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Error Correction Method for Three-Axis Fluxgate Sensors Based on Genetic Algorithm

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Abstract: Three-axis fluxgate sensors are widely applied in both military and civil fields. However, their measurement accuracy is affected by factors such as triaxial non-orthogonality, bias, and inconsistent scale factors, leading to the phenomenon of heading error and thus reducing the reliability of magnetic measurement data. To improve the measurement accuracy of the sensors, precise correction of systematic errors is required. This paper proposes an error correction method based on genetic algorithm (GA). First, the error sources of three-axis fluxgate sensors are theoretically analyzed, and corresponding mathematical models are established. On this basis, a nonlinear objective function containing error parameters is constructed, and the global optimization capability of GA is utilized to solve the optimal error parameters, ultimately achieving high-precision compensation for sensor errors. The simulation results show that this method can effectively correct the systematic errors of magnetic sensors and enhance their measurement accuracy.

Keywords: Three-axis fluxgate sensor; Error correction; Genetic algorithm.

1. Introduction

In recent years, with the development of military forces, submarine and anti-submarine warfare has become a critical pattern of naval warfare under high-tech conditions, whose confrontation results have a significant impact on the development of wars. Meanwhile, in submarine and underground areas affected by wars, a large number of unexploded ordnances (UXOs) exist, constantly threatening people's lives. In the civil field, effective means are urgently needed to address issues such as object salvage, resource exploration, and detection of buried objects like optical cables and cables [1-9].

Due to the characteristics of geomagnetic information, such as insusceptibility to climate and terrain environments, convenient measurement, and non-contact requirement, it demonstrates greater application value compared with other detection methods. Meanwhile, owing to the extensive use of ferromagnetic materials, detecting the magnetic field in areas where magnetic targets are located by sensors has become a feasible detection method. Among them, three-axis fluxgate sensors possess important application value in the field of geomagnetic detection due to their advantages of small size, light weight, simple structure, high sensitivity, low power consumption, convenient use, good robustness, and high resolution [10]. High-quality magnetic measurement serves as the foundation for magnetic measurement applications. However, in practical environments, due to limitations in sensor processing technology and installation level, the three-axis fluxgate sensors actually used inevitably have triaxial orthogonality errors, bias errors, and scale factor errors, which severely affect detection accuracy [11]. Therefore, it is extremely necessary to correct and compensate for the errors of three-axis fluxgate sensors.

Magnetic detection instruments include fluxgate sensors and cesium optical pump sensors. The fluxgate sensor is a vector sensor that can measure the component of the magnetic field in a certain direction. Therefore, combining three orthogonally oriented fluxgates into a three-axis fluxgate can measure the components of the magnetic field in three directions, thereby obtaining magnetic field vector data. The cesium optical pump sensor is a scalar sensor that cannot acquire magnetic field vectors but can only measure the magnitude of the magnetic field. At present, the main error correction methods for three-axis magnetic sensors are scalar correction and vector correction. Scalar correction is performed through the magnetic field magnitude, which is measured by an optical pump. Vector correction is performed through the three components of the magnetic field, which are measured by a three-axis fluxgate sensor.

This paper proposes an error correction method based on the genetic algorithm. First, the error sources of three-axis fluxgate sensors are theoretically analyzed, and corresponding mathematical models are established. On this basis, a nonlinear objective function containing error parameters is constructed, and the global optimization capability of the genetic algorithm is used to solve the optimal error parameters, ultimately achieving high-precision compensation for sensor errors. Simulation results show that this method can effectively correct the systematic errors of magnetic sensors and improve their measurement accuracy.

2. Error Analysis and Modeling of Three - axis Fluxgate Sensors

The error sources of three-axis fluxgate sensors include triaxial non-orthogonality error, sensitivity error, and zero-offset error. An error model is established based on these error factors.

In an ideal case, the three sensitive axes of a three-axis fluxgate sensor are mutually orthogonal. However, due to limitations in manufacturing processes and other reasons, the three sensitive axes cannot be perfectly orthogonal in practice. Therefore, the measured three-component values of the spatial magnetic field deviate from the orthogonal three components of the magnetic field, and this error is referred to as non-orthogonality error.

Suppose the ideal orthogonal coordinate system is oxyz, and the sensor coordinate system is ox'y'z'. The oz axis coincides with the oz' axis, the angle between oy and oy' is γ, the angle between ox' and the xoy plane is β, and the angle between the projection of ox' on the xoy plane and the ox axis is α. The relationship between the fluxgate sensor coordinate system and the orthogonal coordinate system is shown in Figure 1.

