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One-step calibration of magnetic gradient tensor system with nonlinear least square method

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ABSTRACT

Due to technological limitations, the accuracy of magnetic gradient tensor system is tightly affected by different scale factors, bias of each axis, non-orthogonality between axes and misalignment errors between magnetometers. In order to obtain precise measurement, calibration of the magnetic gradient tensor system is quite essential. A mathematical model containing error parameters of magnetic gradient tensor system is established, and one-step calibration method based on nonlinear least square method is proposed. The effectiveness and convergence of the proposed algorithm is proved by simulation and experiments. In experiments, a tri-axial nonmagnetic rotation platform, a proton magnetometer and a cross magnetic gradient tensor system containing four three-axis fluxgate magnetometers are used. Experimental results show that the proposed method can decrease the measurement errors of magnetic gradient tensor system greatly.

1. Introduction

Magnetic gradient tensor surveys have many advantages compared to conventional magnetic vector surveys due to providing valuable additional information, better resolution and relative insensitivity to rotation noise [1]. So magnetic gradient tensor systems received in civil and military applications [2–4]. Some research institutes have developed several kinds of systems comprising fluxgate magnetometers [5] or superconducting quantum interference devices [6] and partial magnetic gradient tensor systems have been used to do some tentative experiments.

Being restricted by manufacture arts and crafts, vector magnetometers always have many systematic errors. On the other hand, misalignment errors between different sensitive axes are brought when multi-magnetometers are used to construct magnetic gradient tensor system. So measurement error of magnetic gradient tensor may be thousands of nanoteslas (nT) due to existence of these different errors, and they should be eliminated at the most extent.

Magnetic gradient tensor systems are always constructed by several vector magnetometers. So calibration method of single vector magnetometer [7,8] can be introduced to the magnetic gradient tensor system and they can be divided into vector calibration and scalar calibration [9]. Although both methods can obtain good calibration results, vector calibration technique [10] needs an ultra-high precision tri-axial nonmagnetic rotation platform and rigorous calibration field. So vector calibration is impractical according to the production cost. Conversely, scalar calibration, described as a “poor-man’s” calibration method [11], has been widely used in real applications. Considering the error parameters of scale factors, biases, non-orthogonality and misalignment errors, Chen et al. [12], Huang et al. [13], Pang et al. [14] and Schiffler et al. [15] did some scalar calibrations for the magnetic gradient tensor system and obtained good calibration results. It is worth noting that these kinds of calibration methods are all two-step method. Calibration for the single vector magnetometer was provided as a first step and calibration for the misalignment errors was provided as the second step. However, the second step, choosing one of the magnetometers as reference magnetometer to calibrate the misalignment errors, cannot transform outputs of the magnetic gradient tensor system along the platform frame-orthogonal coordinate. Yin et al. [16] rotated the magnetic gradient tensor system in three mutually perpendicular axes to calibrate the misalignment errors and transformed outputs of different magnetometers into the platform frame-orthogonal coordinate. However, little work has been done on the one-step calibration of magnetic gradient tensor system.

In this paper, mathematical model consisting of scale factors, biases, non-orthogonality and misalignment errors is built, then

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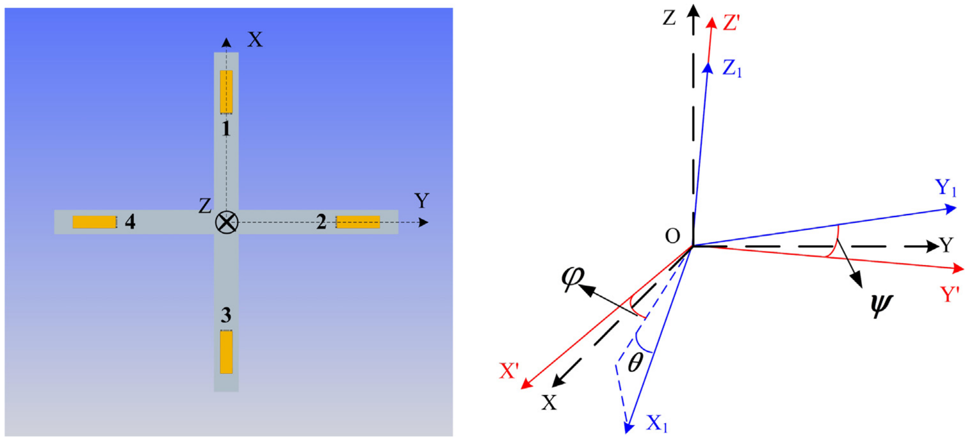

Fig. 1. Sketch map of the cross magnetic gradient tensor system and different coordinates for calibration.

calibration equations are established based on the invariant characteristics during the random rotation of magnetic gradient tensor system. Finally, we achieve one-step calibration of magnetic gradient tensor system by solving the error parameters using nonlinear least square method.

