1. Introduction

Magnetic positioning technology, with characteristics of all-weather, low power consumption, and simple signal processing, has gradually drawn people’s attention. Due to the lower noise level of the magnetic sensor and the higher measurement accuracy, it would be easier to detect weak magnetic signals. Using the magnetic field signal of the target detected by a magnetic sensor or magnetic sensor array, the position information and motion state of the target were obtained by data inversion, which could be widely used in identification of vehicles [1], monitoring of magnetic field [2, 3], prediction of earthquake [4], diagnosis of pipeline failure [5], and exploration of crude oil [6].

Because the positioning algorithm of the magnetic target based on the static magnetic field is greatly influenced by the interference of the geomagnetic environment and other magnetic sources, some researchers have studied the localization of alternating magnetic dipole sources. In 2001, Paperno et al. proposed a method for magnetic position and orientation tracking. Based on two-axis generation of a quasi-static rotating magnetic field and three-axis sensing, two mutually orthogonal coils fed with phase-quadrature currents comprise the excitation source could be equivalent to a mechanically rotating magnetic dipole [7]. In 2006, Nara et al. presented a simple reconstruction formula for localization of a magnetic dipole. In order to calculate the locating information, the dipole position is expressed in terms of the magnetic field and its spatial gradients at a single place [8]. In 2010, Plotkin et al. developed a new scleral search coil (SSC) to track the target. The theoretical deduction and numerous simulations have shown that the proposed method could obtain the orientation and location information of SSC [9]. In 2013, Sheinker et al. proposed a locating method in 3D using beacons of low-frequency magnetic field. The method could be used in many applications, such as the navigation of indoor robot and the mapping of underground cavity [10]. Using beacons of low-frequency magnetic field, the authors proposed a method of remote tracking a year later [11]. In 2016, Pasku et al.
described a positioning system based on low-frequency magnetic field. The system could accommodate an arbitrary number of users without any additional infrastructure [12]. In 2015, Li et al. proposed an approach based on the genetic algorithm to search the location of the dipole. Only an electric field sensor in seawater is needed to measure the modulus of electric field intensity at the corresponding positions. Then, the position of the dipole could be determined accurately [13]. In 2017, the author proposed a positioning method for moving objects with alternating magnetic fields using coherent demodulation. However, the magnetic fields were measured by using a tri-axis magnetometer. The magnetic field measurement precision is influenced by the nonorthogonal error of tri-axis magnetometers [14, 15]. In 2018, Dai et al. proposed a new 6D tracking method using the 3D linear motion, 2D rotational motion, and 3D orientation tracking. The hybrid method of magnetic tracking and inertial sensing verified that the full 6D pose could be used to track the target accurately [16]. In 2020, Song et al. proposed a positioning method of low-frequency magnetic beacons based on the genetic algorithm. In a wide-range measurement, the theoretical simulation and field experiment had been tested to show the accuracy of localization for the target [17].

A positioning method of alternating magnetic dipole in the near-field zone with single-component magnetometers was introduced in this paper. A measuring array consisting of at least six single-component magnetic sensors was used to collect the magnetic field emitted by the alternating magnetic dipole. Through the process of coherent demodulation, the varying curve of alternating magnetic field could be obtained. A hybrid algorithm combining the Gauss–Newton algorithm and genetic algorithm was applied to obtain the track of a moving target, which showed a good agreement with the actual motion information [18–22].

2. Materials and Methods

2.1. The Vertical Component of Alternating Magnetic Dipole. The alternating magnetic dipole source is a transmitting coil that radiates a low-frequency sinusoidal electromagnetic signal, and the working frequency of the signal is set as a fixed frequency. For example, the working frequency of the signal ranges from 100 Hz to 1000 Hz, and the corresponding wave length is between 3 × 105 meters and 3 × 106 meters correspondingly. The geometry of the radiation coil is much smaller than its working wavelength so that the radiation coil could be equivalent to a magnetic dipole. The schematic diagram of magnetic dipole in the cylindrical coordinate system is shown in Figure 1.

