Geomagnetic/inertial navigation integrated matching navigation method

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ABSTRACT

The accuracy of an a priori geomagnetic reference map is a significant constraint on the geomagnetic matching navigation method. Especially when the aircraft enters an unknown environment, it is impossible to accomplish the navigation task using traditional geomagnetic navigation methods. Therefore, a geomagnetic/INS integrated matching navigation algorithm for long-scale navigation is proposed in this paper, which can perform navigation tasks regardless of whether there is an a priori geomagnetic map. This method combines a magnetogram-based matching navigation method with a geomagnetic bionic navigation method that does not require a geomagnetic map. The navigation trajectory is first analyzed in the area where the geomagnetic map is available, and the matching results are further corrected by filters for the inertial navigation system. Furthermore, when the aircraft flies through an unknown area without the a priori geomagnetic map, the nonmagnetic map navigation method is used to guide the aircraft to the destination. Finally, simulations are performed for the geomagnetic map distribution and noise effects that may occur during actual flight, and the obtained results show the effectiveness of the proposed algorithm in a complicated geomagnetic environment.

1. Introduction

Inertial navigation systems (INSs), which can continuously and autonomously provide full navigation information about aircraft, are widely used in current unmanned aerial vehicle (UAV) navigation. However, it is difficult to adapt INS to the long-scale navigation requirements because its error accumulates over time. Therefore, to ensure the accuracy of navigation, INS is usually combined with other navigation systems to achieve complementary capabilities and high positioning precision [1, 2].

Geomagnetic navigation, as a natural coordinate system in the navigation field, has the advantages of passive autonomy and high concealment [3, 4]. Geomagnetic navigation has become an important aided navigation system because it is not restricted by time and terrain and can overcome the shortcomings of INS that accumulate errors over time and distance [5].

The most widely used research on geomagnetic navigation is to correlate the measured geomagnetic information on the navigation path with the onboard prior geomagnetic map to obtain the actual position of the aircraft, which is known as the geomagnetic matching navigation method [6]. Thus, the precision of geomagnetic navigation is in part dependent on the accuracy of the prior geomagnetic map [7, 8]. However, the accuracy and completeness of a priori geomagnetic maps are difficult to guarantee for various reasons. This imposes a great constraint on the geomagnetic matching navigation method, which heavily relies on the accuracy of the magnetic map.

Most geomagnetic matching navigation methods, such as the traditional magnetic contour matching (MAGCOM) [9] and iterative closest contour point (ICCP) [10] algorithms, the genetic algorithm (GA) [11], and the particle swarm optimization (PSO) [12] algorithm, are based on high-precision geomagnetic maps. When the accuracy of the magnetic map is not high, various interpolation methods (such as kriging [13] and neural networks (NNs) [14]) are usually used to refine the magnetic map. However, if the interpolation method is applied directly to low-resolution geomagnetic data instead, it may lead to distortion of the geomagnetic reference map. The matching results of short-scale navigation will be clearly affected, while long-scale navigation matching accuracy may also be affected due to the inherent error accumulation. Therefore, we used the triangle algorithm in star-map matching and proposed a geomagnetic matching navigation algorithm based on the triangle constraint, which uses as little information as possible to reduce the matching distance and complete navigation under the condition of low magnetic map resolution [22].

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Furthermore, traditional geomagnetic navigation algorithms are unusable in the absence of an a priori geomagnetic map. However, recent studies have shown that many creatures, such as birds [15], turtles [16], salmon [17], and many other organisms, are able to use geomagnetic field information to correct their courses [18, 19], although their brains lack an a priori geomagnetic map. Inspired by this biological property, Liu et al. [20] proposed a geomagnetic bionavigation method without a geomagnetic map, but because this method is based on a random walk model, its navigation path is rather tortuous and not suitable for aircraft. It is known that the Earth’s magnetic field has a magnetic tendency over a large area, based on which we proposed a gradient-based geomagnetic bionavigation algorithm using the geomagnetic gradient information of the current position, which is more suitable for long-scale aircraft navigation [24].

Considering these problems, this paper proposes a geomagnetic/INS integrated navigation method for long-scale navigation when the accuracy of the a priori geomagnetic map is low or even when the aircraft passes through the area without a geomagnetic reference map. The triangle matching positioning algorithm is combined with the filter to analyze the geomagnetic trend of the navigation path in the area with the magnetic map. When the aircraft flies out of the magnetic map area or is in an area without a geomagnetic reference map, the geomagnetic gradient navigation algorithm is adopted to guide the aircraft to complete the navigation task, solving the integrated navigation problem in the complex geomagnetic environment.