2. Magnetic gradient tensor measurements

Magnetic field is a vector field and its spatial rate of change in three orthogonal directions is defined as magnetic gradient tensor. In the case of static magnetic fields, for regions free of electric currents Maxwell's equations impose restrictions which imply that the magnetic gradient tensor is symmetric and traceless. All nine elements of the magnetic gradient tensor can be calculated from only the five independent components.

Magnetic gradient tensor G can be shown as follows.

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

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_{xx}, B_{xy}, B_{xz}, B_{yy} and B_{yz} can be considered as five independent components and other components can be calculated by these five components.

It is not available to intrinsically measure gradient of magnetic vector field in real measurement applications, so magnetic gradient tensor is approximated by the difference between measurement values of magnetic vector field. However, measurement values and theoretical values of magnetic gradient tensor have some deviations in nature and these deviations cannot be eliminated once the structure of magnetic gradient tensor system has been determined. In this situation, we can only calibrate the systematic errors of magnetometers and misalignment errors to improve the measurement precision.

A cross magnetic gradient tensor system is chose as an example to investigate one-step calibration process based on nonlinear least square method. The cross magnetic gradient tensor system comprising four tri-axial magnetometers is shown in Fig. 1. The x and y axes lie along the orthogonal baselines and the z axis is chosen to make a right-handed Cartesian coordinate system. Baseline distance between two magnetometers in the same direction is d. The measured magnetic gradient tensor can be written as

$$G = \begin{pmatrix} \dfrac{B_{1x} - B_{3x}}{d} & \dfrac{B_{2x} - B_{4x}}{d} & \dfrac{B_{1z} - B_{3z}}{d} \\ \dfrac{B_{1y} - B_{3y}}{d} & \dfrac{B_{2y} - B_{4y}}{d} & \dfrac{B_{2z} - B_{4z}}{d} \\ \dfrac{B_{1z} - B_{3z}}{d} & \dfrac{B_{2z} - B_{4z}}{d} & -\dfrac{B_{1x} - B_{3x}}{d} - \dfrac{B_{2y} - B_{4y}}{d} \end{pmatrix} \quad (2)$$

where B_{ij}, $i = 1, 2, 3, 4$, $j = x, y, z$ denote magnetic vector component in the j direction of the i magnetometer.

3. Calibration model

Magnetic gradient tensor systems are always constructed by magnetometers array. Obviously, the systematic errors of single magnetometer still exist and misalignment errors are introduced. These existing errors influence the measurement precision severely. So in order to calibrate single magnetometer errors and misalignment errors, one-step calibration technique based on nonlinear least square method is proposed. It is worth noting that the single magnetometer errors are general terms that describe scale factors errors, biases and non-orthogonality errors.

We define that outputs of the ideal magnetic gradient tensor system are under the platform frame-orthogonal coordinate system $O-XYZ$, outputs of each tri-axial magnetometer are under a non-orthogonal coordinate system in actual system due to existence of different errors. So we need twice coordinate transformations to transform actual outputs of single magnetometer into the platform-orthogonal coordinate system. Based on the process of coordinate transformations, we can build mathematical model to calibrate the magnetic gradient tensor system.

As shown in Fig. 1, three actual sensitive axes of magnetometer 1 constitute a non-orthogonal coordinate system $O-X_1Y_1Z_1$. Choose OZ_1 as one axis to build an orthogonal coordinate system $O-X'Y'Z'$ and let OZ' align with the axis OZ_1 completely. The axis OY' underneath the plane Y_1OZ_1 and the angle between OY_1 and OY' is defined as ψ. Then the axis OX' is obtained according to the right-handed Cartesian coordinate theorem and the angle between the axis OX_1 and the plane $X'OY'$ is defined as θ. Angle between OX' and projection of OX_1 in the plane $X'OY'$ is φ. So the orthogonal coordinate system $O-X'Y'Z'$ is determined uniquely.

Each axis of the actual magnetometer has different sensitivities and biases, so we defined that k_i, $i = x, y, z$ are scale factors and $\boldsymbol{B}_0 = (bx, by, bz)^T$ are biases for three different axes. Then outputs of the magnetometer can be converted to the orthogonal coordinate $O-X'Y'Z'$ from $O-X_1Y_1Z_1$ according to the aforementioned