An Intelligent Geomagnetic Search Navigation Method Based on Evolutionary Gradient Strategy

Xintian Ren\textsuperscript{1,a}, Qi Zhang\textsuperscript{1,b}, Mengchun Pan\textsuperscript{1,c,*}, Dixiang Chen\textsuperscript{1,d}, Zhongyan Liu\textsuperscript{1,e}, Jiafei Hu\textsuperscript{1,f}, Zhenxiong Wang\textsuperscript{1,b} and Ze Wang\textsuperscript{1,i}

\textsuperscript{1}College of Intelligence Science and Technology, National University of Defense Technology, Changsha, Hunan, China

\textsuperscript{a}email: renxintian14@nudt.edu.cn, \textsuperscript{b}email: 13141317443@163.com, \textsuperscript{d}email: chendixiang@163.com, \textsuperscript{e}email: liuzhongyan2008@163.com, \textsuperscript{f}email: garfield_nudt@163.com, \textsuperscript{g}email: lansedexin26@126.com, \textsuperscript{h}email: 951117492@qq.com, \textsuperscript{i}email: 1876067012@qq.com

\textsuperscript{*}email: panmengchun@nudt.edu.cn

Abstract. Currently, most of the geomagnetic navigation methods are matching navigation algorithms, which require the geomagnetic maps retrieved in advance, and saved in a database. However, there are a great number of unknown environments exist worldwide that limit the extensive application of the geomagnetic matching method in practice. In this paper, an intelligent geomagnetic search navigation method based on the evolutionary gradient search (EGS) algorithm is proposed. The performance of the search and navigation method is analysed with both simulated and real geomagnetic data. And the conclusion is that compared with other intelligent search strategies, the proposed algorithm has better navigation performance with less average navigation error, 161m, which is equivalent to the most traditional geomagnetic matching algorithms. Thus, the EGS algorithm proposed in this paper can effectively improve the performance of geomagnetic navigation without prior geomagnetic information.

1. Introduction

High precision autonomous navigation technology is an important technology in the military field. At this period, the most extensive navigation methods include inertial navigation, satellite navigation, underwater acoustic navigation, terrain matching navigation, etc. These navigation methods have been widely used in aviation, aerospace, and navigation. However, during long-time and long-distance navigation, there are some problems in the application of the navigation methods above. For example, the position error and velocity error of the inertial navigation system are accumulated with time. The application of terrain matching technology is limited in the region with insignificant terrain and geomorphic features, which causes that stable and reliable navigation information is not available. The satellite navigation system and underwater acoustic navigation system, which are widely mounted on most moving carriers to navigate, are easy to be disturbed and detected, which leads to their limited application on the battlefield. As the Earth’s inherent physical vector field, the geomagnetic field has the advantage of all-time, all-weather, passivity, and so on [1]. Because its positioning error is not accumulated with time, magnetic navigation can be integrated with the INS to realize long-time and high-precision navigation, which can be applied for navigation in most areas of the Earth [2].
Currently, numerous articles have been published about geomagnetic matching navigation and their associated navigation algorithms, which can be divided into two categories [3]: the algorithms based on magnetic field contour matching (MAGCOM) and the algorithms based on iterative closest contour point (ICCP). Both these two algorithms require the geomagnetic maps retrieved in advance and saved in a database, in which the geomagnetic features can be matched to corresponding geographic coordinates. However, due to the limitation of detection conditions, there are a great number of unknown environments exist in practice. Therefore, it is difficult to map and store a large number of the prior geomagnetic database with good integrity and high accuracy in advance, and the objective environmental factors such as geomagnetic measurements and unpredictable magnetic anomalies have a great impact on the success rate of the matching algorithm, which limits the wide application of geomagnetic matching method [4-5].

Based on the background above, this paper proposes a geomagnetic autonomous navigation method based on an artificial intelligence algorithm, which greatly improves the security, success probability, and application value of geomagnetic navigation, and has considerable development space and application prospect. The proposed method has several advantages:

(1) Based on the theory of Geophysics, the search constraint relationship between geomagnetic multi-parameters and navigation path is analyzed, and the mathematical description of geomagnetic search navigation is given in this paper. The core objective function is built to provide the necessary background knowledge and theoretical support for the subsequent research of search algorithm and combination method.