2. Problem description

Generally, the accuracy of geomagnetic navigation largely depends on the resolution and accuracy of the geomagnetic reference map. However, due to the sparse distribution of magnetic survey stations and other reasons, the grid spacing of prior geomagnetic data may be very large. Because the geomagnetic information between grids is usually smoothed during data modeling, the geomagnetic reference map established by this approach may not reflect the real geomagnetic field changes, as shown in Fig. 1.

Matching navigation generally refers to the similarity matching of the navigation trajectory sequence with the corresponding reference map, and the navigation accuracy largely depends on the setting of the matching step. Generally, to ensure the accuracy and validity of the matching data, the matching length should be a multiple of the grid size. However, if the grid of the a priori reference map is sparse, selecting a sufficient matching length may affect the matching accuracy due to the accumulation of errors in the navigation trajectory itself, and a shorter matching length may cause mismatches due to insufficient effective matching points, which may easily interfere with other information.

When an a priori reference map cannot accurately reflect the geomagnetic characteristic environment of the current navigation area or even the aircraft enters an unknown environment without a high-precision geomagnetic map, in this case, the traditional geomagnetic navigation method will be greatly restricted.

This paper proposes an integrated matching navigation algorithm of geomagnetic/INS that combines the geomagnetic matching method without geomagnetic map navigation. When using a magnetic map, the geomagnetic characteristics of the flight trace are analyzed first; then, fewer geomagnetic characteristics are used for matching, and the matching results are further corrected by filters. In addition, when the aircraft passes through the area without a geomagnetic map, the traditional geomagnetic matching method is unavailable, and then the navigation method that does not need an a priori geomagnetic map is used to guide the aircraft to continue the navigation task.

3. Principles and steps of the navigation algorithm

When an aircraft executes long-scale navigation missions, INS errors are generally corrected by methods such as geomagnetic matching due to INS error accumulation. However, an accurate geomagnetic map of a large area is usually difficult to obtain, and aircraft may pass through areas without an a priori geomagnetic map during actual navigation missions, as shown in Fig. 2. The solid box in the figure indicates the area with the magnetic map, and the dashed box indicates the area without the magnetic map. In this case, the aircraft can only fly to an area where the geomagnetic map is available for correction. The method proposed in this paper allows the aircraft to successfully fulfill the navigation task regardless of whether the navigation path has an a priori geomagnetic map.

When the aircraft is within the range of a geomagnetic reference map, in this paper, the method of rough and fine matching is adopted to correct the INS errors. The geomagnetic features of the flight trajectory are analyzed first, and the matching algorithm based on triangle constraint [22] is used in the suitable zone to roughly match the navigation trajectory utilizing less geomagnetic feature information. Then, the matching results are combined with the geomagnetic filter based on simultaneous location and mapping (SLAM) [23] to estimate the errors of the remaining navigation state, such as speed and attitude. Additionally, if the aircraft flies outside of the matching area of the geomagnetic map or into an area without a geomagnetic reference map, because there is no a priori geomagnetic map to correct the INS trajectory, the navigation strategy can be switched to the geomagnetic gradient navigation algorithm [24], which does not require an a priori geomagnetic map to complete the navigation without INS.

3.1. Geomagnetic triangle matching algorithm

The geomagnetic triangle matching algorithm takes advantage of the high short-time accuracy of INS to give the triangle constraint [21] and constructs the matching triangles based on the contour information...
corresponding to the geomagnetic measurements. Then, the similarity of triangles is described as a matching characteristic quantity, and the optimal matching parameters can be obtained by combining the motion parameters of aircraft to complete matching positioning navigation. The detailed procedure is described in Reference [22].

Let the aircraft fly along the reference trajectory, and when passing the preset point \((H_1, H_2, H_3, \ldots)\), record the geomagnetic measured value of the current position. Then, on the geomagnetic reference map, \(H_i\) is taken as the search matching center, and matching points are searched on the contour of geomagnetic measurements \(C_i\) within the search range of the estimated error of the matching center position, denoted as matching point set \(X_i\).

