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An eight-position self-calibration method for a dual-axis rotational Inertial Navigation System

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ABSTRACT

An eight-position self-calibration method for a dual-axis rotational Inertial Navigation System (INS) is provided in this paper. By experiencing two more positions with tilt attitudes than those experienced in a conventional six-position method, not only constant biases, scale factor errors, and misalignment errors, but also g-dependent biases can be calibrated. Field tests indicate that, after the calibration and compensation of the g-dependent biases, both a latitude error and a longitude error remain within a small range over time. In contrast, by using the conventional six-position method, a latitude error is several times larger and a longitude error diverges rapidly over time. Compared with the six-position method, accuracy of the dual-axis rotational INS is significantly improved more than 50% by the eight-position self-calibration method. The self-calibration method is feasible both in static and over a ship at the dockside.

1. Introduction

A dual-axis rotational Inertial Navigation System (INS) is developed from strap-down inertial sensing unit rotation (SISUR) technology [1]. In the dual-axis rotational INS, drifts are averaged out by rotating an inertial measurement unit (IMU) about its azimuth and roll axes every few minutes. With a benefit of high performance and low cost, the dual-axis INS is widely equipped on naval ships and submarines in North Atlantic Treaty Organization (NATO) and the United States [2–4].

The IMU generally includes a gyro triad and an accelerometer triad. Measurements of the gyro triad are integrated to yield attitude, and measurements of the accelerometer triad are integrated to yield velocity and position. Thus, even a very small sensor error of the IMU causes a great navigation error during the integrations [5–7]. Therefore, accuracy of the IMU is a crucial issue of the dual-axis rotational INS.

Many techniques, such as static and dynamic calibration tests [6,8,9], fusion of sensors' data [5,10–14], have been presented for improving the accuracy of IMU in previous work. Usually, errors of inertial sensors are treated as deterministic or stochastic (nondeterministic) [5,15,16]. The deterministic errors mainly include: g-dependent biases, constant biases, scale factor errors, and misalignment errors [6,8,17]. The stochastic error describes for example random-walk noises [6] and spikes [5] in outputs of the sensors. Generally, deterministic errors of the dual-axis rotational INS can be calibrated and compensated by a multi-position calibration method before real application. A fundamental example of the multi-position calibration method is a six-position method, where the IMU is rotated around each gyro axis clockwise and counter-clockwise, and each accelerometer axis was pointed up and down [18]. Additional examples with a same basic idea include a 12-position method and a 24-position method [19]. The basic idea of the multi-position calibration method is comparing instrument outputs with known reference information and determining coefficients that force the outputs to agree with the reference information over a range of outputs values [18,20]. During the calibration, a precisely controlled mechanical mechanism is adopted to ensure accuracy of the calibration.

In order to release the requirement of the precisely controlled mechanical mechanism, improved multi-position methods which make use of propagation of sensor errors derived in a navigation reference frame were proposed in [7,18,19,21–23]. A basic idea of the improved multi-position methods is that: norms of measured outputs of the accelerometer and gyro cluster are equal to magnitudes of a given specific force (i.e. gravity) and rotation rate inputs

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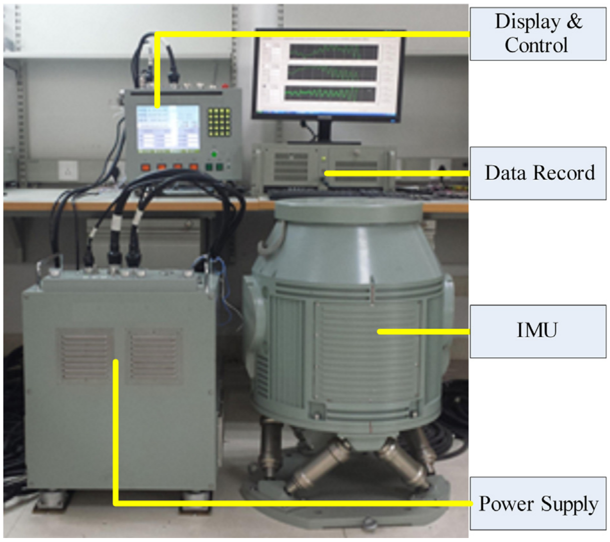

Fig. 1. A dual-axis rotational INS.

(i.e. the Earth's rotation rate), respectively [24]. Given a sufficient number of rotation tests, most dominant sensor errors, such as constant biases, scale factor errors and misalignment errors, can be estimated by a least-squares method [22,25], or by Kalman filtering [18] which is an optimal estimation technique based on an error state. G-dependent biases of the gyros, which are errors proportional to magnitude of applied accelerations [17], are not averaged out automatically in navigation process [3]. Therefore, the g-dependent biases of the gyros are usually calibrated by comparing outputs of gyros with a real angular velocity by using an external precise turntable [6]. It is a great challenge to calibrate the g-dependent biases without using external equipment for a dual-axis rotational INS (called as self-calibration [26]).