(2) The intelligent search navigation strategy is used to solve the problem of geomagnetic search and navigation which completely does not depend on the prior geomagnetic reference map. The advantages and disadvantages of different methods such as random walk model and evolutionary algorithm are summarized. Aiming at some shortcomings of the search navigation in the literature, such as the randomness of navigation trace and the huge time cost, this paper optimizes the search strategy to improve the search efficiency and navigation accuracy.

2. Problem Description

2.1. Establishment of carrier motion model

In this paper, the main carrier is aircraft. The flight navigation problem of aircraft can be simplified as the geomagnetic navigation problem in two-dimensional coordinate system. The equation of motion can be expressed by

\[
\begin{align*}
    x_{k+1} &= x_k + v \cdot \Delta t \cdot \cos(\theta_{k+1}) \\
    y_{k+1} &= y_k + v \cdot \Delta t \cdot \sin(\theta_{k+1}) \\
    u &= (v, \theta_{k+1})
\end{align*}
\]

Where \((x, y)\) is position of the carrier, \(k\) is current time point of movement, \(v\) is travel speed, \(\Delta t\) is sampling period, \(\theta\) is course angle, \(u\) is the input information, including speed and heading angle.

2.2. Mathematical description of geomagnetic search navigation problem

The geomagnetic field is a mixed field with multiple geomagnetic parameters, which can be described as \(B = \{B_x, ..., B_y\}\). Presently, the geomagnetic field vector is described by seven elements. These are the northerly intensity \(B_x\), the easterly intensity \(B_y\), the vertical intensity \(B_z\) (positive downwards) and the following quantities derived from \(B_x\), \(B_y\) and \(B_z\): the horizontal intensity \(B_{\|}\), the total intensity \(B_t\), the inclination angle \(I\), (also called the dip angle and measured from the horizontal plane to the field vector, positive downwards) and the declination angle \(D\) (also called the magnetic variation and measured clockwise from true north to the horizontal component of the field vector).
According to the constraint and induction relationship between the motion path and the geomagnetic parameters in search navigation, the geomagnetic parameters can converge to the geomagnetic target simultaneously in navigation process. Therefore, the problem of geomagnetic search and navigation can be summarized as the optimization of multiple sub objective functions in the case of unknown geomagnetic parameters, so that the objective function can be minimized. The basic model of search and navigation can be expressed as

$$\min F(B^k) = F(f(B^1), f(B^2), \ldots, f(B^N))$$

s.t. $$g_i(B^k, B^*, S^k) \leq \varepsilon \quad i = 1, 2, \ldots, N$$

(2)

Where $$F$$ is the objective function, $$f(B^i)$$ is the sub objective function of geomagnetic parameter $$i$$ at time-point $$k$$. $$S^k$$ is navigation path of carrier from time $$k-1$$ to $$k$$. $$g_i$$ is the constraint condition, when the objective function $$F$$ reaches to the minimum along the path, the carrier is considered to reach the target point position. $$B^k$$ is geomagnetic parameter of the current position, and $$B^*$$ is geomagnetic parameter of the target position.

Guided by the difference between the geomagnetic parameters of the current position and the target position, the aircraft keeps approaching the target point. The sub objective function corresponding to the geomagnetic parameter $$i$$ at time-point $$k$$ can be expressed by

$$f(B^i) = (B^* - B^i)^2, \quad i = 1, 2, \ldots, N$$

(3)

In the objective function $$F$$, multiple objective functions are weighted linearly and normalized by mean square difference (MSD) method, which can be expressed by

$$F(B^k) = \sum_{i=1}^{N} \frac{f(B^i)}{f(B^*)} = \sum_{i=1}^{N} \frac{(B^i - B^*)}{B^* - B^*}$$

(4)

Geomagnetic search navigation is a process that makes geomagnetic parameters converge to the target position, which can be characterized as the objective function tends to zero, that is

$$\lim_{k \to \infty} F(B^i) \to 0$$

(5)

In this case, we can judge that the carrier has arrived at destination.