Comparing the matching triangle \(\triangle X_1X_2X_3\) with the navigation triangle \(\triangle H_1H_2H_3\), the matching distance should meet the constraints of Equation (1):

\[
\begin{align*}
\|X_1X_2 - H_1H_2\| &< R \\
\|X_2X_3 - H_2H_3\| &< R \\
\|X_1X_3 - H_1H_3\| &< R \\
\end{align*}
\]

where \(R\) is the distance matching tolerance.

Thus, a set of matching triangles can be obtained, in which the optimal triangle can be selected by the similarity criterion, and the optimal parameters of this matching triangle can be obtained by combining the aircraft motion parameters (see Reference [22] for details).

### 3.2. Integrated navigation algorithm

During navigation, the planning track should be analyzed first, and the segment in which the geomagnetic value can be linearized should be selected when the aircraft is within the geomagnetic reference map. In this selected segment, an appropriate matching method was used for rough matching. Then, the matched information, such as position, was fed back to the filter, and the position of INS could be corrected by a simultaneous navigation and map correction algorithm [23].

A geomagnetic profile curve is drawn with aircraft path \(S\) as the horizontal axis and geomagnetic measurement \(B\) as the vertical axis, and the segment that can be linearized in the curve is selected, as shown in Fig. 3.

We assume that the geomagnetic estimation \(\hat{B}_k\) at a certain point in the linearization segment can be described as Equation (2):

\[
\hat{B}_k = \hat{B}_0 + K \cdot \Delta S_k + \eta_k = \hat{B}_0 + K \cdot (S_k - S_0) + \eta_k
\]

where \(K\) is the fitting slope of the segment; \(\Delta S_k\) is the distance difference between the \(k\)th sampling point \(S_k\) and the first sampling point \(S_0\) in the current linearization segment; \(\eta_k\) is the error of the fitting line, which can be approximated as a type of colored noise.

![Fig. 2. Inertial navigation/geomagnetic integrated navigation strategy.](image)

![Fig. 3. Linearized segment of the geomagnetic curve.](image)

Modeling with the geomagnetic difference in the linearization segment reduces the effects of magnetic diurnal variation or other errors on the system during navigation. The difference \(\delta B_k\) between the geomagnetic measurement \(\Delta B_k\) and the value in the reference map \(\Delta \hat{B}_k\) can be described as Equation (3):

\[
\delta B_k = \Delta B_k - \Delta \hat{B}_k
\]

\[
= (K + \Delta K_k) \cdot (\Delta S_k + \delta S_k + \Delta \delta S_k) + \eta_k - (K \cdot \Delta S_k + \eta_k) + \xi_k
\]

\[
= K \cdot \Delta S_k + K \Delta S_k \cdot \delta S_k + K \Delta S_k \cdot \Delta \delta S_k + \delta \eta_k + \xi_k
\]

where \(\delta S_k\) is the fitting slope error, \(\delta S_k\) is the distance error, \(\delta \eta_k\) is the angle error, \(\xi_k\) is the measurement noise, and \(\delta \eta_k\) is the fitting noise.

The system error equations are established on the basis of INS, where \(X\) denotes the state equations, and \(W\) denotes the system noise. The state equations of the system include the errors of velocity, position, platform angle, gyro drift and accelerometer drift, totaling 18-dimensional state variables, described as

\[
X = [\delta v_x \  \delta v_y \  \delta \phi \  \delta \psi \  \delta \theta \  \epsilon_{bx} \  \epsilon_{by} \  \epsilon_{bz} \  \epsilon_{rx} \  \epsilon_{ry} \  \epsilon_{rz} \  \nu_x \  \nu_y \  \nu_z]^T
\]

and the system noise is described as

\[
W = [\omega_{ax} \  \omega_{ay} \  \omega_{az} \  \omega_{bx} \  \omega_{by} \  \omega_{bz} \  \omega_{rx} \  \omega_{ry} \  \omega_{rz} \  \omega_{nu} \  \omega_{nv} \  \omega_{nw}]^T
\]

In combination with Equation, the dimension of the state equations in integrated navigation is extended as Equations (4)–(7).

