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Magnetic heading compensation method based on magnetic interferential signal inversion

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ABSTRACT

This paper presents a method for compensation of disturbances introduced by near-surface interference sources in the estimation of magnetic heading, based on the inversion of the interference signal. Firstly, magnetometer array is designed to measure magnetic vector and gradient signals of the same point. Invariants of magnetic gradient tensor measured by the array are used to determine whether there exists magnetic heading perturbation. Then the magnetic vector signals generated by the near-surface magnetic interference sources are calculated using the measured magnetic gradient signals based on the phase shift theorem of discrete cosine transform (DCT), and the background geomagnetic vector field is obtained by subtracting the inversed magnetic anomaly vector signals from the measured magnetic vector signals. Finally, the magnetic heading angle is obtained based on the compensated background geomagnetic vector field. Numerical examples and real experiments based our prototype array reveal reliability and the applicability of the proposed method.

1. Introduction

Magnetic heading information, the pointing direction of the three-axis magnetometer block with respect to the magnetic North, is one of most essential parameters in navigation and it is basis of geomagnetic directional navigation and dead-reckoning navigation [1]. However, the implementation of accurate heading estimation is not easy and it is often affected by many factors, which can be divided into two major groups including system itself and external environment. The system error contains installation error, manufacturing error, and the magnetic disturbances of the hosting platform. This kind of error can be mitigated with proper field calibration [2,3], and then the directional accuracy can be $\pm 0.5^\circ$ for the magnetic perturbation-free environments. However, the errors from external environments are still difficult questions to study. The sources of magnetic disturbances, like ferromagnetic materials, high-voltage wires, mechanical and electrical infrastructures, are numerous in an unknown environment and their impact can hardly be modeled [4,5]. Without proper magnetic disturbances detection and mitigation technique, the magnetic heading estimation errors derived by the external magnetic field disturbances can even exceed 100° [6]. Consequently, specific approaches need to be investigated for detecting and mitigating the existing magnetic heading disturbances in the observations.

Many approaches have been proposed to mitigate the impact of external magnetic field disturbances on heading estimation [7], which can be divided into two major groups including data fusion of different types of sensors and compensation method only using the signals of magnetometers. As the most common algorithm, Kalman filter and its improved algorithms have been proposed to improve the accuracy of heading estimation by fusing the gyroscopes, accelerometers and magnetometers. When the magnetic disturbances occur, less weight is assigned to the magnetometers and the heading estimation trusts more on the gyroscopes and accelerometers [8,9,10]. This kind of method has a drawback that pure integration of the gyroscope while neglecting the magnetometer reading will work only for the trivial case of quickly vanishing disturbances [11]. The second heading compensation method barely using the signals of magnetometers also got a lot of attention from researchers. Ojeda et al. [12] constituted a differential compass with two sensors aligned in the same direction but separated from each other by a fixed distance to identify environmental magnetic interferences. Yun et al. [13] presented a similar differential compass for driving assistance. Afzal et al. [14] proposed a Multiple Magnetometer Platform (MMP) composed of 12 tri-axial magnetometers to detect magnetic heading disturbance and mitigate heading error. Valerie Renaudin et al. [15] proposed

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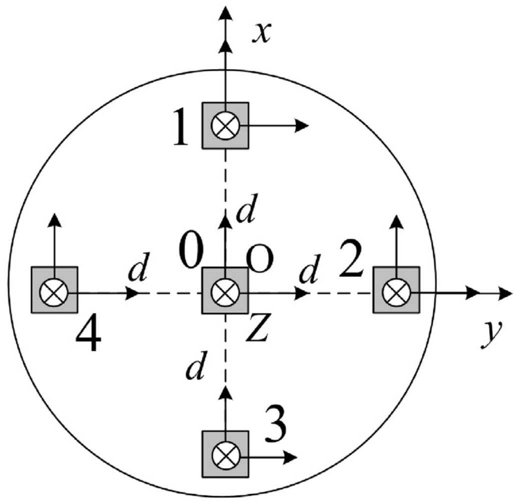

Fig. 1. Structural conception of the magnetometer array.

a fuzzy inference system for evaluating the joint impact of four different parameters on the accuracy of magnetic heading estimates. All of these methods have achieved good results in their respective applications. Previously, we presented an algorithm for heading estimation using a single magnetometer and compensated the heading error using the calculated magnetic gradient signals and inversed magnetic anomaly vector signals [16], However, the calculation process of magnetic gradient signals is easily disturbed by the noise, then the inversed magnetic anomaly vector signals by the disturbed gradient signals will have some deviations from the real value and will therefore distort the heading estimation. To avoid the noise in the calculation process, we designed a magnetometer array to measure the magnetic gradient signals directly and compensated the heading error using magnetic interferential signal inversion method in this study.

