Journal of Magnetism and Magnetic Materials 374 (2015) 289–297

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Integrated calibration of magnetic gradient tensor system

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ARTICLE INFO

Article history:
Received 22 June 2014
Received in revised form
2 August 2014
Available online 14 August 2014

Keywords:
Magnetic gradient tensor
Scalar calibration
Error compensation
Least squares ellipsoid fitting
Strapdown system
Parameter estimation

ABSTRACT

Measurement precision of a magnetic gradient tensor system is not only connected with the imperfect performance of magnetometers such as bias, scale factor, non-orthogonality and misalignment errors, but also connected with the external soft-iron and hard-iron magnetic distortion fields when the system is used as a strapdown device. So an integrated scalar calibration method is proposed in this paper. In the first step, a mathematical model for scalar calibration of a single three-axis magnetometer is established, and a least squares ellipsoid fitting algorithm is proposed to estimate the detailed error parameters. For the misalignment errors existing at different magnetometers caused by the installation process and misalignment errors aroused by ellipsoid fitting estimation, a calibration method for combined misalignment errors is proposed in the second step to switch outputs of different magnetometers into the ideal reference orthogonal coordinate system. In order to verify effectiveness of the proposed method, simulation and experiment with a cross-magnetic gradient tensor system are performed, and the results show that the proposed method estimates error parameters and improves the measurement accuracy of magnetic gradient tensor greatly.

1. Introduction

Magnetic gradient tensor measurements are predominant over conventional vector magnetic surveys. Gradient measurements yield largely gradients from anomalous sources because the background geomagnetic gradient is low, and they can offer better spatial resolution than magnetic field vectors and total magnetic intensity. On the other hand, gradient measurements are most appropriate as a strapdown device for airborne applications [1]. Because of these superiorities, magnetic gradient tensor systems have been widely used in civil and military applications [2].

Magnetic gradient tensor systems are always constructed by multiple vector magnetometers. In the last decades many kinds of magnetic gradient tensor systems based on fluxgate magnetometers or superconducting quantum interference devices have been developed, and some tentative experiments have been done [3–6]. Being restricted by manufacture arts and crafts, magnetometers have problems of biases, different scalar factors, non-orthogonality of three axes and misalignment errors between the different sensitive axes [7]. On the other hand magnetic gradient tensor systems are always mounted in the ferromagnetic vehicle's structure [8,9], and the magnetometer readings are distorted by the ferromagnetic elements in the vicinity of the magnetometer. Hence magnetic gradient tensor errors may be thousands of nanoteslas and they have to be calibrated and compensated.

Chen et al. [10], Huang and Wu [11], and Pang et al. [12] did some calibration works for the magnetic gradient tensor system based on scalar calibration method, but hard-iron and soft-iron magnetic distortion errors we are ignored. Lv et al. [13] and Pei Yeo [14] did some compensation works for the soft-iron and hard-iron magnetic distortions, but errors of the magnetometer itself we are ignored. Pang et al. [15] accomplished vector calibration for the magnetic gradient tensor system considering errors of the magnetometer itself and magnetic distortions of external ferromagnetic elements. However, little work has been done on the scalar calibration of magnetic gradient tensor system considering internal and external magnetic distortions simultaneously.

In this paper, a scalar calibration strategy is designed and the calibration process is divided into two steps. Firstly, a single three-axis magnetometer is calibrated considering errors of the magnetometer itself and magnetic distortions of external ferromagnetic elements. Secondly, combined misalignment errors between different magnetometers are calibrated. The proposed method shows good performance in simulation and experiment, and hence it can be used to improve the measurement accuracy of strapdown magnetic gradient tensor system.

