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ITJ

ISSN 1812-5638

INFORMATION TECHNOLOGY JOURNAL

ANSInet
Asian Network for Scientific Information
308 Lasani Town, Sargodha Road, Faisalabad - Pakistan

Information Technology Journal 13 (7): 1376-1380, 2014
ISSN 1812-5638 / DOI: 10.3923/itj.2014.1376.1380

Error Compensation of Geomagnetic Azimuth Sensor Based on Model Identification

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Abstract: In this study, the GMR sensor and triaxial attitude sensor were used to constitute a geomagnetic azimuth measurement system. Based on the error analysis of the triaxial GMR sensor and carrier interfering field, the study proposed an error compensation model which includes the non-orthogonal compensation, sensitivity compensation, zero compensation, hard and soft magnetic interference compensation. Meanwhile, the inversion algorithm based on model identification is studied and the parameter of error characteristics is calculated by it. After compensation, the azimuth error of the measurement system is reduced to 0.34% from 3.83% and the expected objective is realized.

Key words: Azimuth measurement, triaxial non-orthogonal compensation, magnetic interference, inversion algorithm

INTRODUCTION

With the development of science and technology, magnetic field measurement plays an irreplaceable role in the field of scientific research, industrial production, national defense and military. But magnetic sensor is susceptible to hard and soft magnetic interference. Meanwhile, manufacturing error of magnetic sensor also affected accuracy of magnetic measurement. Therefore, how to separate geomagnetic information from complex magnetic field of the carrier is a problem to be solved.

There are many methods of magnetic measurement error compensation but most of them have the disadvantage of model parameters uncertain or complex calculation and some can only be calibrated hard or soft magnetic interference. Qiao *et al*. (2009) proposed a compensation method of carrier magnetic field based on elliptic constraints, it can only compensate two-dimensional magnetometer. Yun *et al*. (2008) using two measurement system for compensation has obtained good effect but increased complexity and cost of the system. Using least squares method to calculate scale factor and zero drift, Yuan (2001) has obtained higher compensation accuracy but the demand of equipment and experimental operation is higher. With external reference information, Jurman *et al*. (2007) has estimated the error model coefficients based on filter technique but it will cause filter divergence when noise is too big. In this study, an azimuth measurement system is constituted. Then based on error analysis of triaxial GMR sensor and carrier interfering field, an azimuth mathematical model is proposed. After that, the inversion algorithm based on model identification is studied and use it to compensate measurement system.

ERROR ANALYSIS AND MODELLING OF AZIMUTH SENSOR BASED ON MODEL IDENTIFICATION

Measurement system of magnetic: During the geomagnetic measurement, the triaxial acceleration sensor ADXL345 is used to measure roll and pitch angle as attitude sensor. The triaxial magnetic field component of the carrier coordinate system is measured by the GMR sensor. According to the measurement requirements, choose NVE AAH02-002 GMR sensor as magnetic measuring element, the DS18B20 digital sensors as temperature measurement modules and choose MSP430 F149 microcontroller as the core processing chip (Zheng and Fu, 2012).

Triaxial GMR sensor error analysis: Due to the limitation of manufacturing process level and installation error of actual circuit, triaxial GMR sensor can't be completely orthogonal. Defining GMR sensor actual coordinate as oxyz, output value of each axis is h_x h_y h_z Meanwhile, the idea coordinate is oxyz and values of each axis is H_X H_Y H_Z. Hypothesis ox and OX is coincidence, the angle between ox and plane YOZ is α_1, oz and plane XOZ is α_3. And the angle between oy and its projection on plane YOZ is α_2, oz and its projection on planeXOZ is

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α_4. And assume that zero draft is B_x B_y B_z and sensitivity coefficient is K_x, K_y, K_z. Then the relationship of h_x, h_y, h_z and H_X, H_Y, H_Z can be deduce as Eq. 1:

$$\begin{bmatrix} h_Z \\ h_Y \\ h_Z \end{bmatrix} = \begin{bmatrix} K_X & 0 & 0 \\ 0 & K_Y & 0 \\ 0 & 0 & K_Z \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ -\sin\alpha_1 & \cos\alpha_2\cos\alpha_1 & \sin\alpha_2\cos\alpha_1 \\ \sin\alpha_4\cos\alpha_3 & -\sin\alpha_3 & \cos\alpha_4\cos\alpha_3 \end{bmatrix} \begin{bmatrix} H_X \\ H_Y \\ H_Z \end{bmatrix} + \begin{bmatrix} B_X \\ B_Y \\ B_Z \end{bmatrix} \tag{1}$$