The radiation magnetic moment of the magnetic dipole is expressed by the formula as follows:

\[ M = \mu_0 I S. \]  

In formula (1),

\( \mu_0 \) is the magnetic permeability of the medium

\( I \) is the current intensity in the coil

\[ \omega \] is the angular frequency of the alternating electromagnetic field

\( R \) is the distance from the magnetic dipole source to the observation point

\( K \) is the number of complex waves, which is plural in the conductive medium

Formula (2) contains the item labelled as \( KR \). According to the distance labelled as \( R \) between the magnetic dipole source and the receiving point, the wavelength of the radiated electromagnetic wave in the propagation medium is labeled as \( \lambda \). The electromagnetic field magnetic transmitted by the magnetic dipole could be divided into three regions.

(1) When \( KR \ll 1 \), it is called the near zone, also known as the quasi-stationary zone or the zone of stability

(2) When \( KR \gg 1 \), it is called the far zone

(3) The region between the near zone and the far zone is called intermediate zone

Usually, \( R \ll 0.1 \lambda \). Considering of the target’s working frequency, the positioning region of the target is the near-field zone of the magnetic dipole source.

The distribution of the electromagnetic field in the near zone of the alternating magnetic dipole approximates that of the static magnetic dipole (\( \omega = 0 \), promptly, \( K = 0 \)), which is similar to the constant stability field. It is assumed that the magnetic moment of an alternating magnetic dipole source located at the point labelled as \( P_0 (x_0, y_0, z_0) \) could be recorded as

\[ S \] is the cross-sectional area of the coil, whose direction is the normal direction of the right-handed spiral

Using Maxwell’s equations and boundary conditions, the electromagnetic field expression of magnetic dipole radiation could be expressed as

\[ H_R = \frac{2M}{4\pi\mu_0 R}\cos \theta (1 + jKR)e^{-jKR}, \]

\[ H_\theta = \frac{M \sin \theta}{4\pi\mu_0 R^2} [1 + jKR + (jKR)^2]e^{-jKR}, \]

\[ E_\varphi = \frac{\omega M}{4\pi R^2} \sin \theta (KR - j)e^{-jKR}. \]
\[ \vec{M} = M_{x0} \cos(2\pi ft + \rho) \hat{i} + M_{y0} \cos(2\pi ft + \rho) \hat{j} + M_{z0} \cos(2\pi ft + \rho) \hat{k}. \] (3)

The magnetic vector potential and magnetic fields at the receiving point labelled as \( P(x, y, z) \) are as follows:

\[
\begin{align*}
\min_{\vec{x} \in \mathbb{R}^n} S(x), \\
(t_i, B_i), \quad i = 1, 2, \ldots, N,
\end{align*}
\] (4)

\[
\begin{bmatrix}
H_{x2} \\
H_{y2} \\
H_{z2}
\end{bmatrix} = \frac{1}{4\pi r^5} \begin{bmatrix}
3(x - x_0)^2 - r^2 & 3(x - x_0)(y - y_0) & 3(x - x_0)(z - z_0) \\
3(x - x_0)(y - y_0) & 3(y - y_0)^2 - r^2 & 3(y - y_0)(z - z_0) \\
3(x - x_0)(z - z_0) & 3(y - y_0)(z - z_0) & 3(z - z_0)^2 - r^2
\end{bmatrix} \begin{bmatrix}
M_{x0} \cos(2\pi ft + \rho) \\
M_{y0} \cos(2\pi ft + \rho) \\
M_{z0} \cos(2\pi ft + \rho)
\end{bmatrix}
\] (5)

From a strictly mathematical point of view, at least six single-component sensors are required since there are six unknown quantities: the three position coordinates labelled as \( P_0(x_0, y_0, z_0) \) and the three moment components labelled as \( M_0(M_{x0}, M_{y0}, M_{z0}) \), and each sensor provides only one equation.