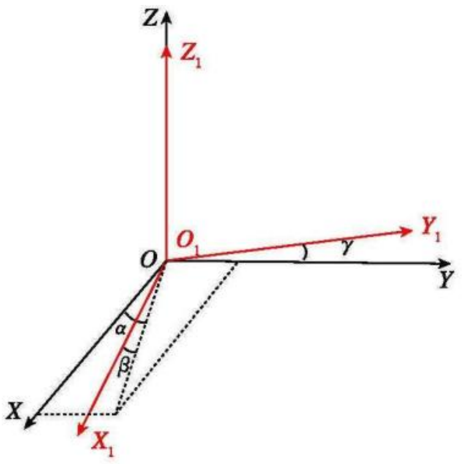

Figure 1. Relationship between Fluxgate Sensor Coordinate System and Orthogonal Coordinate System

Let the ideal value of the geomagnetic field be $\mathbf{B}=\begin{bmatrix}B_x\\B_y\\B_z\end{bmatrix}$ and the sensor measurement value be $\mathbf{B}_1=\begin{bmatrix}B_{x1}\\B_{y1}\\B_{z1}\end{bmatrix}$. According to Figure 1, it can be obtained Equation 1.

$$\boldsymbol{B}_1=\boldsymbol{AB} \tag{1}$$

where A is the transformation matrix. A can be expressed as Equation 2.

$$\boldsymbol{A}=\begin{bmatrix}\cos\alpha\cos\beta & \sin\alpha\cos\beta & \sin\beta\\ 0 & \cos\gamma & \sin\gamma\\ 0 & 0 & 1\end{bmatrix} \tag{2}$$

Since α, β, and γ are all small values, it can be simplified as Equation 3.

$$\boldsymbol{A}=\begin{bmatrix}1 & \alpha & \beta\\ 0 & 1 & \gamma\\ 0 & 0 & 1\end{bmatrix} \tag{3}$$

In general, the output value of a magnetic sensor with scale factor errors is proportional to the true magnetic field value. Assuming that the scale factor error matrix is K, there is Equation 4.

$$\boldsymbol{K}=\begin{bmatrix}K_x & 0 & 0\\ 0 & K_y & 0\\ 0 & 0 & K_z\end{bmatrix} \tag{4}$$

The zero-offset error is equivalent to superimposing a fixed magnetic field on each axis of the fluxgate sensor, causing a shift in the component values of the measured magnetic field. Assuming the zero-offset error is b, there is Equation 5.

$$\boldsymbol{b}=\begin{bmatrix}b_x & b_y & b_z\end{bmatrix}^T \tag{5}$$

Through the above analysis, the error parameter model can be established to obtain Equation 6.

$$\begin{bmatrix}B_{x2}\\B_{y2}\\B_{z2}\end{bmatrix}=\begin{bmatrix}1 & \alpha & \beta\\ 0 & 1 & \gamma\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}K_x & 0 & 0\\ 0 & K_y & 0\\ 0 & 0 & K_z\end{bmatrix}\begin{bmatrix}B_x+b_x\\B_y+b_y\\B_z+b_z\end{bmatrix} \tag{6}$$

where $\mathbf{B}_2=\begin{bmatrix}B_{x2} & B_{y2} & B_{z2}\end{bmatrix}^T$ is the sensor measurement value and $\mathbf{B}=\begin{bmatrix}B_x & B_y & B_z\end{bmatrix}^T$ is the true value of the measured magnetic field.

3. Error Correction Method for Three-Axis Fluxgate Sensors Based on Genetic Algorithm

The genetic algorithm (GA) is an optimization algorithm simulating the process of biological evolution, proposed by John Holland in 1975. Its core idea is based on Darwin's theory of natural selection, searching for the optimal solution in the solution space through operations such as selection, crossover (recombination), and mutation. GA is particularly suitable for nonlinear, multi-modal, or high-dimensional optimization problems. The key steps of GA are as follows:

(a)Coding: Represent the solution of the problem as chromosomes (usually binary strings, real numbers, or permutations). Common coding methods include: Binary coding: The solution x is represented as an n-bit binary string, e.g., x=1011. And Real coding: Directly use real-valued vectors, suitable for continuous optimization problems.

(b)Initializing the population: Randomly generate N individuals (chromosomes) to form the initial population P(t), where t=0.

(c)Fitness function: Define a function f(x) to evaluate the quality of individuals, usually related to the objective function.

(d)Selection: Select high-quality individuals to enter the next generation based on fitness. Common methods include:

Tournament selection: Randomly select k individuals and retain the one with the highest fitness.

(e)Crossover: Exchange parts of the genes of two parent individuals with probability pc to generate offspring. Single-point crossover: Randomly select a point and exchange subsequent genes.

(f)Mutation: Randomly change gene values with probability pm to maintain population diversity.

(g)Termination condition: Stop iterating when the following conditions are met: reaching the maximum number of generations T or fitness convergence (e.g., no significant change in the optimal solution for k consecutive generations).

By combining the error modeling of three-axis magnetic sensors with the genetic algorithm, the objective function f is constructed. Taking the modulus of the sensor measurement values $\mathbf{B}_2=\begin{bmatrix}B_{x2} & B_{y2} & B_{z2}\end{bmatrix}^T$ in Equation (6) yields: $\mathbf{B}_{2\mathrm{T}}=\sqrt{B_{x2}^2+B_{y2}^2+B_{z2}^2}$.

The ideal total geomagnetic field modulus is B_T. When there is no error: $B_{2T}=B_T$,Thus, we can construct the objective function as follows: $f = \min\left|B_{2T} - B_T\right|$.

where B_{2T} contain the error parameters. Solving the objective function f completes the error correction.

