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A multi-position self-calibration method for dual-axis rotational inertial navigation system

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ABSTRACT

In order to compensate errors of inertial measurement unit which is the core of rotational inertial navigation system, self-calibration is utilized as an effective way to reduce navigation error. Error model of navigation solution and initial alignment is used to establish the relationship between navigation errors and inertial measurement unit (IMU) errors. A second order damper is added to the vertical velocity channel to suppress the divergence and then the vertical velocity error can be regarded as an effective observation to estimate the error parameters. Since the accuracy of the self-calibration method is susceptible to the positioning error of gimbals, total least squares (TLS) method is utilized in identification of the error parameters. Experimental results show that all of the twenty-one error parameters can be estimated with the proposed rotation scheme. Compared to least squares (LS) method, TLS method can improve the position accuracy of 8 h by 46.2%.

1. Introduction

Navigation error divergence of the strapdown inertial navigation system (SINS) could be restrained by rotating IMU periodically. The rotational INS (RINS) could effectively bring a better navigation performance without using higher-level gyros and accelerometers [1,2]. The widely used MK39 and MK49 Ship's INS adopted the single-axis and dual-axis rotation auto compensation technique, respectively, as one of the strategies to improve the accuracy at the system level [3]. However, in RINS, velocity error and position error will fluctuate periodically with amplitudes determined by the IMU errors. Moreover, when angular movement of carrier exists, modulation performance will be affected, the errors of IMU cannot be completely compensated, which leads to divergence of long-endurance navigation error. Therefore, it is important for the system to cope with the calibration of the inertial sensor error parameters. Calibration is believed to be a key process in the use of such systems and its purpose is to estimate inertial sensor stable errors. After calibration, the obtained results can be used to remove repeatable errors caused by manufacturing imperfections. Different from traditional SINS, RINS can stimulate error parameters by rotating gimbals, thus, it can calibrate without turntable.

Calibration is the foundation of navigation system to work in high precision, and then provide conditions for the realization of precision algorithm, especially in autonomous navigation [4–6]. The calibration techniques for SINS can be divided into two categories according to their measurements. The first category is direct calibration method which takes the output of IMU as observations. In this category, multi-position method and continuous rotating method are usually used. In multi-position method, rotation angular rate of the earth and local gravity are taken as the input of sensors, based on the fact that the norms of the measured outputs of the accelerometer and gyroscope are equal to the magnitudes of specific force and rotational velocity inputs, respectively. Many multi-position method approaches have been proposed [7–10]. Despite the good performance of this calibration method in laboratory tests, there is a critical drawback that the excitation for gyro's installation angles and scale factor errors involves only the earth rotation angular rate which is very small. Continuous rotating method can overcome this drawback of the multi-position method [11–13]. When turntable rotates continuously, the errors of IMU are excited by the gravity, earth rotation and reference gimbals angular rate. This method has been successfully applied in the calibration of SINS in laboratory. However, its performance depends on accuracy of the turntable, because the observations are greatly affected by angular rate error and positioning error. Aydemir [14] combines the two methods by calibrating accelerometers only with multi-position method and calibrating gyroscopes only with continuous rotating method, which improves the calibration accuracy.

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Nomenclature

n	navigation frame, with its origin at center of mass of IMU, X axis directs north and Z axis directs upward vertical, i.e., local-level frame
b	body frame, strapdown inertial sensor coordinate frame with its origin at center of mass of IMU, X axis directs the right, Y axis directs the front, and Z axis directs upward of the carrier
a	accelerometer frame with its origin at center of mass of IMU, X axis coincides with x accelerometer, Y axis coincides with y accelerometer, and Z axis coincides with z accelerometer
g	gyro frame with its origin at center of mass of IMU, X axis coincides with x gyro, Y axis coincides with y gyro, and Z axis coincides with z gyro
s	IMU frame, with its origin at center of mass of IMU, X axis coincides with X_a, Y axis lies in the X_aY_a plane and Z axis constitutes a right-handed orthogonal frame with X axis and Y axis
C_s^n	transform matrix from frame s to frame a
λ	longitude
L	latitude
R	earth radius
ω_{ie}	angular rate of earth rotation
∇	accelerometer bias
ε	gyro drift
δV	velocity error
ϕ	misalignment
$\Delta\phi$	change of misalignment
S_{aij}	i-axis accelerometer misalignment toward j-axis ($i \neq j$)
S_{gij}	i-axis gyro misalignment toward j-axis ($i \neq j$)
K_{ai}	scale factor error of i-axis accelerometer
K_{gi}	scale factor error of i-axis gyro
f^s	input of accelerometer
ω^s	input of gyro
δh	height error of the carrier
h_0	real height of the carrier
α	position of the inner gimbal
β	position of the outer gimbal