### 2.2. The Static Locating Method Based on Single-Component of Magnetic Field

Assume that the measuring array consisting of six single-component magnetic field sensors is shown in Figure 2, and their coordinates are labelled as \( P_n(x_n, y_n, z_n) \) where \( 1 \leq n \leq 6 \). The alternating magnetic dipole source is at the point labelled as \( P_0(x_0, y_0, z_0) \).

The vertical component of the magnetic field generated by the alternating magnetic dipole at the point labelled as \( P_0(x_0, y_0, z_0) \) was recorded as

\[ H_n = H_{zn} \cos(2\pi ft + \rho). \] (6)

Using the coherent demodulation, the alternating magnetic field labelled as \( H_n \) could be transformed to the varying curve signed as \( H_{zn} \) [14]. Then, the formula could be described as follows:

\[
\begin{bmatrix}
H_{z1} \\
H_{z2} \\
H_{z3} \\
H_{z4} \\
H_{z5} \\
H_{z6}
\end{bmatrix} = \frac{1}{4\pi r^5} \begin{bmatrix}
3(x_1 - x_0)(z_1 - z_0) & 3(y_1 - y_0)(z_1 - z_0) & 3(z_1 - z_0)^2 - r_1^2 \\
3(x_2 - x_0)(z_2 - z_0) & 3(y_2 - y_0)(z_2 - z_0) & 3(z_2 - z_0)^2 - r_2^2 \\
3(x_3 - x_0)(z_3 - z_0) & 3(y_3 - y_0)(z_3 - z_0) & 3(z_3 - z_0)^2 - r_3^2 \\
3(x_4 - x_0)(z_4 - z_0) & 3(y_4 - y_0)(z_4 - z_0) & 3(z_4 - z_0)^2 - r_4^2 \\
3(x_5 - x_0)(z_5 - z_0) & 3(y_5 - y_0)(z_5 - z_0) & 3(z_5 - z_0)^2 - r_5^2 \\
3(x_6 - x_0)(z_6 - z_0) & 3(y_6 - y_0)(z_6 - z_0) & 3(z_6 - z_0)^2 - r_6^2
\end{bmatrix} \begin{bmatrix}
M_{x0} \\
M_{y0} \\
M_{z0}
\end{bmatrix}
\] (7)
2.3. The Positioning Model of Alternating Magnetic Dipole. The positioning model of alternating magnetic dipole in the near-field zone with a measuring array consisting of six single-component magnetometers could be attributed to the solution for a class of nonlinear unconstrained optimization problem.

\[ E_0 = \min \left\{ (F_0M_0 - H_0)^T(F_0M_0 - H_0) \right\}, \]  

(8)

where \( E_0 \) is the objective function of the nonlinear unconstrained optimization problem.

\[ M_0 = \left(F_0^T F_0\right)^{-1} F_0^T H_0, \]

(9)

which is called the coefficient matrix of magnetic moment parameters.

\[
F_0 = \begin{bmatrix}
\frac{3(x_1 - x_0)(z_1 - z_0)}{4\pi r_1^4} & \frac{3(y_1 - y_0)(z_1 - z_0)}{4\pi r_1^4} & \frac{3(z_1 - z_0)^2 - r_1^2}{4\pi r_1^4} \\
\frac{3(x_2 - x_0)(z_2 - z_0)}{4\pi r_2^4} & \frac{3(y_2 - y_0)(z_2 - z_0)}{4\pi r_2^4} & \frac{3(z_2 - z_0)^2 - r_2^2}{4\pi r_2^4} \\
\frac{3(x_3 - x_0)(z_3 - z_0)}{4\pi r_3^4} & \frac{3(y_3 - y_0)(z_3 - z_0)}{4\pi r_3^4} & \frac{3(z_3 - z_0)^2 - r_3^2}{4\pi r_3^4} \\
\frac{3(x_4 - x_0)(z_4 - z_0)}{4\pi r_4^4} & \frac{3(y_4 - y_0)(z_4 - z_0)}{4\pi r_4^4} & \frac{3(z_4 - z_0)^2 - r_4^2}{4\pi r_4^4} \\
\frac{3(x_5 - x_0)(z_5 - z_0)}{4\pi r_5^4} & \frac{3(y_5 - y_0)(z_5 - z_0)}{4\pi r_5^4} & \frac{3(z_5 - z_0)^2 - r_5^2}{4\pi r_5^4} \\
\frac{3(x_6 - x_0)(z_6 - z_0)}{4\pi r_6^4} & \frac{3(y_6 - y_0)(z_6 - z_0)}{4\pi r_6^4} & \frac{3(z_6 - z_0)^2 - r_6^2}{4\pi r_6^4}
\end{bmatrix},
\]