\[
X(t) = \bar{X}(t) X(t) + G(t) W(t)
\]

where

\[
\bar{X} = [X \ \delta S \ \delta K]^T
\]

\[
\bar{X} = \begin{bmatrix} F \ 0 \ \bar{F} \end{bmatrix} \begin{bmatrix} \delta S \ \delta K \end{bmatrix}^T
\]
\[ F_K = \begin{bmatrix} 0_{3 \times 3} & \sec \phi & 0_{3 \times 16} \\ 0_{3 \times 3} & 0 & 0_{3 \times 16} \end{bmatrix}, \quad F_K = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \]

Then, the geomagnetic field intensity observation equation can be written as Equations (8) and (9)

\[ Z_B = [\delta B_k] = H_B X(t) + V_B \]

(8)

where

\[ H_B = \begin{bmatrix} K_x \Delta S_k & 0_{1 \times 11} & K_k \Delta S_k \end{bmatrix} \]

(9)

The position observation equation based on the matching result is defined as Equation (10):

\[ Z_F = \begin{bmatrix} \varphi(k) - \varphi_m(k) \\ \lambda(k) - \lambda_m(k) \\ h(k) - h_m(k) \end{bmatrix} = H_F X + V_F \]

(10)

where \( \varphi(k), \lambda(k), \) and \( h(k) \) are the longitude, latitude, and altitude of the INS output, \( \varphi_m(k) \) and \( \lambda_m(k) \) are the positions of the geomagnetic matching results, and \( h_m(k) \) is the measurement of the altimeter.

By combining Equations (10) and (8), the observation equation of the system can be obtained as Equation (11):

\[ Z = \frac{Z_F}{Z_B} = H_F X + V_F \]

(11)

Then, the Kalman filter algorithm is used to correct the navigation errors in each linearized segment. When the position of the INS output or the matching correction is not within the range of the geomagnetic reference map, the navigation strategy is changed, and the geomagnetic gradient navigation algorithm without the magnetic map is used to guide the aircraft to complete the navigation.

### 3.3. Geomagnetic gradient navigation algorithm

In the unknown environment or when the accuracy of the a priori magnetic map is not high, the geomagnetic gradient bionic navigation algorithm based on the parallel approach [24] is used in this situation. Taking the geomagnetic multiparameter \( B_{i,d} \) (\( i = 1, 2, \ldots, n \)) as the target values, combined with the geomagnetic field gradient information of the current position, the heading angle \( \theta_k \) is predicted using the following approach, where the transmissions \( \tilde{B}_{i,k} \) are parallel to the destination to guide the aircraft to move continuously to the destination. That is, satisfying Equation (12)

\[ (B_{i,k+1} - B_{i,k}) \propto (B_{i,d} - B_{i,k}) \quad i = 1, 2, \ldots, n \]

(12)

Assuming that the geomagnetic measurement is \( \tilde{B}_{i,k} \) and the actual value of the geomagnetic field is \( B_{i,k} \), then satisfies Equation (13)

\[ \tilde{B}_{i,k} = B_{i,k} + \omega_{i,k} \]

(13)

where \( \omega_{i,k} \) is the measurement noise, which can be approximated as white noise.

The variation in geomagnetic parameters can be described as Equation (14) and (15):

\[ K_{i,k} = \frac{\Delta B_{i,k}}{\Delta B_{i,d}} = \frac{\Delta B_{i,k} - \omega_{i,k}}{\Delta B_{i,d} - \omega_{i,k}} \]

(14)

that is,

\[ \Delta \tilde{B}_{i,k} = K_{i,k} \Delta B_{i,d} + \epsilon_{i,k} \]

(15)

where \( \epsilon_{i,k} = (1 - K_{i,k}) \omega_{i,k} \) can be considered the superimposed term of the white noise sequence, which can be also approximated as white noise.

Therefore, the calculation of heading angle \( \theta_k \) can be transformed into the optimization problem of the least square method in Equation (15), where the sum of squared residuals can be written as Equation (16):

\[ \epsilon^2 = \sum_{i=1}^{n} \left( (\Delta \tilde{B}_{i,k} - K_{i,k} \Delta B_{i,d})^2 \right) \]

\[ = \sum_{i=1}^{n} \left| \Delta \tilde{B}_{i,k} \sin \theta_k - K_{i,k} (B_{i,d} - \tilde{B}_{i,k}) \right|^2, \quad n \leq 7 \]

(16)

Then, the abovementioned formula can be rewritten as Equation (17)-(19)

\[ J = \epsilon^2 \epsilon = (HX - Kz)^T (HX - Kz) \]