Since the calibration accuracy is free of the angular rate error of turntable, the indirect calibration is paid more attention in recent years [15–20]. Based on the relationships between velocity errors and inertial sensor errors, LS method can be applied in the identification of error parameters [15]. Except for velocity errors, attitude errors can also be taken as observations [16,17]. Different from indirect calibration based on turntable in laboratory, dual-axis RINS does not have precise attitude reference with navigation coordinate. The accuracy of calibration will be seriously affected if the initial alignment result were taken as the initial attitude of the system. Therefore, we establish the relationship between initial misalignment and IMU errors to eliminate the impact of the unknown initial attitude.

Compared with calibration based on turntable, another problem in self-calibration of RINS is that the positioning error of its gimbals is conspicuous, which will bring great error to the model of LS and thus affect the calibration accuracy. As different from LS, TLS considers the error both in the coefficients matrix and the observation vector [21–23], which can efficiently reduce the influence of error in data matrix. Since the accuracy of the calibration methods are susceptible to the position error of gimbals, TLS method is utilized in the identification of error parameters.

In this work, the relationship between the unknown initial misalignment and the IMU errors is utilized to reduce the number of unknown variables and obtain more observations. A second order damper is proposed to the vertical velocity channel to suppress the divergence and then the vertical velocity error can be regarded as an effective observation to estimate the error parameters. A ten-position rotation scheme is proposed to observe the error parameters to be calibrated. Total least squares method is utilized in identification of the error parameters to reduce the influence of gimbals positioning error.

The rest of the paper is organized as follows. In Section 2, we propose the error model of the dual-axis RINS considering the relationship between the damping of vertical channel, the initial alignment error and navigation errors. In Section 3 the rotation scheme and calibration process of the multi-position method are described, the application of TLS in estimation of error parameters are presented. Analysis of simulation results and experimental results are discussed in Section 4. The conclusion is given in Section 5.

2. System error model

2.1. The IMU error model

The three sensitive axes of gyroscopes are denoted by X_g, Y_g, Z_g, while the three sensitive axes of accelerometers are denoted by X_a, Y_a, Z_a, in order to simplify the error model, the IMU frame s is defined as follows: X_s coincides with the accelerometer sensitivity axis X_a. Y_s lies in the X_aY_a plane and Z_s constitutes a right-handed orthogonal frame with X_s, Y_s. The installation errors of accelerometers and gyros are shown in Figs. 1 and 2 respectively.

The transform matrix from frame s to frame a and the transform matrix from frame s to frame g are respectively represented as

$$\Delta C_s^a = \begin{bmatrix} K_{ax} & 0 & 0 \\ -S_{ayz} & K_{ay} & 0 \\ S_{azy} & -S_{azx} & K_{az} \end{bmatrix} \quad (1)$$

$$\Delta C_s^g = \begin{bmatrix} K_{gx} & S_{gxz} & -S_{gxy} \\ -S_{gyz} & K_{gy} & S_{gyx} \\ S_{gzy} & -S_{gzx} & K_{gz} \end{bmatrix} \quad (2)$$

Then the error model applied for indirect calibration method can be represented as

$$\nabla^s = \Delta C_s^a f^s + \nabla \quad (3)$$

$$\varepsilon^s = \Delta C_s^g \omega^s + \varepsilon \quad (4)$$

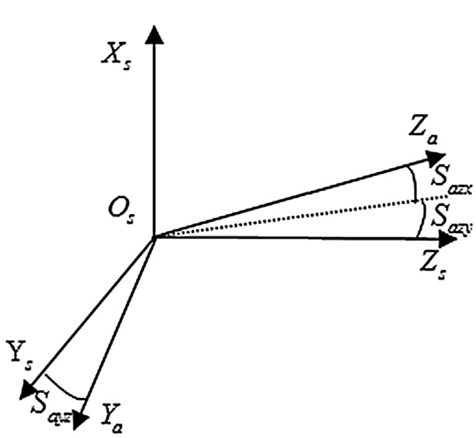

Fig. 1. Installation errors of accelerometers.