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***Journal of Scientific and Engineering Research*, 2025, 12(2):40-45**

Research Article

ISSN: 2394-2630
CODEN(USA): JSERBR

Error Compensation of Gyroscope while Drilling based on IMOA

Longxi Li*, Jinxian Yang

School of Electrical Engineering and Automation, Henan Polytechnic University, Jiaozuo, China,454003
*Email: 17669475@qq.com

Abstract: In view of the influence of the gyro error parameters on MWD environment, an improved sea cat algorithm is proposed to compensate for the gyro error. Firstly, the error model of gyroscope is derived and the error parameters to be identified are determined. Meerkat optimization algorithm (MOA) is used to solve the optimal value of the error vector. Based on the MOA algorithm, a guided spiral global update method is designed, and a dimensional-by-dimension reward mechanism is used to obtain the better solution of each dimensional error factor, set the local migration route, and redefine the deviation to simulate the change of error parameters. Finally, the IMOA algorithm is applied to identify gyroscope error parameters. The results show that the gyro output error after IMAO algorithm compensation is significantly reduced, and the well inclination error is reduced from 9.54° to 2.53°. Compared with PSO algorithm and MOA algorithm, the recognition accuracy is higher.

Keywords: Measurement while drilling; MOA; MEMS gyroscope; Error compensation

1. Introduction

With the development of Micro Electronic Mechanical System (MEMS) technology, MEMS gyroscope is widely used in the field of MWD because of its characteristics of small size, low weight and low power consumption [1]. MEMS gyroscopes are the core components of MWD and can provide direction and inclination data for measurement, but like other sensors, MEMS gyroscopes inevitably produce errors when measuring angular rate due to changes in the external environment or internal structure. The error of MEMS gyroscope can be roughly divided into constant drift and random drift error according to its characteristics. The constant drift includes zero bias error, non-orthogonal error and scale error. Random drift errors include temperature drift error, quantization noise, Angle random walk, etc. [2]. During drilling, due to the interaction between the bit and different geological layers, a large amount of vibration or even shock will be generated, and the gyro output will contain large errors, and the errors will continuously accumulate with the integration process, which seriously affects the attitude solution. Therefore, accurate identification of gyroscope error parameters is particularly important in MWD [3]. All content should be written in English and should be in Single column.

Among the traditional gyroscope data methods, such as finite impulse response filtering and least mean square filtering, they are characterized by large computation and complex structure, and are difficult to apply to the drilling environment [4-5].The meta-heuristic optimization algorithm proposed in recent years is a kind of algorithm used to find the optimal solution or approximate optimal solution by simulating the predation or migration process of natural population, which has good performance in parameter identification. Wei J [6] et al. proposed a gyro hybrid compensation model based on genetic particle swarm variational mode decomposition and improved BP algorithm, which overcomes the problem of falling into local optimality. However, this method has incomplete processing of drift terms from other sources, resulting in limited error elimination effect. Yang Jinjian et al. [7] proposed a gyroscope error parameter identification method based on magnetic gravity floating algorithm to compensate the gyroscope output error, and the well inclination error was reduced from 9.75° to 1.52°, but the algorithm was greatly affected by magnetic intensity interference.

Meerkat optimization algorithm (MOA) is a meta-heuristic optimization algorithm proposed by Xian S et al. [8] to simulate the behavior pattern of sea cats in nature. Its group cooperation, information transfer, adaptive adjustment and other features have certain advantages in the identification of GYRO error parameters while drilling: When the sea cat is in the global search state, it can quickly find the global optimal error parameter with the same probability of hunting prey. Meanwhile, the information exchange between different error parameters obtained in each iteration makes the identification parameters constantly self-adjust to improve the accuracy, which helps to compensate the constant drift error of the gyroscope. In local search, Haicat quickly transforms the search mode in the face of different threats, has good adaptability in identifying error parameters that are constantly changing randomly under the influence of the environment, and can effectively deal with unpredictable random errors in a timely manner.

This paper presents an improved sea-cat algorithm to compensate for the error of gyroscope while drilling. Firstly, the error compensation model of gyroscope is established through error analysis. In the global search state, the global update direction is controlled by guided spiral update and the error vector information is exchanged by setting up a dimensional reward mechanism to ensure the optimal solution of each dimensional error parameter. In the local update, when the current optimal error vector changes, the deviation is redefined and the overall migration route is added to simulate the error parameter changing direction, so that the error parameter quickly converges to the optimal. Finally, the IMOA algorithm is applied to identify the error parameters of the gyroscope. The performance of the IMOA algorithm is verified by the comparison between the rotary table experiment and the actual drilling experiment, and the error compensation problem of MEMS gyroscope is effectively solved.