Interference field analysis of carrier environment: External magnetic interference is mainly caused by hard and soft magnetic materials. Hard magnetic interference is caused by permanent magnetic ferromagnetic material the GMR sensor. And its strength and direction are relatively constant within a certain time. Defining hard magnetic interference is h_{CONS} component is h_{CX}, h_{CY}, h_{CZ} as Eq. 2:

$$h_{CONS} = \begin{bmatrix} h_{CX} \\ h_{CY} \\ h_{CZ} \end{bmatrix} \tag{2}$$

Soft magnetic interference is generated by interaction of geomagnetic field and soft iron materials of carrier. It always changes with attitude of carrier. Defining soft magnetic interference is h_{SOFT}, component is h_{SX}, h_{SY}, h_{SZ}, as Eq. 3. S_{ij} (i, j = 1, 2, 3) is soft magnetic coefficient which represents soft magnetic component of i-axis generated by j-axis. It's a fixed value:

$$h_{SOFT} = \begin{bmatrix} s_{11} & s_{12} & s_{13} \\ s_{21} & s_{22} & s_{23} \\ s_{31} & s_{32} & s_{33} \end{bmatrix} \begin{bmatrix} H_X \\ H_Y \\ H_Z \end{bmatrix} = S \cdot H \tag{3}$$

Azimuth compensation model: Hypothesis that sensor value is h, reference value is H, sensitivity coefficient is K, orthogonal coefficient is A and zero drift is B. Taking into account the influence of hard and soft magnetic interference, the relationship between actual and reference magnetic field value can be draw as Eq. 4:

$$\begin{aligned} h = & \begin{bmatrix} K_X & 0 & 0 \\ 0 & K_Y & 0 \\ 0 & 0 & K_Z \end{bmatrix} \left(\begin{bmatrix} 1 & 0 & 0 \\ -\sin\alpha_1 & \cos\alpha_2\cos\alpha_1 & \sin\alpha_2\cos\alpha_1 \\ \sin\alpha_4\cos\alpha_3 & -\sin\alpha_3 & \cos\alpha_4\cos\alpha_3 \end{bmatrix} + \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{bmatrix} \right) \\ & \begin{bmatrix} H_X \\ H_Y \\ H_Z \end{bmatrix} + \begin{bmatrix} B_X \\ B_Y \\ B_Z \end{bmatrix} + \begin{bmatrix} H_{CX} \\ H_{CY} \\ H_{CZ} \end{bmatrix} \\ = & K \cdot (S + A) \cdot H + B + H_{CONS} \end{aligned} \tag{4}$$

In Eq. 4, soft magnetic coefficient S, triaxial sensitivity K and α_1, α_2, α_3, α_4 fixed value, so k. (S+A) can be expressed as Eq. 5:

$$\begin{aligned} K \cdot (S + A) = & \begin{bmatrix} K_X & 0 & 0 \\ 0 & K_Y & 0 \\ 0 & 0 & K_Z \end{bmatrix} \\ & \left(\begin{bmatrix} 1 & 0 & 0 \\ -\sin\alpha_1 & \cos\alpha_2\cos\alpha_1 & \sin\alpha_2\cos\alpha_1 \\ \sin\alpha_4\cos\alpha_3 & -\sin\alpha_3 & \cos\alpha_4\cos\alpha_3 \end{bmatrix} + \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{bmatrix} \right) \\ = & \begin{bmatrix} K_X(1+S_{11}) & K_X S_{12} & K_X S_{13} \\ K_Y(-\sin\alpha_1 + S_{21}) & K_Y(\cos\alpha_2\cos\alpha_1 + S_{22}) & K_Y(\sin\alpha_2\cos\alpha_1 + S_{23}) \\ K_Z(\sin\alpha_4\cos\alpha_3 + S_{31}) & K_Z(-\sin\alpha_3 + S_{32}) & K_Z(\cos\alpha_4\cos\alpha_3 + S_{33}) \end{bmatrix} \\ = & \begin{bmatrix} a & b & c \\ d & e & f \\ g & h & k \end{bmatrix} \end{aligned} \tag{5}$$