The principle block diagram of geomagnetic search and navigation is shown in Fig.1. During the movement of the carrier, by comparing the geomagnetic parameters of the current position with the target position, the heading angle of the carrier at the next moment is calculated by the search navigation algorithm, and the carrier uses the geomagnetic trend to search for a specific target position during the movement.

![Fig.1 Block diagram of geomagnetic search navigation principle.](image)
3. Algorithm Principles
Evolutionary gradient search (EGS) is a method proposed by Ralf Salomon, which combines features of gradient strategies with ideas from evolutionary computation [6]. EGS was initially applied to the odor source search. The robot can search and locate the odor sources according to the trend of odor concentration. The essence of geomagnetic search and navigation is to use geomagnetic trend to complete the navigation task. Thus, we applied EGS to geomagnetic search and navigation. The geomagnetic trend is used to guide the mobile carrier to approach the target geomagnetic value. The flow chart of the algorithm is shown in Fig.2.

![Flow chart of EGS algorithm for geomagnetic search navigation.](image)

The specific steps can be illustrated as follows:

1. Initializing parameter and constructing the gene library.
   Obtaining the geomagnetic vector parameters of the starting position by the magnetic sensor, and set the geomagnetic parameters of the target position. In the search process, the course angle is regarded as the evolutionary individual, and the sample gene library can be expressed by
   \[ \theta = \{ \theta_1, \theta_2, \ldots, \theta_{2/\Delta \theta} \} \]  

   Where \[ \lambda = 2\pi / \Delta \theta \], \[ \lambda \] is the number of individual space, \[ \Delta \theta \] is the sampling interval of course angle.

2. Selecting the motion direction of next moment by using evolutionary gradient strategy.
The principles of geomagnetic evolutionary gradient strategy are based on the geomagnetic sensors installed on the carrier. The motion direction of the carrier at the next moment is the direction of the minimum objective function corresponding to the geomagnetic value measured by the geomagnetic sensors. Depending on the trend of geomagnetism, the carrier will eventually move towards the minimum direction of geomagnetic objective function, which is the closest geomagnetic value to the target position. The specific steps can be illustrated as steps a to f.

a. Suppose that the current position of the carrier is \((x_k, y_k)\), the geomagnetic value corresponding to the current position is \(B(x_k, y_k)\), the geomagnetic value of the starting position is \(B(x_0, y_0)\), and the geomagnetic value of the target position is \(B(x_T, y_T)\).

b. The geomagnetic values collected by the sensor \(i\) at the moment \(k\) are expressed as \(B(x_{ik}, y_{ik}) = \{i = 1, \ldots, \lambda\}\).

c. According to Eq.7, the objective function corresponding to the geomagnetic value measured by the sensor \(i\) can be calculated by

\[
F(x_{ik}, y_{ik}) = \frac{[B(x_{ik}, y_{ik}) - B(x_T, y_T)]^2}{[B(x_0, y_0) - B(x_T, y_T)]^2} \quad (i = 1, \ldots, \lambda)
\]

(7)

d. The direction of the sensor with the minimum objective function is taken as the motion direction of the carrier at the next time, which can be expressed by

\[
\theta_{k+1} = \theta\{\min F(x_{ik}, y_{ik})\}
\]

(8)

e. The carrier move to the next position \((x_{k+1}, y_{k+1})\). The calculating formulas is

\[
\begin{align*}
x_{k+1} &= x_k + L \cdot \cos(\theta_{k+1}) \\
y_{k+1} &= y_k + L \cdot \sin(\theta_{k+1}) \\
\theta_{k+1} &= \theta\{\min F(x_{ik}, y_{ik})\}
\end{align*}
\]

(9)

f. Establishing reward and punishment mechanism. If \(F_k < F_{k-1}\), the current course angle can be retained, that is \(\theta_{k+1} = \theta_k\). Otherwise, the course angle is calculated by step d.

(3) Judgment of target position. When the geomagnetic objective function value of the current position satisfies the condition \(F_k < \varepsilon\), where \(\varepsilon\) is a minimum quantity tending to zero, we can judge that the carrier has reached the target position. Otherwise, the algorithm go back to step (2) and continue the search until the convergence condition is satisfied.