(17)

where

\[ X = \begin{bmatrix} a \\ \beta \end{bmatrix}, \quad z = \begin{bmatrix} B_{i,k}^T - \tilde{B}_{i,k} \\ \vdots \\ B_{n,k}^T - \tilde{B}_{n,k} \end{bmatrix} \]

\[ H = \begin{bmatrix} \Delta \tilde{B}_{i,k} \ldots \Delta \tilde{B}_{n,k} \\ \Delta \tilde{B}_{i,k} \ldots \Delta \tilde{B}_{n,k} \end{bmatrix}, \quad K = \begin{bmatrix} K_{i,k} \\ K_{n,k} \end{bmatrix}^T \]

(18)

with

\[ a = \cos \theta_k, \quad \beta = \sin \theta_k \]

(19)

By solving the least squares problem, the heading angle \( \theta_k \) can be obtained; see reference [24] for the solving process.

The integrated navigation principle of INS/geomagnetic matching is shown in Fig. 4. First, the INS trajectory is subjected to geomagnetic map analysis. If no a priori geomagnetic map is available at the current location, the geomagnetic gradient bionic navigation method is used directly to guide the aircraft to complete the navigation task. If there is a priori geomagnetic map at the current location, the geomagnetic matched results are combined with the SLAM filtering algorithm to correct the INS errors. Finally, it is detected whether the aircraft reaches the destination, and if it does not, geomagnetic map analysis should be performed again.

Due to the time required for matching location estimation, the geomagnetic matching algorithm has a certain delay compared with other geomagnetic filtering algorithms. Although the matching algorithm has a mismatching probability, a small number of mismatching points can be considered as noise deviation in the filtering process as long as the matching accuracy and matching success probability are high in the whole navigation process, which will not have a great impact on the overall performance of the system. Therefore, theoretically, if the position estimation accuracy of matching positioning is sufficiently high, the navigation system based on geomagnetic matching can further obtain higher navigation performance.

### 4. Simulation and results

#### 4.1. Simulation environment

Simulations with geomagnetic maps are performed by applying digital data grids for the magnetic anomaly map of North America [25], which is provided by the U.S. Geological Survey. The navigation algorithm without a magnetic map requires three-axis geomagnetic field components for calculation, and due to the lack of suitable data in our laboratory, the International Geomagnetic Reference Field (IGRF-12) was superimposed on the geomagnetic anomaly field data for simulations in this study.

#### 4.2. Experiment with different map distributions

In the following experiment, combined with the possible situations in the actual flight process, a variety of discontinuous magnetic map situations are simulated.
(1) With magnetic map in the front section and without map in the back section

In this experiment, the aircraft will pass through an area with a precise geomagnetic reference map during flight. There is no geomagnetic reference map in the area near the destination, but the geomagnetic information at the target point is known. The INS simulations in this paper are performed under the conditions shown in Table 1.

Fig. 5 shows the correction results of the integrated navigation method of INS/geomagnetic matching under the setting of this experiment, and Fig. 6 shows the correction curve of the area with a magnetic map.

In this simulation, the initial matching position is at (20km, 20km), located in the region with a geomagnetic reference map, and the destination is at (300km, 300km), where there is no geomagnetic reference map. Fig. 5 shows that in the area with a magnetic map, the proposed method can better correct the INS output track and track the desired track. When the INS output position is outside the magnetic map, geomagnetic matching or filtering methods cannot be used to correct the track. After switching the navigation strategy, the biomimetic navigation without a magnetic map is used to guide the aircraft to complete navigation and finally successfully reach the target point.
reach the range of the magnetic map, to ensure that the aircraft enters the geomagnetic area and then performs integrated matching navigation, it is set in the experiment that when the aircraft has continuously appeared in the matching area for 10 consecutive sampling points, the navigation strategy is switched, and the navigation path is adopted to navigate to correct the navigation path. Finally, the target point is successfully reached, and navigation is completed.

(3) With magnetic map in the early and later period but without map in the middle

In this simulation, there is a high-precision geomagnetic reference map near the starting position and target position, but there is no geomagnetic map in the middle of the flight. The result of the comprehensive navigation correction of the experiment is shown in Fig. 9.