Because of zero drift and hard magnetic interference are fixed value, $B+H_{CONS}$ can be expressed as Eq. 6 and 5 can be simplified as Eq. 7. In this study, triaxial gravity values are measured by acceleration sensor, then calculated the pitch angle γ and roll angle θ. Then through three times rotating based on θ, γ and azimuth angle Ψ, the attitude matrix is deduced as Eq. 8:

$$B + H_{CONS} = \begin{bmatrix} B_X \\ B_Y \\ B_Z \end{bmatrix} + \begin{bmatrix} H_{CX} \\ H_{CY} \\ H_{CZ} \end{bmatrix} = \begin{bmatrix} H_{BCX} \\ H_{BCY} \\ H_{BCZ} \end{bmatrix} \tag{6}$$

$$\begin{bmatrix} h_X \\ h_Y \\ h_Z \end{bmatrix} = \begin{bmatrix} a & b & c \\ d & e & f \\ g & h & k \end{bmatrix} \begin{bmatrix} H_X \\ H_Y \\ H_Z \end{bmatrix} + \begin{bmatrix} H_{BCX} \\ H_{BCY} \\ H_{BCZ} \end{bmatrix} \tag{7}$$

$$\begin{aligned} \begin{bmatrix} H_{X1} \\ H_{Y1} \\ H_{Z1} \end{bmatrix} = & \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix} \\ & \begin{bmatrix} \cos\gamma & 0 & \sin\gamma \\ 0 & 1 & 0 \\ -\sin\gamma & 0 & \cos\gamma \end{bmatrix} \begin{bmatrix} H_{X3} \\ H_{Y3} \\ H_{Z3} \end{bmatrix} \end{aligned} \tag{8}$$

Through the attitude matrix, combining with the geomagnetic azimuth expression under the geomagnetic coordinate, the mathematical model of geomagnetic azimuth can be deduced as Eq. 9:

$$\psi = -\arctan \frac{H_{X3}\sin\theta\sin\gamma + H_{Y3}\cos\theta - H_{Z3}\sin\theta\cos\gamma}{H_{X3}\cos\gamma + H_{Z3}\sin\gamma} \tag{9}$$

With Eq. 7, the expression of the ideal triaxial orthogonal magnetic field can be obtained as Eq. 10:

$$\begin{aligned} \begin{bmatrix} H_X \\ H_Y \\ H_Z \end{bmatrix} = & \begin{bmatrix} a & b & c \\ d & e & f \\ g & h & k \end{bmatrix}^{-1} \left(\begin{bmatrix} h_X \\ h_Y \\ h_Z \end{bmatrix} - \begin{bmatrix} H_{BCX} \\ H_{BCY} \\ H_{BCZ} \end{bmatrix} \right) \\ = & \begin{bmatrix} l & m & n \\ o & p & q \\ r & s & t \end{bmatrix} \begin{bmatrix} h_X \\ h_Y \\ h_Z \end{bmatrix} - \begin{bmatrix} h_{BCX} \\ h_{BCY} \\ h_{BCZ} \end{bmatrix} \end{aligned} \tag{10}$$

$$\psi = -\arctan \frac{(lh_X + mh_Y + nh_Z - h_{BCX})\sin\theta\sin\gamma + (oh_X + ph_Y + qh_Z - h_{BCY})\cos\theta - (rh_X + sh_Y + th_Z - h_{BCZ})\sin\theta\cos\gamma}{(lh_X + mh_Y + nh_Z - h_{BCX})\cos\gamma + (rh_X + sh_Y + th_Z - h_{BCZ})\sin\gamma} \tag{11}$$

Using H_X, H_Y, H_Z instead of H_{X3}, H_{Y3}, H_{Z3} in Eq. 9 with Eq. 10, the error compensation mathematical model of the azimuth can be obtained as Eq. 11.