4. Results & Discussion

In order to verify the feasibility of the application of evolutionary gradient algorithm in geomagnetic search navigation, we do the simulation experiment in MATLAB R2016a, and the simulated geomagnetic environment was generated by magnetic dipole model.

As the inherent basic physical field of the earth, the geomagnetic field contains rich information of characteristic parameters, such as the total intensity of magnetic field, three-axis component, magnetic inclination, magnetic declination and so on. However, the seven geomagnetic components are not independent of each other. This paper selects the northerly intensity \(B_X\), easterly intensity \(B_Y\) and vertical intensity \(B_Z\) as the search and navigation parameters. The geomagnetic parameters of starting position and target position are set as \(B_X^0 = 32\ 963\text{nT}, \ B_Y^0 = -33\ 068\text{nT}, \ B_Z^0 = 22\ 091\text{nT}, \ B_X^t = 32\ 957\text{nT}, \ B_Y^t = -33\ 073\text{nT}, \ B_Z^t = 22\ 244\text{nT}\).

The initial simulation parameters are listed in Table 1.
In the condition of no prior geomagnetic information, in order to illustrate the effectiveness of the evolutionary gradient search algorithm proposed in this paper, the algorithm is compared with biased random walks strategies (BRWs), evolutionary strategies (ES). Random walks is a kind of discrete-time process, the variables at any time are independent, identically distributed random variables, which are often used in the analysis of biological behavior. And biased random walks model refers to that the motion path contains a consistent bias, which can move towards a specific target. This process emphasizes the global orientation of the motion process. The evolutionary strategy is essentially a trial and error method, which starts from the existing solution, according to the environmental feedback information to guide the search process and improve the development direction of the solution. Compared with BRWs algorithm, the ES has more directionality.

The navigation trails of the three algorithms are shown in Fig.3 (a).

**Table 1 Initial simulation parameters**

| Parameters        | Physical Significance               | Value          |
|-------------------|-------------------------------------|----------------|
| $\Delta \theta$ ($^\circ$) | Sampling interval                  | 45             |
| $T$ / (s)         | Sampling period                     | 3              |
| $v$ / (m·s$^{-1}$) | Carrier velocity                    | 100            |
| $n$ / (nT)        | Radom noise of sensors              | Normrnd(0~10)  |
| $\varepsilon$     | Minimum threshold of objective function | 0.000 1        |
| $K$               | Maximum number of iterations        | 10 000         |

Fig.3 The navigation performance of BRWs, ES and EGS algorithms. (a) shows the navigation trails; (b) shows the convergence curves of the objective functions.
It is illustrated that all these three of the algorithms can complete the geomagnetic navigation task without prior geomagnetic database. The course angle in BRWs algorithm is randomly selected in a certain reward and punishment mechanism, and the selection of heading angle in ES algorithm is based on a certain probability. Therefore, the traces of BRWs and ES are relatively curved, which makes the navigation search process time-consuming. EGS algorithm combines evolutionary search and gradient descent algorithm to search the minimum of geomagnetic objective function, which can not only ensure the optimal objective function, but also ensure the rapid convergence of the objective function, and the navigation trace is relatively straight, which makes the carrier in geomagnetic navigation process more stable. Table 2 has listed the path length, offset distance and error percentage of the three algorithms. The error percentage is defined as the ratio of the distance between the final stop position and the target position of the carrier and the distance between the start position and the target position. In order to unify the unit and facilitate comparison, the percentage method is used to measure the navigation error.