2.The IMOA Algorithm Compensates the Error

Output model of MEMS gyroscope

The deterministic error of MEMS gyroscope is mainly composed of zero bias, scale factor and non-orthogonal error. The error model is established according to the error sources of MEMS gyroscope:

$$\tilde{\boldsymbol{\omega}} = \boldsymbol{\omega} + S\boldsymbol{\omega} + \boldsymbol{b} + \boldsymbol{\varepsilon} \tag{1}$$

where $\boldsymbol{\omega} = [\omega_x \ \omega_y \ \omega_z]^T$ is the measured value of each axis output of the gyroscope, $\tilde{\boldsymbol{\omega}} = [\tilde{\omega}_x \ \tilde{\omega}_y \ \tilde{\omega}_z]$ is the real angular velocity of MEMS gyroscope, is the scale factor error matrix. The scale factor is the ratio of the gyroscope input angular velocity to the measured output angular velocity. Ideally, its value is 1, but it will show nonlinear and asymmetric characteristics under the influence of the MWD environment [9].

The error compensation model obtained from equation (1) is as follows:

$$\boldsymbol{\omega} = P(\tilde{\boldsymbol{\omega}} - \boldsymbol{b}) \tag{2}$$

where $p = (I_3 + \boldsymbol{S})^{-1}$, I_3 is the identity matrix. Let the error compensation matrix be:

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

Finally, the 12-dimensional error factor vector of MEMS gyro while drilling is obtained:

$$Q = [p_{11} \ p_{12} \ p_{13} \ \cdots \ b_x \ b_y \ b_z]^T \tag{4}$$

Objective function

The error in the output angular velocity of MEMS gyroscope will accumulate with the integration, which makes the gyroscope produce cumulative error and affect the measurement accuracy. However, there is no cumulative error in attitude calculation by the accelerometer of the MWD system [10]. If there is C_n^b deviation in gyro solution, the rotation matrix C_n^b from the navigation coordinate system (n- system) to the drill tool coordinate system (b- system) will be deviated accordingly, and the gravitational acceleration $\hat{\boldsymbol{g}}_b$ calculated by the accelerometer through rotation matrix A will also be deviated from the actual gravitational acceleration $\boldsymbol{g}_b$. Defined by the cross product: $\|\hat{\boldsymbol{g}}_b \times \boldsymbol{g}_b\| = \|\hat{\boldsymbol{g}}_b\|\|\boldsymbol{g}_b\|\sin\theta$, the magnitude of the deviation is positively correlated with the Angle between the two vectors, so the objective function is established by using the output characteristics of the accelerometer [11].

$$f_{\min} = \left| \arcsin \frac{\left\| \hat{\boldsymbol{g}}_b \times \boldsymbol{g}_b \right\|}{\left\| \hat{\boldsymbol{g}}_b \right\| \left\| \boldsymbol{g}_b \right\|} \right| \tag{5}$$

Error parameters are identified in IMOA global state

The update mode in the global state is reset as follows:

$$\boldsymbol{X}_i^{t+1} = \boldsymbol{X}_i^t + step * [(1-\beta)_2 e^{\beta} \cos 2\pi\alpha_1 + \beta \boldsymbol{X}_{gb}^t] \tag{6}$$

where $\beta = \left\| \boldsymbol{g}_b \right\| / \left\| \hat{\boldsymbol{g}}_b \right\|$ is the boot factor. The value range is 0,1. The actual gravitational acceleration in vertical drilling is equal to the gravitational acceleration modulus theory calculated by rotation matrix. When β is small, the error parameter is poor, and the randomness of the search space is increased by spiral updating. When β is large, the error parameters obtained at this time have better precision, and the smaller spiral traversal in the process of convergence towards the current optimal error parameters prevents the algorithm from falling into the local optimal. The orientation of error parameter identification is controlled by guided spiral updating, and the efficiency and accuracy of the error parameters are improved.