Inversion compensation algorithm based on model identification: Inversion algorithm with fast convergence and high estimation accuracy is to find out unknown properties of the objects which used in scientific and engineering areas more and more widely (Jing-Lei and Zhi-Jian, 2011). It's a kind of iterative algorithm based on principle of least squares and combined with statistical average thought. For multiple unknown input structures, the inversion algorithm can be used to identify the structural parameters. Therefore, it can be a good solution to the parameter estimation of this system. In order to facilitate calculation, g_i (j = 1, 2, 3) is used to instead of unknown parameters h_{SCX}, h_{SCY}, h_{SCZ} use θi(i = 1...9) instead of l, m, n, o, p, q, r, s, t, as Eq. 12:

$$\psi = f(\theta_i, g_j) \tag{12}$$

Assuming that sampling points is N, the steps of inversion algorithm based on model identification is shown in Fig. 1:

Step 1: Initialization: Normalized sample data

Step 2: Setting initial value of the estimated parameters $\hat{\theta}_{0i}$ and $\hat{g}_{0j}$ i = 1..9 j = 1,2,3

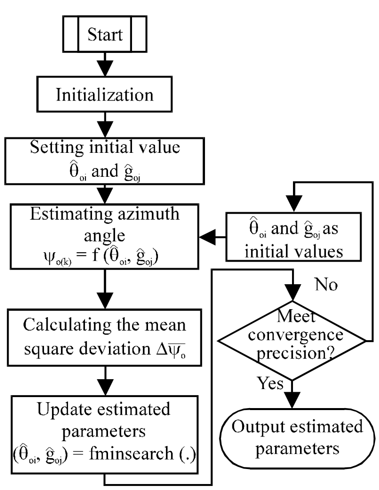

Fig. 1: Inversion algorithm flow chart based on model identification

Step 3: Estimating azimuth $\psi_{O(k)}$ through Eq. 13, k = 1,2...N, i = 1...9, j = 1,2,3:

$$\psi_{O(k)} = f(\hat{\theta}_{0i}, \hat{g}_{0j}) \tag{13}$$

Step 4: Calculating mean square deviation $\Delta\overline{\psi}_O$ between reference angle $\psi_{M(k)}$ and estimated azimuth angle $\psi_{O(k)}$:

$$\Delta\overline{\psi}_O = \frac{1}{N}\sum_{k=1}^{N}(\psi_{M(k)} - \psi_{O(k)})^2 \tag{14}$$

Step 5: Calculating statistical average of sample data, then though parameter inversion algorithm update $\hat{\theta}_{1i}$ and $\hat{g}_{1j}$ with the condition of $\Delta\overline{\psi}_O$ is minimum, among them fminsearch(.) is multidimensional unconstrained optimization function:

$$(\hat{\theta}_{1i}, \hat{g}_{1j}) = \text{fminsearch}\left(\frac{1}{N}\sum_{k=1}^{N}(\psi_{M(k)} - \psi_{O(k)})^2\right) \tag{15}$$

Step 6: Determine whether $\hat{\theta}_{1i}$ and $\hat{g}_{1j}$ meet the convergence condition:

$$\frac{\sum_{i=1}^{9}\left(\hat{\theta}_{ki} - \hat{\theta}_{k-1i}\right)^2}{\sum_{i=1}^{9}\hat{\theta}_{k-1i}^2} + \frac{\sum_{j=1}^{3}\left(\hat{g}_{kj} - \hat{g}_{k-1j}\right)^2}{\sum_{j=1}^{3}\hat{g}_{k-1j}^2} \le \varepsilon \tag{16}$$

Among them $\hat{\theta}_{ki}$ and $\hat{g}_{kj}$ are the estimated value of θ_i and g_j, is ε the target convergence accuracy. If it meets Eq. 16, estimated parameters achieved required accuracy. Or it needs further iteration $\hat{\theta}_{ki}$ and $\hat{g}_{kj}$ will serve as estimated initial value and repeat steps 3-6 until it converge to target accuracy or reach the maximum number of iterations.