(11)

which is the varying curve of the vertical component for the alternating magnetic dipole in the near-field using the coherent demodulation [14, 15].

which is the coefficient matrix of positions for the target.

3. Simulations

The measuring array consisting of six single-component magnetic field sensors is in the plane labelled as XOy of the Cartesian coordinate system and is shown in Figure 3, and the origin is signed as O. The magnetic target at the point \( P \) moves along a straight line from the point \( P(-20, -20, 2) \) to the point \( Q(20, 20, 2) \). The velocity is a constant of 10 m/s in the x-axis and 10 m/s in the y-axis. The coordinates of the six sensors are labelled as \( P_1(-2, 1, 0), P_2(0, 1, 0), P_3(2, 1, 0), P_4(-2, -1, 0), P_5(0, -1, 0), \) and \( P_6(2, -1, 0) \). The vertical component of the alternating magnetic fields is acquired by a measuring array consisting of six single-component magnetic field sensors.
In the whole movement, the source of alternating magnetic dipole moves from $-20$ m to $20$ m in the $x$-axis and $-20$ m to $20$ m in the $y$-axis. The height is set as $2$ m in the $z$-axis. The magnetic moment of an alternating magnetic dipole source is

$$ M = 40 \cos \left(400\pi t + \left(\pi/3\right)\right) \hat{i} + 30 \cos \left(400\pi t + \left(\pi/3\right)\right) \hat{j} + 20 \cos \left(400\pi t + \left(\pi/3\right)\right) \hat{k} \text{ Am}^2. $$

The alternating magnetic field data acquired by six single-component magnetometers are shown in Figure 4.

The varying curve of alternating magnetic field data acquired by six single-component magnetometers during the target's whole movement was obtained by the coherent demodulation (see Figure 5). Then, the localization for moving target with the alternating magnetic field could be transformed to the problem of that with the static magnetic field.

As shown in Figure 6, the locating results show a good agreement with the actual values as predetermined in the simulation. It could also be seen that the target moved from $-20$ m to $20$ m in the $X$-axis, and the average velocity is $10$ m/s. The result in the $Y$-axis is the same as that in the $X$-axis. The result in the $Z$-axis is a constant value of $2$ m at the time from $1$ s to $5$ s.

From the results of above simulation, the position information calculated by the model is completely consistent with the predetermined position information of the moving target. These verify the feasibility of localization for alternating magnetic dipole source using the single-component magnetic field.

4. Experiment

The field experiment was operated in Xi’an, China. An experimenter pushed the trolley carrying the transmitting equipment through the measuring array at the speed of about $0.2$ m/s. The height of the solenoid as an alternating magnetic dipole source is about $1.2$ m from the ground (see Figure 7(a)). The magnetic field is acquired by a measuring array consisting of eight single-component magnetometers (see Figure 7(b)).

The relationship between the movement of the solenoid and the position of the measuring array is shown in Figure 8. The target moved from the starting point $P(-3, -5, 1.2)$ to the ending point $Q(-3, 5, 1.2)$ along a straight line. The horizontal pitch of the measuring array is $0.5$ m, and the vertical pitch is also $0.5$ m.

The frequency of the sinusoidal signal emitted by the solenoid is set as $500$ Hz. The measuring array consisting of eight single-component magnetometers collected the vertical component of the magnetic field, which is transferred to a PC via a data acquisition card. The sampling rate is set as $5000$ Hz. Because the experimental environment is not ideal, there is strong interference of power frequency and other frequencies. It is impossible to directly use the signals collected by the single-component inductive magnetic field sensors.