The overall layout of this paper is as follows. A magnetometer array is designed to measure magnetic field vector and magnetic gradient tensor of the same point synchronously in Section 2. Magnetic heading disturbance detector combining the magnetic vector field parameters and tensor invariants is proposed in Section 3. In Section 4, magnetic vector signals generated by near-surface magnetic interference sources are calculated from measured magnetic gradient tensor signals using DCT, and error compensation of magnetic heading disturbances is achieved. Section 5 tests performance of the proposed method with simulations. In Section 6, we present experimental results of our method and prototype system, which are followed by the conclusions in Section 7.

2. Design of magnetometer array

As the geomagnetic field is available everywhere on the Earth, it has been contributing to the measurement of magnetic heading. However, the external magnetic interference sources increase greatly with the increase of human activities. Magnetic interference sources are causing magnetic anomalies that disturb the magnetometer's measurements of the Earth's magnetic field, and then lead to the measurement error of magnetic heading. In other words, the magnetic anomaly field must be detected and separated in order to obtain accurate magnetic heading value. However, scalar and vector signals measured by magnetometers both are sum of magnetic anomaly field and the Earth's magnetic field. It is difficult to separate the Earth's magnetic field from the measured scalar or vector value of magnetometer [17].

Although the scalar and vector magnetic anomaly field are mixed with the geomagnetic field, it is noteworthy that the geomagnetic field gradient is low and in local measurement can be considered negligible. Magnetic gradient measurements mainly reflect magnetic field gradients of near-surface magnetic sources [18]. Therefore, we can obtain the magnetic anomaly gradient of magnetic interference sources by gradient measurement, and then inverse the magnetic anomaly field vector. On this basis, the inversed magnetic anomaly field vector can be used to separate the geomagnetic field to obtain the real background geomagnetic field. In order to measure magnetic field gradient signals, a magnetometer array is designed and its structural conception is shown in Fig. 1. The array is composed of five tri-axial magnetometers with the baseline distance of d. The x and y axes lie along the orthogonal baselines and the z axis is chosen to make a right-handed Cartesian coordinate system.

The peripheral four magnetometers constituting cross magnetic gradient tensor system are designed to measure gradient signals which are used to inverse the magnetic anomaly vector signals. For static magnetic fields and for the common case where conduction currents are negligible, the magnetic gradient tensor is symmetric and traceless. Then only five of the gradient components are independent for a second rank tensor [19]. So the measured magnetic gradient tensor $\boldsymbol{G}$ can be shown as follows [20].

$$\boldsymbol{G}=\begin{pmatrix}\frac{\partial Bx}{\partial x} & \frac{\partial By}{\partial x} & \frac{\partial Bz}{\partial x}\\ \frac{\partial Bx}{\partial y} & \frac{\partial By}{\partial y} & \frac{\partial Bz}{\partial y}\\ \frac{\partial Bx}{\partial z} & \frac{\partial By}{\partial z} & \frac{\partial Bz}{\partial z}\end{pmatrix}=\begin{pmatrix}B_{xx} & B_{xy} & B_{xz}\\ B_{yx} & B_{yy} & B_{yz}\\ B_{zx} & B_{zy} & B_{zz}\end{pmatrix}=\begin{pmatrix}\frac{B_{1x}-B_{3x}}{2d} & \frac{B_{2x}-B_{4x}}{2d} & \frac{B_{1z}-B_{3z}}{2d}\\ \frac{B_{1y}-B_{3y}}{2d} & \frac{B_{2y}-B_{4y}}{2d} & \frac{B_{2z}-B_{4z}}{2d}\\ \frac{B_{1z}-B_{3z}}{2d} & \frac{B_{2z}-B_{4z}}{2d} & -\frac{B_{1x}-B_{3x}}{2d}-\frac{B_{2y}-B_{4y}}{2d}\end{pmatrix} \quad (1)$$

Where Bx, By and Bz are measured magnetic field components in three orthogonal directions, $B_{pq}, p, q = x, y, z$ denote magnetic gradient tensor components in different directions. $B_{ij}, i = 1, 2, 3, 4, j = x, y, z$ denote magnetic vector component in the j direction of the i magnetometer. Then $B_{xx}, B_{xy}, B_{xz}, B_{yy}, B_{yz}$ can be considered as five independent components.

3. Magnetic heading estimation and magnetic anomaly detection

When a magnetometer is installed on the vehicle along the body frame, magnetic heading and declination angle can be used to determine the vehicle heading. Define two horizontal components of background geomagnetic field as H_y and H_x. Therefore, the magnetic heading can be calculated as following [16].

$$\varphi_m = \tan^{-1}\left(\frac{H_y}{H_x}\right) \quad (2)$$

According to the Eq. (2), we know that the magnetic heading can be estimated using the horizontal components of background geomagnetic field. However, the existing near-surface magnetic anomalies disturb horizontal components of geomagnetic field [10] and result in further magnetic heading disturbance although the physical heading angle is stationary (The sketch map is shown in Fig. 2). Therefore, in order to obtain accurate magnetic heading,