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Direction identification of a moving ferromagnetic object by magnetic anomaly

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ABSTRACT

We propose a novel method for identifying heading direction of a ferromagnetic target by processing magnetic measurements of two directions. The proposed method relies on the phase of the complex signal composed of two dimensions (2-D) magnetic anomaly signals accessed by two perpendicularly placed sensing units. Theoretical analysis based on a magnetic dipole model shows the derivative of phase of the composed complex signal can indicate the heading direction of a moving ferromagnetic object, no matter what the target magnetic moment magnitude and orientation are. Given flexibility and power savings of the measurement systems, a kind of small size, low power and low-frequency search coil magnetometer is developed as sensing units with the equivalent noise level of approximate 12 $\mathrm{pT}/\sqrt{\mathrm{Hz}}$ at about 1 Hz. Computer simulation and real-word experiments have been conducted to test the performance of the method. The results show that the algorithm can identify the heading direction correctly at SNR of 9 dB or more against $1/f^{\alpha}$ noises. Furthermore, the method can classify the direction with available saturated data. The simple implementation and low-computational complexity make the proposed method a potential candidate for real-time underwater area passive surveillance.

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1. Introduction

Nowadays, magnetometer network is broadly used in area surveillance and boundary security [1–4], such as Intelligent Transportation System (ITS) [1,5,6], Navigation System (NS) [7–9] and Intrusion Detect System (IDS) [10–12]. For these applications, detection information from a single magnetometer such as the location [13] and the velocity [14] regarding targets of interest should be as much as possible to minimize the required number of magnetometers to cover a given area. Among these informations, heading direction is one of the key parameters, which can provide specific information for traffic management [1,5,6] and objects tracking [15–17], etc.

However, current existing direction identification studies for moving ferromagnetic targets have mainly been performed by few researchers [18–23]. Ege et al. formulate an excellent mathematical model to estimate moving direction and velocity of ferromagnetic objects using single magnetometer and multi-sensor network [18,19]. Considering magnetometer networks have many disadvantages such as high maintenance cost, poor real-time performance and cannot deploy flexibly [14], etc., simple and effective schemes to gather movement direction information regarding targets of interest are more desired. Some techniques have been employed, such as lissajous circle [20] as well as cross relation [21]. But the challenge work has not been actively studied for practical implementation, which is vital to the intelligent parking system researched in the previous work [24–27].

In this work, we are only interested in finding the heading direction of ferromagnetic targets in a fast and efficient way. A novel alternative heading direction of ferromagnetic objects estimation algorithm using two dimensions (2-D) magnetic anomaly signals is put forward. The algorithm bases on the phase characteristics of the accessible magnetic anomaly signals. A complex signal is defined utilizing the acquired 2-D signals. The derivative of phase regarding the composed complex signal can infer the heading directions of moving ferromagnetic objects. In the scheme, the magnetometer can been easily placed at any points of interest in the plane of target motion and due to the low-complexity of the

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identification algorithms, the heading direction can be determined almost instantly with available measurement data. The proposed scheme is very suitable for underwater surveillance applications such as defense of harbors [3,4] and anti-submarine warfare [4,28].

The remainder of this paper is organized as follows. In Section 2, we describe the theoretical analysis of the direction identification algorithm. A small size, low power and low-frequency search coil magnetometer is described in Section 3. Section 4 presents the performances of the algorithm by series of simulations and real experiments. Further work is drawn in Section 5 followed by conclusions in Section 6.

2. Theoretical analysis

Consider the coordinate system of a ferromagnetic target and magnetometers shown in Fig. 1. Two magnetometers are located at the origin aligned in parallel to the X, Y coordinate axes, respectively. The ferromagnetic target moves along a straight line track paralleling to the X axes with a constant velocity v in XOY plane. $\vec{r}$ represents the distance vector from the target to the magnetometers and r_y is the so-called CPA (closest proximity approach) distance. Generally r_y is normally large in comparison to the characteristic length of the target, therefore, the ferromagnetic target can be modeled as a magnetic dipole [29]. The magnetic anomaly signal $\vec{B}$ generated by the ferromagnetic target with a moment $\vec{m}$ at some distance $\vec{r}$ is expressed as in matrix form [30]

$$\begin{bmatrix} B_x \\ B_y \\ B_z \end{bmatrix} = \frac{\mu_0}{4\pi r^5} \begin{bmatrix} 3r_x^2 - r^2 & 3r_x r_y & 3r_x r_z \\ 3r_y r_x & 3r_y^2 - r^2 & 3r_y r_z \\ 3r_x r_z & 3r_y r_z & 3r_z^2 - r^2 \end{bmatrix} \begin{bmatrix} m_x \\ m_y \\ m_z \end{bmatrix} \tag{1}$$

the target magnetic moment is denoted by $\vec{m} = m_x\vec{x} + m_y\vec{y} + m_z\vec{z}$, and the distance $\vec{r} = r_x\vec{x} + r_y\vec{y} + r_z\vec{z}$ represents a vector from the target to the magnetometer, where $\vec{x}, \vec{y}, \vec{z}$ are the unit vectors in the Cartesian coordinate frame. B_x, B_y, B_z are the three components of magnetic anomaly signal $\vec{B}$, i.e. $\vec{B} = B_x\vec{x} + B_y\vec{y} + B_z\vec{z}$, and $\mu_0 = 4\pi \times 10^{-7}$ H/m is the permeability of free space.