The signals collected by the single-component inductive magnetic field sensors were passed through a band-pass filter with a cut-off frequency from $480$ Hz to $520$ Hz. Taking the signal collected by sensor #2 as an example, Figure 9 shows the time domain signals before and after filtering. It also showed that the signals emitted by the signal source collected by sensor #2 were well extracted.

Figure 10 shows the magnetic signals collected by the induction magnetic field sensor #1 to #4 processed after filtering.

Figure 11 shows the magnetic signals collected by the induction magnetic field sensor #5 to #8 processed after filtering.

Since the radiating rod inevitably has the problem of swaying during the movement, the curves obtained by
coherent demodulation have a certain amount of shaking compared with the smooth curves in the simulation. The peak values of sensor #1 in Figure 12 are significantly greater than those of sensor #2, sensor #3, and sensor #4 located in the same line. At the same time, it could be found that the peak values of sensor #7 in Figure 13 are significantly smaller than those of sensor #5, sensor #6, and sensor #8 located in the same line. These were caused by the different sensitivities of each sensor. In order to reduce the impact of different sensitivities of the sensor, the signals collected by sensor #7 and sensor #1 were excluded in the final positioning solution.

Using the hybrid algorithm combining the Gauss–Newton algorithm and genetic algorithm, the positioning results of the target in the X direction are shown in Figure 14. The location result is about $-3$ m in the X direction from the time of 20 s to 55 s. These show a good agreement with the actual value. This is the reason that the magnetic field signal gradually increases as the distance between the target and the sensor becomes close.
The error curve between the positioning result and the actual movement trajectory of the target in the x direction is shown in Figure 15. It could be found that when the target passed through the array, the positioning error was very small and the positioning effect was very good. The average error of positioning is 0.17 m from the time of 20 s to 55 s. However, as the target moved away from the array, the positioning error became larger and the positioning effect became poorer.

As shown in Figure 16, the average velocity was about 0.2 m/s in the Y direction from the time of 20 s to 55 s. These also showed a good agreement with the actual value and a disagreement in the other times.

The error curve between the positioning result and the actual movement trajectory of the target in the Y direction is shown in Figure 17. It could be found that when the target passed through the array, the positioning error was very small and the positioning effect was very good. The average
Figure 6: Contrast of location result and actual values for the moving target.

Figure 7: (a) Radiation source and (b) single-component magnetometers.
error of positioning is 0.12 m from the time of 20 s to 55 s. However, as the target moved away from the array, the positioning error also became larger and the positioning effect became poorer.

Figure 8: Overhead view of experimental tests.

Figure 9: Alternating magnetic field collected by sensor #2 before and after filtering.

Figure 10: The signals collected by the induction magnetic field sensor #1 to #4 processed after filtering.

Figure 11: The signals collected by the induction magnetic field sensor #5 to #8 processed after filtering.

Figure 12: The varying curves of alternating magnetic field data collected by the sensor labelled as from #1 to #4.

Figure 13: The varying curves of alternating magnetic fields collected by the sensor labelled as from #5 to #8.

error of positioning is 0.12 m from the time of 20 s to 55 s. However, as the target moved away from the array, the positioning error also became larger and the positioning effect became poorer.
As the simulation result in the Z direction was the same as that in the X direction, the analysis would not be repeated in this paper.

5. Conclusions

Most of the traditional research studies on magnetic positioning technology are based on the magnetic target location of static magnetic anomalies, and the positioning effect is easily affected by geomagnetic anomalies and other magnetic interference noise. The magnetic field positioning methods of the alternating magnetic dipole model are studied, which have strong anti-interference ability. The methods could overcome the interference of geomagnetic environmental interference and reduce the influence of other frequency interference signals on the positioning through some signal processing methods. Using single-component magnetometers could reduce costs and avoid the steering differential calibration of tri-axis magnetometers. The theoretical analysis of simulation and experimental results showed that the position information agreed well with the actual moving state of the target, which verified the feasibility and practicability of the localization algorithm. It is of great significance in the application of engineering.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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