Table 2  Initial simulation parameters

| Evaluation indexes | BRWs  | ES    | EGS    |
|--------------------|-------|-------|--------|
| Path length        | 9600m | 8700m | 7800m  |
| Offset distance    | 603m  | 267m  | 77m    |
| Error percentage   | 8.53% | 3.78% | 1.09%  |

Fig.3 (b) shows the convergence curves of the objective functions of the three search algorithms. As time goes on, the convergence curves of the three algorithms can gradually approach to zero, which can guide the carrier to approach to the target position continuously, and realize the geomagnetic navigation without prior database. Because the sampling period and speed of navigation are fixed, the number of iterative steps in the navigation process can reflect the navigation time-consuming situation. As can be concluded from Fig.3, the iterative time of BRWs algorithm is 30, the iterative time of ES algorithm is 28, and the iterative time of EGS algorithm is 25. Therefore, the navigation efficiency of EGS is better than that of BRWs and ES algorithm. At the same time, the convergence curve of the EGS algorithm is always below the BRWs and ES algorithm, which fully reflects the fast convergence of the EGS algorithm and its higher efficiency of navigation search.

To further illustrate the effectiveness and superiority of the algorithm, BRWs, ES and EGS are simulated for several times in four different geomagnetic navigation tasks, and the traces of four navigation tasks are shown in Fig.4. This figure shows that the algorithm proposed in this paper can complete navigation mission in different conditions.
Table 3 and table 4 respectively count the path ratio and the average error percentage of 50 navigation tasks in four different positions in Fig.4. The navigation path ratio is defined as the ratio of the actual distance to the shortest distance in a straight line.

Table 3  The average path ratio of three algorithms on four positions

| Algorithms | Position | 1   | 2   | 3   | 4   |
|------------|----------|-----|-----|-----|-----|
| BRWs       |          | 2.78| 2.94| 2.68| 2.84|
| ES         |          | 1.90| 2.07| 2.34| 2.13|
| EGS        |          | 1.10| 1.12| 1.05| 1.08|

Table 4  The average error percentage of three algorithms on four positions

| Algorithms | Position | 1   | 2   | 3   | 4   |
|------------|----------|-----|-----|-----|-----|
| BRWs       |          | 5.93%| 7.58%| 7.29%| 5.13%|
| ES         |          | 3.20%| 3.68%| 2.45%| 4.98%|
| EGS        |          | 1.55%| 1.78%| 1.56%| 1.38%|

It can be concluded from table 3 that all the three algorithms can guide the carrier to the target position without prior geomagnetic information effectively. The average path ratio of BRWs is 2.81, ES is 2.11, and EGS is 1.09, which improves the navigation efficiency. And as can be concluded from table 4, the average navigation error percentage is 6.48% for BRWs, 3.58% for ES and 1.57% for EGS. Obviously, navigation based on EGS algorithm improves the navigation efficiency and accuracy. Considering the geomagnetic distortion caused by geomagnetic anomaly in the actual navigation environment, the navigation performance of algorithm in the magnetic anomaly environment is further studied. Fig.5 has built an abnormal magnetic field environment and the carrier is guided by EGS algorithm.

![Fig.5](image)

Fig.5  The navigation trails of EGS algorithm in abnormal magnetic field.

It can be concluded from Fig.5 that in the case of magnetic anomaly, the EGS algorithm can still complete the navigation task. In the abnormal magnetic area, the algorithm will continue to carry out random search, and then jump out of the abnormal area, and finally continue to converge to the target point. However, in the process of random search, the navigation time is greatly increased, and the navigation distance ratio is increased to 12.78.
Finally, the algorithm is tested with the real geomagnetic data from Boao, Qionghai, Hainan Province, as shown in Fig.6. The picture shows that the algorithm can complete the geomagnetic navigation task in the practical application scene without prior geomagnetic data, and the offset distance is 161m, which is equivalent to the most traditional geomagnetic matching algorithms.

Fig.6 The EGS algorithm is tested with measured geomagnetic data from Boao, Qionghai, Hainan Province.

5. Conclusions
In this paper, an intelligent geomagnetic search navigation method based on evolutionary gradient strategy is illustrated, which break the constraints of prior geomagnetic information in the process of geomagnetic navigation. Compared with biased random walks strategies and evolutionary strategy, evolutionary gradient search algorithm proposed in this paper is superior to these two algorithm above in navigation time, search performance and navigation accuracy. Simulation results show that EGS algorithm can more effectively complete the navigation task, and has good navigation performance in the case of magnetic anomaly. Experiments based on real geomagnetic data also support the above conclusions.

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