SIMULATION RESULTS AND ANALYSIS

In order to verify the compensation algorithm, its performance is evaluated in Matlab with the experimental data. In experimental, high-precision turntable, standard azimuth instrument and GMR azimuth system are used. Firstly, the standard azimuth instrument and GMR azimuth system installed on the turntable and make the standard azimuth instrument coordinate and the GMR azimuth system coordinate coincide as far as possible. Then rotate turntable and record the reference azimuth, output value of GMR sensor, pitch and roll angle under different attitude. And repeat it 27 times. According to the Eq. 9,

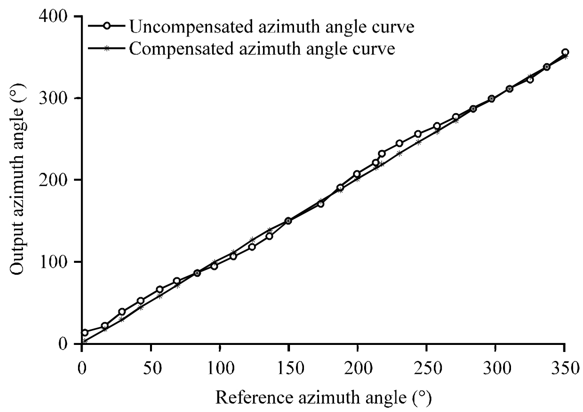

Fig. 2: Compensation contrast chart of the GMR azimuth output angle

Table 1: Experimental data comparison table of the reference azimuth, the measured azimuth calculated by Eq. 9 and the compensated azimuth calculated by Eq. 11

No.	Reference azimuth (°)	Measured azimuth (°)	Compensated azimuth (°)
1	3	12.03	2.36
2	17	21.38	16.78
3	30	38.44	29.59
4	44	52.90	44.20
5	57	64.88	57.60
6	70	76.02	70.57
7	84	85.92	85.21
...	...	...	...
17	218	231.78	218.28
...	...	...	...
25	324	321.90	323.8641
26	337	336.07	336.5882
27	350	353.49	349.3381
Error	0	3.83%	0.34%

uncompensation azimuth angle of system is calculated as shown in Table 1.

Using experiment data through inversion compensation algorithm in Matlab, the compensation coefficient is obtained as:

$$\begin{bmatrix} l & m & n \\ o & p & q \\ r & s & t \end{bmatrix} = \begin{bmatrix} 1.021 & 0.025 & -0.008 \\ -0.118 & 1.175 & 0.023 \\ 0.057 & -0.018 & 0.982 \end{bmatrix} \begin{bmatrix} h_{BCX} \\ h_{BCY} \\ h_{BCZ} \end{bmatrix} = \begin{bmatrix} 22 \\ 43 \\ -29 \end{bmatrix}$$

Simulation with the compensation coefficient and Eq. 11, compensated azimuth angle can be obtained as Table 1. The compensation contrast chart of the GMR azimuth angle is shown in Fig. 2, effect of error contrast is shown in Fig. 3.

As shown in Table 1, Fig. 2 and 3, the experiments show that: The proposed compensation model for the GMR azimuth measurement system in this study is very effective and the inversion compensation algorithm based on model identification is applicable to the system. By compensation, the accuracy of the system has been greatly improved.

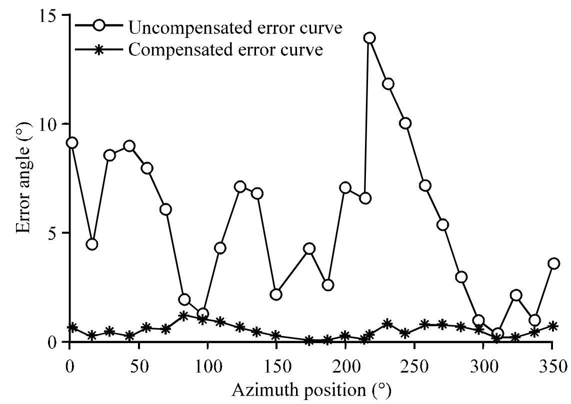

Fig. 3: Error comparison curve chart of uncompensated azimuth calculated by Eq. 9 and compensated azimuth calculated by Eq. 11

CONCLUSION

In this study, an error compensation model is proposed, which includes the non-orthogonal compensation, sensitivity compensation, zero compensation, hard and soft magnetic interference compensation. Then the inversion algorithm based on the model identification is studied and use it to calculate error characteristics parameters and implement the compensation of the system. Experiments show that: The azimuth deviation angle of the system is reduced to 1.21 degree from 13.78%. The azimuth error decreased to 0.34 from 3.83% and achieved a good compensation effect.

ACKNOWLEDGMENT

This study was supported by Key Project of Science and Technology Commission of Shanghai Municipality under Grant 11dz1121602, the National 863 high-tech research projects 2011AA040103-7, the Shanghai Key Laboratory of Power Station Automation Technology.

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