In this paper, an eight-position self-calibration method, which is another improved multi-position self-calibration method using Kalman filtering, is proposed to calibrate the g-dependent biases of gyros in a dual-axis rotational INS. By experiencing two more positions with tilt attitudes than those experienced in a six-position method, not only constant biases, scale factor errors, and misalignment errors, but also g-dependent biases can be calibrated through the eight-position self-calibration method.

This paper is organized into 7 sections. Background of this work is given in Section 1. A dual-axis rotational INS is presented in Section 2. Error models for the eight-position self-calibration method are explained in Section 3. Based on the error models explained in Section 3, the eight-position self-calibration method is proposed and described in detail in Section 4. Simulations are discussed in Section 5. Results of field tests carried out on the dual-axis rotational INS are discussed in Section 6. And a conclusion is given in Section 7.

2. A dual-axis rotational INS

Table 1
Specifications of the dual-axis rotational INS.

Characteristics	Description
Output rates	200 Hz
Gyro constant bias (1σ)	0.005°/h
Gyro stochastic error	$0.0007°/h^{1/2}$
Gyro scale factor error	< 30 ppm
Gyro misalignment error	< 40″
Gyro g-dependent bias	0.0005°/h/g
Accel. constant bias (1σ)	100 μg
Accel. stochastic error	$50\,\mu g/Hz^{1/2}$
Accel. scale factor error	< 30 ppm
Accel. misalignment error	< 40″
Sensor range	Gyros: ±300°/s FS Accel.: ±40 g FS
Turntable (1σ)	18″

A dual-axis rotational INS is shown in Fig. 1. Specifications of the dual-axis rotational INS are illustrated in Table 1. As shown in Fig. 1, in the dual-axis rotational INS is equipped with a navigation grade IMU, a power supply, and a display and control panel. The IMU includes three dithered ring laser gyros (0.005°/h), three quartz accelerometers (100 μg), a low-cost dual-axis turntable (18″ in 1σ) and a shock isolation system. The turntable has two orthogonal gimbals, including an azimuth (inner) gimbal and a roll (outer) gimbal. A dimension of the IMU is: 550 mm (Φ) × 800 mm (h). The weight of the IMU is about 120 kg, and average power consumption is less than 500 watts. To minimize the number of slip-rings, four PCB cards are mounted around a sensor block assembly. These PCB cards, including a high voltage PCB card configured to ignite a laser in a Ring Laser Gyro, a data acquisition PCB card, a central processor PCB card and a navigation PCB card, can be easily replaced by a design of plug-in slots, as desired. A functional diagram of the dual-axis rotational INS is shown in Fig. 2.

3. Error model of the dual-axis rotational INS

An error model of the dual-axis rotational INS is explained in detail in this section. The self-calibration method described in Section 4 is based on the error model.

3.1. System error model

The dual-axis rotational INS evolves from a strap-down INS, and error propagation equations of a system error model of the dual-axis rotational INS are the same as those of a strap-down INS [27]. There are two equivalent approaches to derive the error propagation equations of the dual-axis rotational INS: a phi-angle-based approach and a psi-angle-based approach [28,29]. In this section, the phi-angle error model is adopted to illustrate error propagation characteristics of the dual-axis rotational INS.

The error propagation equations of the system error model of the dual-axis rotational INS are as follows:

$$\dot{\phi}^n = -(\omega_{ie}^n + \omega_{en}^n) \times \phi^n + \delta\omega_{in}^n - \mathbf{C}_b^n \varepsilon^b \tag{1}$$

$$\begin{aligned} \delta\dot{\upsilon}^n = {} & \mathbf{f}^n \times \phi^n - (2\omega_{ie}^n + \omega_{en}^n) \times \delta\upsilon^n - (2\delta\omega_{ie}^n + \delta\omega_{en}^n) \\ & \times \upsilon^n + \delta\mathbf{g}^n + \mathbf{C}_b^n \nabla^b \end{aligned} \tag{2}$$

$$\delta\dot{\mathbf{r}}^n = -\omega_{en}^n \times \delta\mathbf{r}^n + \delta\upsilon^n \tag{3}$$

where n, b, i and e indicate a navigation frame, a body frame, an inertial frame and an Earth frame, respectively; superscripts of the vectors denote frames to which the vectors are projected; ϕ^n, $\delta\upsilon^n$ and $\delta\mathbf{r}^n$ are a phi-angle error (attitude error), a velocity error and a position error, respectively; $\mathbf{f}^n$ is a force vector sensed by the accelerometer triad, $\boldsymbol{\omega}$ is an angular rate vector sensed by the gyro triad, and $\delta\boldsymbol{\omega}$ is an angular rate error; the symbol '×' denotes taking cross product of two vectors; $\mathbf{C}_b^n$ is a direction cosine matrix (DCM) of the b-frame with respect to the n-frame; $\boldsymbol{\varepsilon}^b$ is a gyroscope drift error vector, ∇^b is an accelerometer drift error vector.

3.2. IMU error model

The number of error terms included in an IMU error model should be a compromise between accuracy and complexity of the