From the above descriptions, we can have

$$\begin{cases} r_x = vt \\ r_y = c \quad (c \text{ is a constant}) \\ r_z = 0 \end{cases} \tag{2}$$

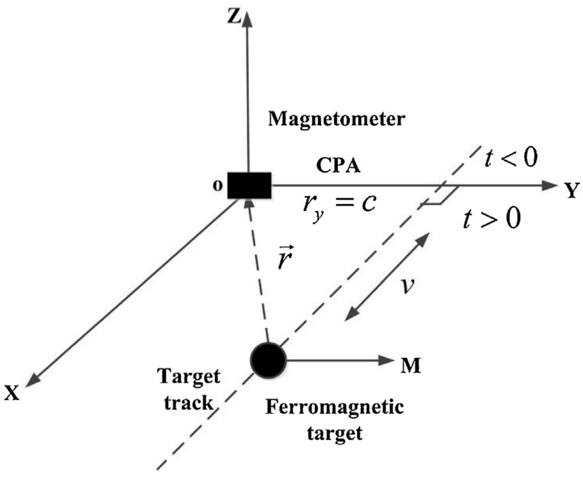

Fig. 1. Relative position of the ferromagnetic object and magnetic sensors.

According to Eq. (2), the target track can be expressed as a function of time t by

$$\vec{r}(t) = v \cdot t \cdot \vec{x} + c \cdot \vec{y} \tag{3}$$

At time $t = 0$, the target passes the magnetometers at a CPA of c. In the following equations we omit the term $\mu_0/4\pi r^5$ for better clarity. The magnetic anomaly signals of the x, y direction from Eq. (1) are denoted by $H_x(t)$ and $H_y(t)$, respectively.

$$\begin{cases} H_x(t) = (2v^2t^2 - c^2)m_x + 3m_y cvt \\ H_y(t) = (2c^2 - v^2t^2)m_y + 3m_x cvt \end{cases} \tag{4}$$

Now, we define a complex signal $\tilde{H}(t)$ with $H_x(t)$ as the real component and $H_y(t)$ the imaginary component

$$\tilde{H}(t) = H_x(t) + jH_y(t) = \left|\tilde{H}(t)\right| e^{j\theta(t)} \tag{5}$$

where $\left|\tilde{H}(t)\right|$ and $\theta(t)$ represent the amplitude and phase of $\tilde{H}(t)$, respectively. The phase can be described as

$$\theta(t) = \text{angle}\,[\tilde{H}(t)] = \tan^{-1}\left[\frac{H_y(t)}{H_x(t)}\right] \tag{6}$$

By substituting Eq. (4) into Eq. (6), we get the expression of the derivative of phase as a function of a single variable $r_x(t)$ and the parameters m_x, m_y, m_z and c

$$\theta'(t) = \frac{d\theta(t)}{dt} = \frac{H_y'(t)H_x(t) - H_x'(t)H_y(t)}{H_x^2(t) + H_y^2(t)} = -\beta cv \tag{7}$$

where $H_j'(t), (j = x, y)$ and $\theta'(t)$ represent the derivatives of magnetic fields and the derivative of phase, respectively. Apparently, we will arrive at the result in Eq. (7)

$$\beta = \frac{3\left[2m_x^2r_x^2 + 2m_y^2c^2 + (m_yr_x^2 + m_xc)^2\right]}{\left[H_x^2(t) + H_y^2(t)\right]} > 0 \tag{8}$$

From Eqs. (7) and (8), it follows that when $c > 0$, $H_y'(t)H_x(t) - H_x'(t)H_y(t)$ (i.e. $\theta'(t)$) has the opposite sign as v, no matter what the target magnetic moment magnitude and orientation are. That is to say, if we know the sign of c and $H_y'(t)H_x(t) - H_x'(t)H_y(t)$, we will know the heading direction of targets as well.

From the above derivation, we can now define an indicator for moving direction identification based on the magnetic field components and corresponding derivatives.

$$C = \int \left[H_y'(t)H_x(t) - H_x'(t)H_y(t)\right] dt \tag{9}$$

Finally, solving Eq. (9) numerically, one can get the discrete time version

$$C = \sum_{i=1}^{N-1} (H_i^x H_{i+1}^y - H_i^y H_{i+1}^x) \tag{10}$$

where the magnetic field is simplified as $H_k^j = H^j(kT)(j = x, y)$ for clarity with T as the sample interval and k the sample index. With the sign of indicator C, one can identify the heading direction of ferromagnetic targets efficiently.

3. Search coil magnetometer

In order to measure magnetic anomaly signals induced by moving ferromagnetic targets, a kind of small size, low power and low-frequency search coil magnetometer (see Fig. 2) is developed according to the excellent contribution of Grosz [31,32].

The magnetometer occupies an about 80-cm^3 volume 6.5 cm × 3.5 cm × 3.5 cm. Its coil is enameled copper wire with

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