\sqrt{a'-\beta^2 b'}\Big/F_e \\ &\hat{k}_{y1}=\sqrt{b'}\Big/F_e \\ &\hat{k}_{z1}=\sqrt{c'-\alpha^2\left(a'-\beta^2 b'\right)-\gamma^2 b'}\Big/F_e \\ &\hat{\boldsymbol{H}}_0=X_0 \end{aligned} \tag{23}$$

According to the estimated value of the model parameters, the errors of magnetometer can be compensated using Eq.(6) to obtain the higher accuracy in magnetic field measurement.

D. the Steps of Auto-calibration of vector magnetometer

Through the above analysis, the basis steps of the auto-calibration method for vector magnetometer are described in the following processes:

1. Choose the measure site and time in which the geomagnetic field varies slowly and can be viewed as a constant vector. Then accurately measure the intensity F_e of geomagnetic field.
2. Collect the measured vector data $\boldsymbol{H}_{m,i}=[H_{m,x1,i}, H_{m,y1,i}, H_{m,z1,i}]^T$ (i = 1,2,…, N) from the magnetometer executing a few attitude maneuvers at the measure site. The maneuvers require that the attitude angle such as: heading angle, pitch angle or roll angle must change in a wide range.
3. Fit the optimal ellipsoid to the 3D data set $\{\boldsymbol{H}_{m,i};\ i=1,2,\ldots,N\}$ using the direct least square algorithm to obtain the ellipsoid parameters $\boldsymbol{\xi}=[a, b, c, d, e, f, p, q, r, g]$, and solving the matrix A, the vector X_0.
4. Estimate the model parameters of the vector magnetometer using Eq.(23).
5. Adjust the raw measure vector data using Eq.(6) to improve the accuracy in magnetic field measurement.

Ⅳ. EXPERIMENTATION RESULT

To evaluate the performance of the new auto-calibration method proposed in this paper, the simulation experiments were performed. In this section a representative simulation and the corresponding results are presented.

According to the technical specifications of a precise vector fluxgate magnetometer for sale [7], the accuracy of each axis sensor is ±(0.25% of reading + 5 nT), the corresponding resolution is 1 nT, and the x and y axes sensors are aligned parallel to the base surface and along its length and width edges, respectively, to within ±0.25 degrees. The z axis sensor is aligned normal to the base surface within ±0.25 degrees. In the simulation, the sensitiveness parameters (k_{x1}, k_{y1}, k_{z1}), the offset vector ($H_{0,x}$, $H_{0,y}$, $H_{0,z}$) and the nonorthogonal angles (α, β, γ) are list in Tables 1, 2 and 3, the sensor noise is a normal random signal with mean 0 nT and standard deviation 1 nT. Other simulation conditions are written in following:

- Calibrating site: Long. is 112°E, Lat. is 39°N, High is 0 m.
- Geomagnetic Model: IGRF2005.
- Date: 2009-1-1
- Attitude maneuvers for magnetometer: Heading angle changes from 0° to 360°; Pitch angle from -90° to 90°; Roll angle from -180° to 180°.
- Angle interval of sample points: 10°.

Table 1 Setting Value and Estimated Value of Sensitiveness

	k_{x1}	k_{y1}	k_{z1}
Setting Value	1.0025	0.9975	1.0020
Estimated Value	1.002497	0.997504	1.001980

Table 2 Setting Value and Estimated Value of Offsets

	$H_{0,x}$ (nT)	$H_{0,y}$ (nT)	$H_{0,z}$ (nT)
Setting Value	-5	5	-3
Estimated Value	-4.5607	5.4413	-3.0229

Table 3 Setting Value and Estimated Value of Nonorthogonal Angles

	α (")	β (")	γ (")
Setting Value	900	700	-900
Estimated Value	904.2113	699.1461	-904.4280

Table 4 Statistic of the Measured Error and the Corrected Error

	Measured Error (nT)		Corrected Error (nT)	
	Mean	RMS	Mean	RMS
$H_{m,x}$	-122.5	145.2	0.4204	1.290
$H_{m,y}$	80.00	189.7	-0.4582	1.068
H_{mzy}	-55.87	60.92	-4.323	1.270
F_m	46.15	123.8	0.2662	1.249

The rectangular components of geomagnetic field vector at the calibrating site are $[28215.45, -2613.50\ 47096.29]^T$ nT in the local horizon coordinates, the intensity of geomagnetic field is 54963.64 nT.

The measured vector points and the fitting locus ellipsoid are plot in Fig. 2. It is apparent that the measured points all locate the locus ellipsoid similar a sphere. The optimal ellipsoid parameters $\hat{\xi}$ =[1.0050, 0.9950, 1.0040, 0.003, 0.0044, -0.0044, -4.5607, 5.4413, -3.0229, 1]^T are solved using the direct least square method. The fitting residual mean and standard-deviation are -5.195e-017 and 3.218e-005, separately.