2. Magnetic gradient tensor measurement principle and system

Magnetic gradient tensor is spatial rate of change of magnetic vector field in three orthogonal directions. If B denotes magnetic

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http://dx.doi.org/10.1016/j.jmmm.2014.08.022
0304-8853/

field vector, magnetic gradient tensor Gcan be shown as the product of two matrices which contain three vector elements:

$$G = \begin{bmatrix} \partial/\partial x \\ \partial/\partial y \\ \partial/\partial z \end{bmatrix} \begin{bmatrix} Bx & By & Bz \end{bmatrix} = \begin{bmatrix} B_{xx} & B_{xy} & B_{xz} \\ B_{yx} & B_{yy} & B_{yz} \\ B_{zx} & B_{zy} & B_{zz} \end{bmatrix} \tag{1}$$

where Bx, By and$Bz$are measured magnetic field components along three orthogonal directions.

The geomagnetic field and magnetic anomalies caused by the ferromagnetic matters are magnetostatic fields which do not contain conduction currents. So the gradient tensor is traceless and symmetric according to Maxwell's magnetostatic equations. And all nine elements of the gradient tensor can be calculated from only five independent gradient measurements.

In real measurement application, magnetic gradient tensor is deduced from the difference between measurement values of magnetic field vectors normalized by the separation distance [3]. But high-order derivatives of Taylor series of magnetic field vectors, which arise by geometric configuration of the vector magnetometers array and are defined as structure errors, are neglected during the calculative process. So the structure errors also affect measurement precision of the magnetic gradient tensor system. Several different configurations of magnetic gradient tensor system are analyzed in [16]; simulation results show that the plane cross tensor structure has the minimal structural errors that are lesser than those of vector magnetometers. Based on these research results, a cross-magnetic gradient tensor system comprising four tri-axial magnetometers is designed in this paper and its sketch map is shown in Fig. 1. A right-handed Cartesian coordinate system is constructed and the baseline distance between two magnetometers in the same direction is$2d$.

Estimated elements of the magnetic gradient tensor at the point Oare shown as follows:

$$\boldsymbol{G} = \begin{pmatrix} \frac{B_{1x}-B_{3x}}{2d} & \frac{B_{2x}-B_{4x}}{2d} & \frac{B_{1z}-B_{3z}}{2d} \\ \frac{B_{1y}-B_{3y}}{2d} & \frac{B_{2y}-B_{4y}}{2d} & \frac{B_{2z}-B_{4z}}{2d} \\ \frac{B_{1z}-B_{3z}}{2d} & \frac{B_{2z}-B_{4z}}{2d} & -\frac{B_{1x}-B_{3x}}{2d}-\frac{B_{2y}-B_{4y}}{2d} \end{pmatrix} \tag{2}$$

where B_{ij}, $i=1,2,3,4$, $j=x,y,z$, denote magnetic vector components in the jth direction of the ith magnetometer. The matrix shown here is not symmetric. Measurement noises and high-order gradients will create differences between the estimates of B_{xy} and B_{yx}. So we average the two estimates and use a truly symmetric matrix with off-diagonal elements in practice.

3. Calibration and compensation for three-axis magnetometer

3.1. Mathematical model

Three sensitive axes of an actual three-axis magnetometer may not be perfectly orthogonal and they constitute a non-orthogonal coordinate system O–$X_1Y_1Z_1$. Suppose that O–$X'Y'Z'$ is an ideal sensor's orthogonal coordinate system in which OZ' is defined to be completely aligned with axis OZ_1. The coordinate plane Y_1OZ_1 is coplanar with the plane $Y'OZ'$. ψ denotes angle between the axis OY_1 and OY'. θ denotes the angle between the axis OX_1 and the plane $X'OY'$. Angle between OX' and projection of OX_1 in the plane $X'OY'$ is φ. O–XYZ is the ideal platform frame-orthogonal coordinate system. Sketch map of different coordinates systems is shown in Fig. 2.

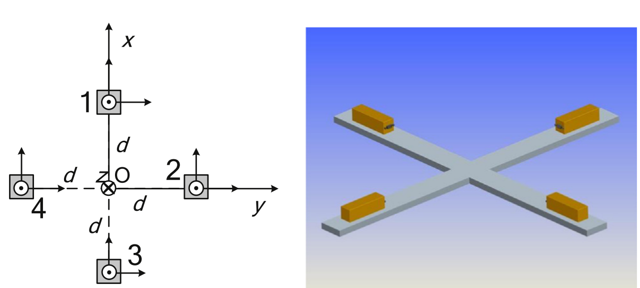

Fig. 1. Sketch map of the cross-magnetic gradient tensor system.