4. Simulation Experiments and Result Analysis

MATLAB is used for simulation verification, where the ideal total geomagnetic field is set to 50000 nT, the magnetic dip angle is 56°, and the magnetic declination angle is 24°. In the simulation, 100 groups of ideal three-component magnetic fields are first generated, and then error parameters of non-orthogonality, zero-offset, and scale factors are added. The added error parameters are the preset values in Table 1, and the values estimated by the genetic algorithm are the estimated values in Table 1. The simulation results are shown in Table 1 below:

Table 1. Simulation Experiment results

Error Parameters	Non-orthogonality Error Parameters			Scale Factor Error Parameters			Zero-Offset Error Parameters		
	α	β	γ	K_x	K_y	K_z	b_x	b_y	b_z
Preset Values	0.099	0.08	0.065	1.1	0.9	099	54	65	73
Estimated Values	0.095	0.075	0.06	1.0	0.85	0.96	51	62	73

From Table 1, it can be seen that the preset values in the table are the error parameters we set, and the estimated values are the parameter estimates obtained by optimizing the objective function containing error parameters using the genetic algorithm. From the simulation results, the estimated values are quite close to the preset error parameters.

We substitute the obtained estimated values into the error-contained measured values for inversion to obtain the corrected results. Moreover, we use the magnetic field magnitude as an index to evaluate the correction effect before and after correction.

It can be seen from Figure 2 that the total magnetic field magnitude of the sensor before correction is between 30000 and 70000 nT, while the ideal total geomagnetic field we set is 50000 nT. It can be seen that the error of the uncorrected sensor is relatively large. As shown in Figure 3, the magnetic field magnitude of the sensor after correction is between 50100 and 49940 nT, which is very close to the ideal total geomagnetic field of 50000 nT. In addition, we made a comparison before and after correction, and the difference between the sensor magnitude before correction and the ideal magnitude, as well as the difference between the sensor magnitude after correction and the ideal magnitude, are shown in Figure 4. It can be seen that the correction has achieved good results.

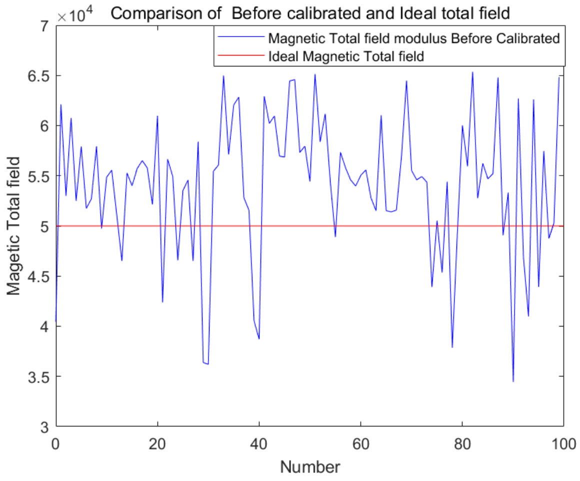

Figure 2. Effect Before Correction

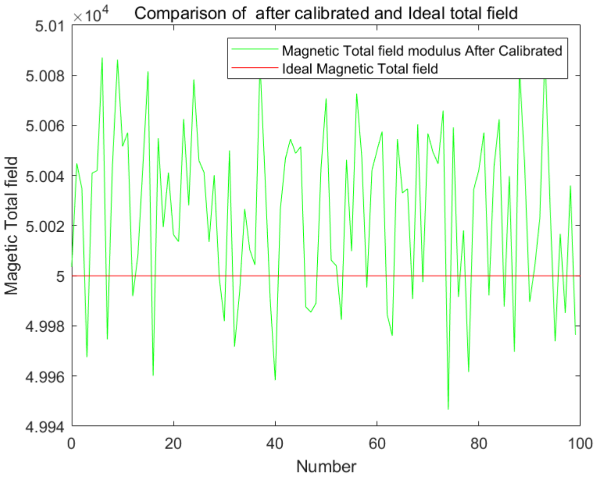

Figure 3. Effect After Correction

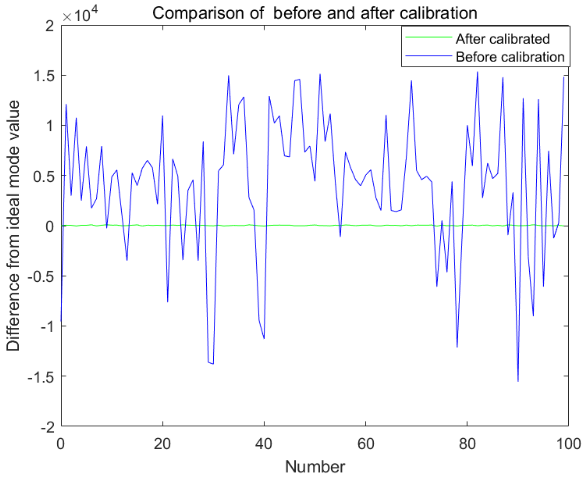

Figure 4. Comparison Before and After Correctio

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