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Magnetic interference compensation method for geomagnetic field vector measurement

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ABSTRACT

Ferromagnetic interferential field from platforms is one of the most dominating error sources for magnetometer. For magnetic vector and gradient tensor measurement, what is cared about most is the effect of compensating magnetic field vector. In this paper, a magnetic compensation method is proposed, which uses host platform's attitude from inertial sensor as auxiliary information and sets up a vectorial compensation model. By introducing three intermediate parameters, the issue of parameter estimation is linearized and solved with least squares method. Simulations show that errors of magnetic field vector and magnitude can both be reduced to several nT after compensation. Experiment has been conducted with a geomagnetic vector measurement system and results suggest that the method is an effective way for compensating both magnetic field magnitude and vectors.

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1. Introduction

Triaxial magnetometer (TAM) can measure magnetic field vector and provide abundant information, which has been widely used on satellite, airplane, underwater vehicle for geomagnetic navigation, mineral resources prospecting and anomaly detecting [1–3]. For geomagnetic field vector measurement, errors are caused by not only sensor errors (deviations from bias, scale factors and nonorthogonality) but also impacts of adjacent ferromagnetic materials, which are commonly called permanent and induced interferential fields. The first kind of error has been studied widely [4–7]. However, it is still challengeable to compensate both magnitude and vector of magnetic interference field.

Ellipsoid fitting methods, based on fact that magnetic interferential model is an ellipsoid, have been commonly used for compensating magnetic interference field [8,9]. Fang et al. propose a constraint least squares method to estimate model calibration parameters and constraint condition is applied to insure the conicoid to be an ellipsoid [10]. Renaudin et al. provide an adaptive least squares estimator to deal with ellipsoid fitting problem [11]. Gebre-Egziabher et al. propose a two-step method to compensate magnetometer offset, permanent field and scale factor error based on ellipsoid fitting [12]. In fact, there are only 9 independent parameters in ellipsoid model, while a total of 12 parameters are contained in magnetic interferential model. Although Symmetrical form of interferential model with singular value decomposition has been adopted to solve the problem, there still exists multi-solutions for magnetic field vector. Some other methods, such as a fast iterative method, differential evolution (DE) algorithm and UKF, have been proposed to estimate interferential model parameters and compensate magnetic interference [13–16].

Above-mentioned methods can be called scalar compensation method, which only uses magnitude of external magnetic field and minimizes the square of differences between norms of magnetometer outputs and magnitude of the field. Although magnitude can be compensated with high accuracy, it is hard to ensure the correctness of magnetic field vector. Hence, auxiliary information should be introduced and equation should be linearized for compensating magnetic field vector accurately.

For aircraft's magnetic interference problem, Tolles and Lawson introduce direction cosines between geomagnetic field vector and each of aircraft's major axes into measurement equations and set up a linear model [17–19]. During compensation process, a triaxial magnetometer and a scalar magnetometer are fixed at wingtips to measure and calculate direction cosine. But for marine and submarine applications, magnetometers usually have to be fixed inside and magnitude of interferential field can reach more than thousands of nT, which will result in invalidation of direction cosine calculation. Multi-sensor systems, which contain magnetometer, gyro and accelerometer etc., have been widely used. The host platform's movement information is valuable and helpful to compensate magnetometer. Li propose a dot product invariance method [20], which utilizes gravity vector that has a constant

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dot product with geomagnetic field vector in reference frame. But, when the auxiliary vector is parallel or perpendicular to geomagnetic field vector, the compensation accuracy drops.

In the paper, a new compensation method is proposed, which implements "vectorial compensation" strategy. The rest of this paper is organized as follows. Section 2 sets up measurement models and presents a vectorial compensation method. In Section 3, simulations are conducted to evaluate the method. Experiment results are reported in Section 4. Finally, conclusion is drawn in Section 5.