Using Eq.(23), the model parameters of the vector magnetometer is estimated and listed in Tables 1, 2 and 3. Obviously, under the measured noise with standard deviation 1 nT the estimated sensitiveness can reach 10^{-5} precision level; the estimated offset can reach 0.1 nT level; the nonorthogonal angles can reach 1 arc-second level.

Using Eq.(6), the measured data can be corrected. To verify the precision of the auto-calibration method, the statistic of the measured error and the corrected error is compared in Table 4. The theoretical magnetic measured data is obtained from the ideal magnetometer executing the attitude maneuvers and is shown in Fig. 3. The corresponding error curves are plot in Figs. 4 and 5. From Table 4, the corrected data precision improves to 1% of the raw measured data of magnetometer, and reaches to 1 nT precision level. It is shown in Fig.6 that the errors of the corrected data are the random signals without regularity, similar to the white noise.

According to the analysis of a serial of experiments result, the advantages of the auto-calibration method are listed by following:

1. The auto-calibration method does not require the high precision measurement instruments on magnetic field vector and the north reference at the calibration site, only needs obtain the magnitude F_e of geomagnetic field vector.

2. The auto-calibration method is more convenient the conventional methods and only need change randomly the magnetometer attitude, collect the measured vector sequence in that the sample number N >10.

3. The ellipsoid fitting algorithm and the model parameter solution are all linear to avoid the nonlinear calculation and the complex iteration. The auto-calibration method is quick, stable and insensitive to small errors in the data, and the calibration precision is so high that reach the sensor level.

4. Under the low SNR measurement environment, the high calibration precision can be obtained by increasing the angle range of the attitudes change and the sample number.

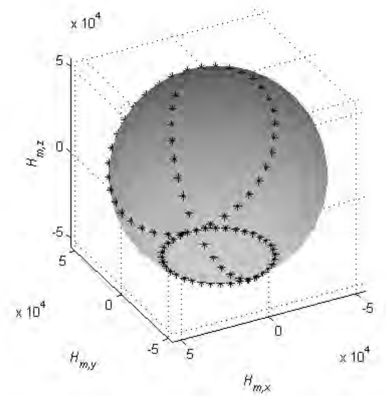

Fig 2 3D figure of fitting ellipsoid and the measured points

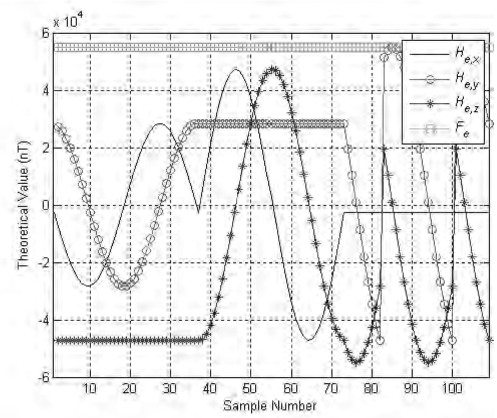

Fig. 3 Theoretical Value of $\boldsymbol{H_m}$

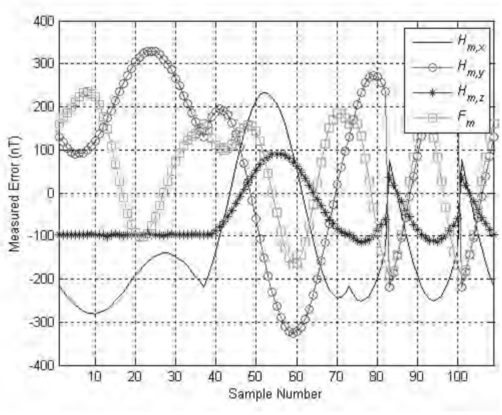

Fig. 4 Measured Error Curves

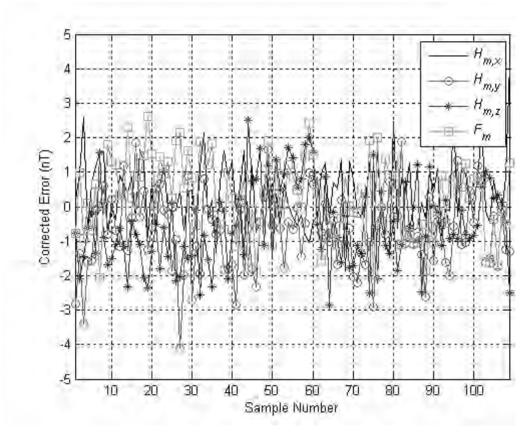

Fig. 5 Corrected Error Curves

Ⅴ. CONCLUSION

In this paper a novel auto-calibration method of the vector magnetometer is presented. Based on the locus-constraint calibration though, the auto-calibration method can be separated into two steps: fitting ellipsoid to the 3D measured data and solving the model parameters of magnetometer from the fitting ellipsoid. According to the model parameters the measured data is corrected to improve the precision of magnetometer. To evaluate the performance of the auto-calibration method, the simulation experiments were performed. The results show that the method is more convenient the conventional methods, and have some advantages such as: quick, stable, high precision and insensitive to small errors in the data.

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