Two of the most significant error sources of three-axis magnetometer are that errors of the magnetometers itself being restricted by manufacture and magnetic distortions of external ferromagnetic elements such as hard-iron interferences and soft-iron interferences. Considering these two kinds of error sources, a mathematical model of magnetometer output could be described as follows [17]:

$$\boldsymbol{B}_m = \boldsymbol{C}_{SF}\boldsymbol{C}_{NO}(\boldsymbol{B}+\boldsymbol{B}_{SI}+\boldsymbol{B}_{HI})+\boldsymbol{B}_{m0}+\boldsymbol{\omega}_m \tag{3}$$

where $\boldsymbol{B}_m$, $\boldsymbol{B}_{m0}$, and $\boldsymbol{\omega}_m$ are, respectively, output, bias error and measurement noise of magnetometer under the coordinate system $O-X_1Y_1Z_1$. $\boldsymbol{B}$, $\boldsymbol{B}_{SI}$ and $\boldsymbol{B}_{HI}$ are, respectively, geomagnetic field vector, soft-iron magnetic distortions and hard-iron magnetic distortions in the coordinate system $O-X'Y'Z'$. $\boldsymbol{C}_{SF}$ and $\boldsymbol{C}_{NO}$ are, respectively, error matrices of scale factors and non-orthogonality.

There are rich literatures about soft-iron interferences and hard-iron interferences of magnetometers [18]. And the hard-iron interference can be considered as a constant bias to the magnetometer output [19]. The soft-iron interferences are generated by interaction of external magnetic field with ferromagnetic elements in the vicinity of the magnetometer; they depend on magnitude and direction of the external magnetic field [20]. We assume that a time-invariant linear relationship exists between the soft-iron interferences and the external magnetic field; then $\boldsymbol{B}_{SI}$ can be written as

$$\boldsymbol{B}_{SI} = \mathrm{KB} = \begin{bmatrix} \alpha_{xx} & \alpha_{xy} & \alpha_{xz} \\ \alpha_{yx} & \alpha_{yy} & \alpha_{yz} \\ \alpha_{zx} & \alpha_{zy} & \alpha_{zz} \end{bmatrix} \boldsymbol{B} \tag{4}$$

where $\boldsymbol{K}$ is the soft-iron effect matrix, $\alpha_{ij}, i, j=x,y$, are the soft-iron coefficients and they represent the coefficient relating the field generated in the i-direction in response to the external magnetic field along the j-direction.

According to eqs. (3) and (4), we can get the following mathematical model:

$$\boldsymbol{B}_m = \boldsymbol{C}_C B + O + \boldsymbol{\omega}_m \tag{5}$$

where $\boldsymbol{C}_C = \boldsymbol{C}_{SF}\boldsymbol{C}_{NO}(\boldsymbol{I}+\boldsymbol{K})$ represents the combined error coefficient matrix and $\boldsymbol{O} = \boldsymbol{C}_{SF}\cdot\boldsymbol{C}_{NO}\cdot\boldsymbol{B}_{HI}+\boldsymbol{B}_{m0}$ represents the total bias vector.

Measurement noises are small enough relative to magnetic distortions arising by the other error parameters. So a mathematical model can be written as follows when measurement noises

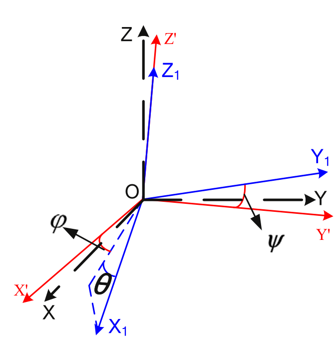

Fig. 2. Sketch map of different coordinates systems for magnetometer calibration.