At the same time, the dimensional information reward is set when updating, and different error parameters under the current iteration are selected for information exchange:

$$\boldsymbol{X}_i^{t+1} = \boldsymbol{X}_i^t + step * \left(\frac{T_m(\boldsymbol{X}_j^t)}{T_m(\boldsymbol{X}_j^t) + T_m(\boldsymbol{X}_i^t)} * X_j^t - \frac{T_m(\boldsymbol{X}_i^t)}{T_m(\boldsymbol{X}_j^t) + T_m(\boldsymbol{X}_i^t)} * \boldsymbol{X}_i^t \right) \tag{7}$$

Combined with the gyro error model, the 12-dimensional [12] error vector estimate of MEMS gyroscope is obtained by least square method:

$$\tilde{\boldsymbol{Q}} = [\tilde{p}_{11}\ \tilde{p}_{12}\ \tilde{p}_{13}\ \cdots\ \tilde{b}_x\ \tilde{b}_y\ \tilde{b}_z]^T \tag{8}$$

A one-dimensional error parameter that X_i^t and X_j^t need to compare is brought into the estimation error parameter for comparison. If the objective function is low, one point is scored. If the objective function is not scored, the total score is the dimensional-by-dimension information reward score:

$$T_m(\boldsymbol{X}_i^t) = \sum_{k=1}^{n} \tau_{ik} \tag{9}$$

where τ_{ik} is the score obtained by the k-dimensional error parameter of the error vector X_i^t.

$$\tau_{ik} = \begin{cases} 0 & F(X_{ik}) > F(X_{jk}) \\ 1 & F(X_{ik}) \le F(X_{jk}) \end{cases} \tag{10}$$

where, $F(X_{ik})$ is the value of the objective function obtained after the Jth dimension of the error vector X_i is substituted into the error vector estimate. The dimensional-by-dimension reward mechanism enables the error vector to retain the dominant solution to a greater extent during information exchange, preventing the error vector from falling into the local optimal.

Identification error parameters in IMOA local state

When the historical optimal error parameter changes, the local update will be carried out in random direction, which makes the original algorithm produce more work and there is a risk of falling into the local optimal. In the environment of intermittent disturbance while drilling, the error parameters of gyroscope will be disturbed up and down around the historical optimal value. Therefore, an all-over transfer local update method to determine the deviation is proposed to identify the error parameters:

$$\boldsymbol{X}_i^{t+1} = [1 - \sin(2t/T)] * div * \boldsymbol{X}_i^t - (2 * rand * \boldsymbol{X}_{gb}^t - \boldsymbol{X}_i^t) \tag{11}$$

The random deviation div in the original algorithm is defined as the Cartesian distance between the error parameter of the current individual identification and the historical optimal error parameter:

$$div = \sqrt{\sum_{k=1}^{n} (\boldsymbol{X}_{ik}^t - \boldsymbol{X}_{gk}^t)^2} \tag{12}$$

At this time, when the error parameters change, the sinusoidal migration update is introduced to make the error parameters quickly migrate to the new optimal solution.

3. Results

3.1Turntable experiment

In order to verify the accuracy of IMOA algorithm in the identification of gyroscope error parameters in MWD environment, PSO algorithm, MOA algorithm and IMOA algorithm were used to identify the gyroscope error parameters respectively. The IMU composed of gyroscope, accelerometer and magnetometer was fixed on the turntable. At this time, the X-axis and Y-axis were placed horizontally and the Z-axis was placed vertically. The turntable was set to rotate along the Z-axis with the rotating speed of 180°/s and the gyro sampling frequency of 30Hz. The population number is set to 50, the maximum number of iterations is set to 500, and the fitness functions are all objective functions established by the formula. Error compensation was performed on 5000 data points, and the convergence curves of the three algorithms were obtained as shown in the figure:

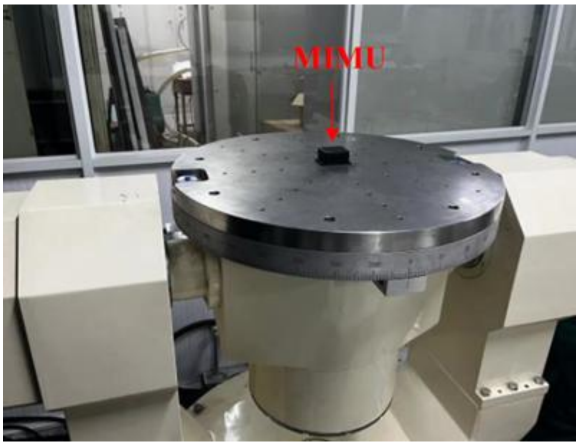

Figure 1: Turntable experiment

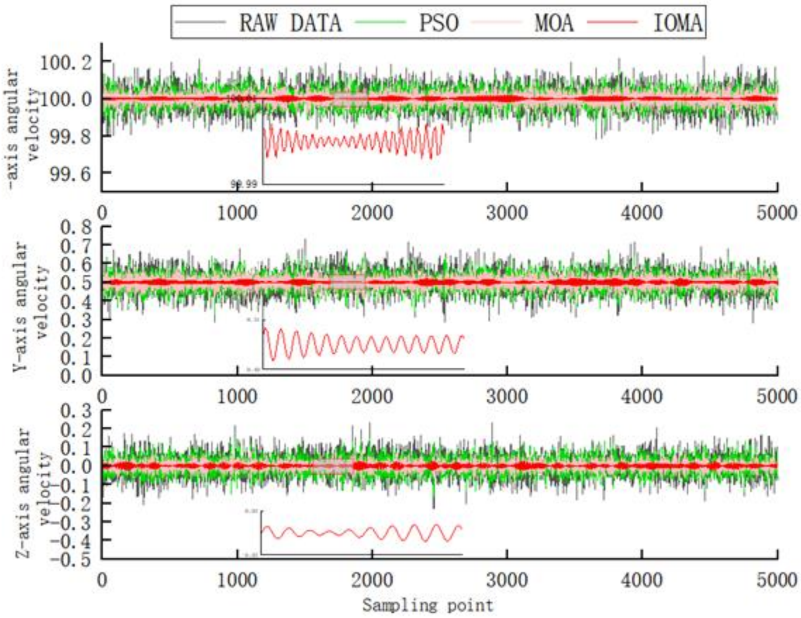

Figure 2: The compensation results of three axis output of gyroscope in Turntable experiment

It can be seen from the above figure that compared with PSO and MOA algorithms, IMOA algorithm has significantly smaller error after compensation, indicating that the algorithm has higher accuracy.

Real drilling experiment

In order to further verify the accuracy of IMOA algorithm in the actual drilling process, a vertical section of a coal mine in Jiaozuo City was selected for drilling experiment, and the borehole inclination Angle was calculated every 30s with 6min data as samples. Because the selected vertical section is drilled, the theoretical output Angle is 0°. However, due to the harsh drilling environment in the process of drilling, the gyro error accumulates continuously through integration, which makes the attitude Angle settlement error gradually increase.

Figure 3: Actual drilling experiment

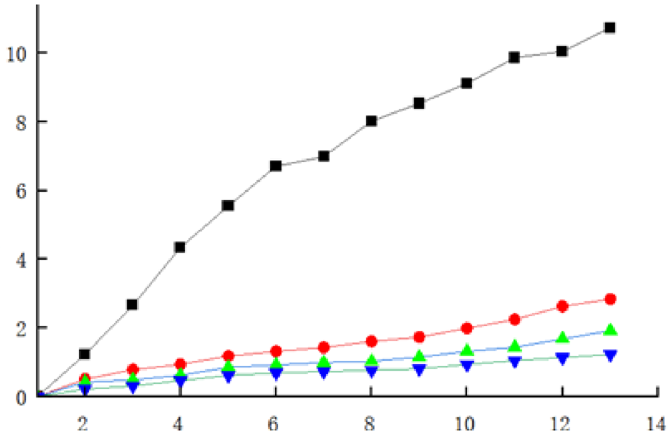

Figure 4: Well inclination error

Table 1: Root mean square error

Algorithm	**Original well inclination**	**PSO**	**MOA**	**IMOA**
Root mean square error /deg	5.3	4.6	3.3	1.2
Running time/s	/	12.31	7.65	6.67

Compared with PSO and MOA algorithms, IMOA algorithm has better compensation effect in the actual drilling process. The deviation error of borehole inclination after compensation by IMOA algorithm is controlled between [-2.5,2.5], which is about 75% lower than the original borehole inclination. As shown in Table 1, the root mean square error of well inclination after IMOA compensation is reduced to 1.2, which is significantly reduced compared with the previous two errors, and the running time of 6.67 seconds meets the drilling requirements, which verifies the effectiveness and accuracy of the algorithm from the side.

4. Conclusion

An error compensation method of improved Sea Cat algorithm is proposed for MEMS gyroscope output signal containing a large number of errors. The effectiveness and accuracy of the proposed algorithm are verified by shaking table experiment and drilling experiment, compared with the classical PSO algorithm and the MOA algorithm before improvement.

Experiments show that compared with PSO and MOA, IMOA algorithm is more suitable for compensating MEMS gyroscope in MDR environment. After compensating by IMOA algorithm, the root mean square error of borehole inclination is reduced to 1.2°, and the running time of the algorithm is 6.67s, which has certain engineering value.

However, the algorithm still has some defects. When there are severe environmental changes such as shock, the algorithm still has the possibility of falling into local optimal. The next research focus is to further adapt to the complex environment while drilling, so as to obtain higher precision error compensation.

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