Fig. 9 shows that the simulation starts from the starting position (14 km, 10 km), and the target position is located at (88 km, 88 km). At the beginning of navigation, the geomagnetic matching method is used to correct the trajectory. When the aircraft is in the nonmagnetic map area, the mapless navigation strategy is switched, and the geomagnetic gradient navigation algorithm is used to guide the aircraft to the target point. When the aircraft enters the magnetic map area near the target, the strategy is switched after advancing for a certain distance, and finally, the navigation task is corrected and the task is completed.

In summary, this experiment mainly aimed at the actual application situation, considering that the geomagnetic information near the origin and destination is easier to obtain, but the geomagnetic information during cruising is generally not easily obtained or cannot be obtained at all. The proposed method can comprehensively deal with the geomagnetic navigation task with and without the magnetic map in a complex geomagnetic environment, which has a wider application range and improves the adaptability of the system to uncertain complex geomagnetic environments.

4.3. Experiment with different measurement noise

In this experiment, measurement noise is considered in the simulation. The following is based on the experiments in Section 4.2 (Fig. 5) with a magnetic map in the front section and without a map in the back section, with four different levels of Gaussian noise used in simulations. The daily variation in the geomagnetic field is approximately 0.1% of the geomagnetic field variation, i.e., 50 nT. Therefore, the measured noise in this paper is as follows: without noise, with 0.1% measurement noise (approximately 50 nT), with 0.2% measurement noise (approximately 100 nT), and with 1% measurement noise (approximately 500 nT). The simulation result is shown in Fig. 10.

Fig. 10 shows that all abovementioned experiments were able to complete the navigation. However, when there is measurement noise, navigation takes slightly longer, and the path is slightly convoluted.
If the measurement noise is high, the geomagnetic value of the final destination may be fuzzy due to noise, which results in completing the navigation earlier or even being navigated to the wrong place.

To further verify the effect of measurement noise on the proposed method, approximately 100 samples were randomly simulated with noise in this experiment. The Monte Carlo simulation results are shown in Fig. 11 and Table 2.

The simulation results in the abovementioned figures show that using the proposed method, the distance error to the destination is significantly reduced compared to the INS cumulative drift error when the aircraft completes the navigation. In addition, it can be seen from 100 Monte Carlo simulations with different noise that, the lower is the noise, the higher is the accuracy of navigation.

### 4.4. Experiment with different navigation durations

Navigation tasks of different navigation durations were also performed in this experiment, which was based on the experiment with a magnetic map in the front section and without a map in the back section in Section 4.2. The simulation results are shown in Fig. 12 and Fig. 13.

In this experiment, two navigation tasks of different durations were performed. As shown in Fig. 13, in the short-scale case, due to the small variation in geomagnetic values in a small area and the influence of measurement noise, the target point may be missed when guiding the vehicle to the destination because the target geomagnetic data are relatively similar. During the long-scale navigation process, the navigation process in the presence of noise may be more circuitous, but it is generally possible to guide the vehicle to the vicinity of the destination and complete the navigation.

### 5. Conclusion and future research

#### 5.1. Conclusions

The geomagnetic matching result is constrained by the accuracy of the geomagnetic reference map to a certain extent. In particular, traditional geomagnetic navigation methods are useless when aircraft enters an unknown environment. This paper proposes a geomagnetic/INS integrated matching navigation algorithm, which can be used regardless
of whether there is a geomagnetic map. To improve the overall performance of the system, the triangle matching algorithm is combined with the filtering algorithm, and the matched information is used to estimate the navigation information of the whole state. At the same time, the mapless navigation method is used to improve the adaptability of the system to the uncertain region. The simulation results show that the geomagnetic/INS integrated matching navigation method proposed in this paper can comprehensively address integrated navigation tasks in various complicated geomagnetic environments in practical applications, improve the adaptability of the system to uncertain complex geomagnetic environments, and provide a feasible scheme for the large-scale application of geomagnetic integrated navigation.

5.2. Future research

During the experimental process, we found that navigation using the proposed method has a better effect when the magnetic information is smoother or without disturbance. If the magnetic curve seems more circuitous or magnetic interference exists, the whole navigation process will be affected. This deserves further investigation in the future.

Declarations

Author contribution statement

Wang Qiong: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.
Zheng Chen: Analyzed and interpreted the data.
Wu Peili: Performed the experiments; Wrote the paper.
Wang Xiaoyu: Contributed reagents, materials, analysis tools or data.

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The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.
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