2. Vectorial compensation method

2.1. Coordinate frames

There exist several coordinate frames for geomagnetic vector measurement system (GVMS), such as magnetic coordinate frame (m), gyro coordinate frame (g) and geographical coordinate frame (n). The magnetic coordinate frame is fixed to magnetometer sensing axes. The gyro coordinate frame is fixed to gyro sensing axes. The geographical coordinate frame is also called the East, North, Up frame. Its y-axis points to the local North, x-axis is toward the East in the local level plane, and z-axis is along the local Vertical. The three frames can be transformed with each other.

The geomagnetic field vector in geographical frame ($H_n = [h_{nx}, h_{ny}, h_{nz}]^T$) can be transformed into gyro frame ($H_g = [h_{gx}, h_{gy}, h_{gz}]^T$) with (1).

$$H_g = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\gamma & \sin\gamma \\ 0 & -\sin\gamma & \cos\gamma \end{bmatrix} \begin{bmatrix} \cos\beta & 0 & -\sin\beta \\ 0 & 1 & 0 \\ \sin\beta & 0 & \cos\beta \end{bmatrix} \begin{bmatrix} \cos\alpha & \sin\alpha & 0 \\ -\sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} H_n = \mathbf{A_g} H_n \tag{1}$$

where α, β, γ are three Euler angles between geographical and gyro frame, which are calculated from angular velocities of gyro outputs.

There must exist misalignment angles between magnetometer and gyro sensing axes, so geomagnetic field vector in magnetic frame ($H_m = [h_{mx}, h_{my}, h_{mz}]^T$) can be transformed from gyro frames with (2).

$$H_m = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\gamma_0 & \sin\gamma_0 \\ 0 & -\sin\gamma_0 & \cos\gamma_0 \end{bmatrix} \begin{bmatrix} \cos\beta_0 & 0 & -\sin\beta_0 \\ 0 & 1 & 0 \\ \sin\beta_0 & 0 & \cos\beta_0 \end{bmatrix} \begin{bmatrix} \cos\alpha_0 & \sin\alpha_0 & 0 \\ -\sin\alpha_0 & \cos\alpha_0 & 0 \\ 0 & 0 & 1 \end{bmatrix} H_g = \mathbf{A_m} H_g \tag{2}$$

where $\alpha_0, \beta_0, \gamma_0$ are three Euler angles between gyro and magnetic frame, which are unknowable and constant.

2.2. Measurement model

Permanent and induced magnetic interferential fields are identified as two main sources of magnetic perturbation when host platform's speed is slow. In magnetic frame, permanent magnetic field H_p can be expressed as (3), whose magnitude remains constant in a long period and direction is firmly attached to magnetometer. The bulk susceptibility of platform is assumed to be isotropic and induced magnetic field H_i can be expressed as (4), whose direction and magnitude are proportional to external magnetic field. Eddy current magnetic field can be ignored for low speed condition. So, total field measurement model can be expressed as (5).

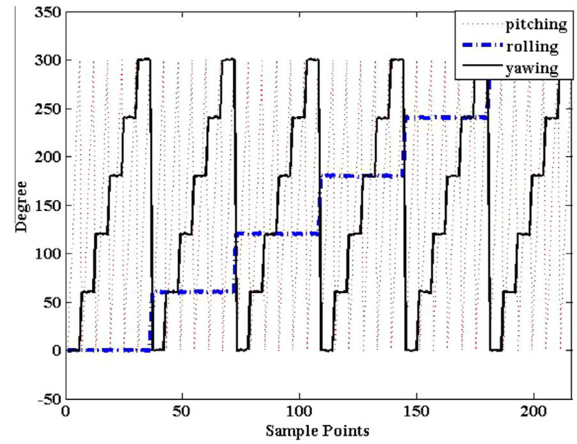

Fig. 1. Measurement curves of attitude angles.

$$H_p = \begin{bmatrix} h_{px} & h_{py} & h_{pz} \end{bmatrix}^T \tag{3}$$

$$H_i = \begin{bmatrix} h_{ix} \\ h_{iy} \\ h_{iz} \end{bmatrix} = \begin{bmatrix} a_{xx} & a_{xy} & a_{xz} \\ a_{yx} & a_{yy} & a_{yz} \\ a_{zx} & a_{zy} & a_{zz} \end{bmatrix} \begin{bmatrix} h_{mx} \\ h_{my} \\ h_{mz} \end{bmatrix} = \mathbf{A_s} H_m \tag{4}$$

$$H_o = \begin{bmatrix} h_{ox} & h_{oy} & h_{oz} \end{bmatrix}^T = H_m + H_p + \mathbf{A_s} H_m \tag{5}$$

where $\mathbf{A_s}$ is induced magnetic coefficient matrix, H_o is output of magnetometer.

Substituting (1) and (2) in (5), complete measurement model can be expressed as following:

$$H_o = (\mathbf{A_s} + \mathbf{I})\mathbf{A_m}\mathbf{A_g} H_n + H_p \tag{6}$$

Expanding (6) and introducing a new variable $\mathbf{A_{sm}}$, measurement model becomes

$$H_o = \mathbf{A_{sm}}\mathbf{A_g} H_n + H_p \tag{7}$$

where $\mathbf{A_{sm}} = (\mathbf{A_s} + \mathbf{I})\mathbf{A_m}$ is the combined error matrix.

2.3. Parameters estimation

In (7), H_o and $\mathbf{A_g}$ .can be acquired from output of magnetometer and gyroscope, H_n can be calculated with IGRF. $\mathbf{A_{sm}}$ and H_p are to be estimated. From (7), H_n can be calculated with (8):

$$H_n = \mathbf{A_g^{-1}}\mathbf{A_{sm}^{-1}}(H_o - H_p) = \mathbf{A_g^{-1}}\mathbf{A_{sm}^{-1}} H_o - \mathbf{A_g^{-1}}\mathbf{A_{sm}^{-1}} H_p \tag{8}$$

Introducing following three intermediate parameters:

$$\mathbf{D} = \mathbf{A_g^{-1}} = [d_{ij}] \quad (i,j = 1,2,3) \tag{9}$$

$$\mathbf{L} = \mathbf{A_{sm}^{-1}} = [l_{ij}] \quad (i,j = 1,2,3) \tag{10}$$

$$P = \mathbf{A_{sm}^{-1}} H_p = [p_i] \quad (i = 1,2,3) \tag{11}$$

Eq. (8) becomes

$$H_n = \mathbf{D} \cdot \mathbf{L} \cdot H_o - \mathbf{D} \cdot P = \mathbf{X} \cdot \theta \tag{12}$$

where $\mathbf{X}, \theta$ are identified to be

$$\mathbf{X} = \begin{bmatrix} d_{11}h_{ox} & d_{11}h_{oy} & d_{11}h_{oz} & d_{12}h_{ox} & d_{12}h_{oy} & d_{12}h_{oz} & d_{13}h_{ox} & d_{13}h_{oy} & d_{13}h_{oz} & d_{11} & d_{12} & d_{13} \\ d_{21}h_{ox} & d_{21}h_{oy} & d_{21}h_{oz} & d_{22}h_{ox} & d_{22}h_{oy} & d_{22}h_{oz} & d_{23}h_{ox} & d_{23}h_{oy} & d_{23}h_{oz} & d_{21} & d_{22} & d_{23} \\ d_{31}h_{ox} & d_{31}h_{oy} & d_{31}h_{oz} & d_{32}h_{ox} & d_{32}h_{oy} & d_{32}h_{oz} & d_{33}h_{ox} & d_{33}h_{oy} & d_{33}h_{oz} & d_{31} & d_{32} & d_{33} \end{bmatrix} \tag{13}$$

$$\theta = \begin{bmatrix} l_{11} & l_{12} & l_{13} & l_{21} & l_{22} & l_{23} & l_{31} & l_{32} & l_{33} & -p_1 & -p_2 & -p_3 \end{bmatrix}^T \tag{14}$$

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