The field self-calibration method of MEMS gyroscopes and accelerometers for Micro inertial measurement system

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ABSTRACT

The Micro Inertial Measurement System (MIMS) is important equipment for micro aircraft and robot. The biases calibration of MEMS gyroscopes and accelerometers are an effective way to reduce measurement error. In according to error mathematical model of MIMS, a fast field self-calibration method of MEMS gyroscopes and accelerometers is proposed, using the electrolytic gradienter and magnetic compass. The experiment results show that the method can accurately calibrate the biases error of MIMS, improve inertial measurement precision, and verify the efficiency of the proposed method.

Keywords: micro inertial measurement system; MEMS; gyroscope; accelerometer; calibration

1 INTRODUCTION

In control systems, a universal problem is that of determining the attitudes of the spacecraft and robot with respect to a chosen reference frame [1]. The microelectromechanical system (MEMS) gyroscope and accelerometer can be used to measure the angular rate and acceleration with respect to inertial reference frame [2,3]. The benefits of MEMS inertial sensor compared with classical devices include robustness, low power consumption, the potential for miniature dimensions, and low cost [3,4]. But, their performance are degraded due to the manufacturing tolerances, material inhomogeneity, and inevitable mechanical characteristic variation of the structure [5]. The MEMS gyro and accelerometer biases calibration are an effective way to reduce measurement error. In according to error mathematical model of MIMS, a fast field self-calibration method of MEMS gyroscopes and accelerometers is proposed, using a high-precise electrolytic gradienter and magnetic compass. The experiment results show that the method can accurately calibrate the bias error of gyroscopes and accelerometers, improve precision of inertial navigation for MIMS, and verify the efficiency of the proposed method.

2 FILED SELF-CALIBRATION METHOD OF MIMS

The electrolytic gradienter is dual-axes sensor that can directly measure the body attitude angular with respect to the Horizon frame of MIMS in static condition. The initial head angular can be decided by a magnetic compass. Based on the filed initial attitude information, the bias error of MEMS gyroscopes and accelerometers can be calibration. The electrolytic gradienter (PL2M) and the digital magnetic compass (HRM3300) are installed to the body frame with MIMS together. The initial pitch, θ , can be decided by the output of gradienter, q_y ,that is $\theta = q_y$. The initial roll can be obtained as :

$$\gamma = \arcsin\left(\frac{\sin(q_x)}{\cos(\theta)}\right) \tag{1}$$

The initial head angular can be measured by the digital magnetic compass. According the initial body attitude matrix with respect to the navigation frame, the bias of gyroscopes and accelerometers for MIMS can be calibrated.

3 THE CALIBRATION METHOD OF MEMS ACCELEROMETER

According to the initial pitch angular, θ_0 and roll angular, γ_0 , the local gravity vector in three axes for MIMS can be obtained as:

$$\bar{g}^b = \begin{bmatrix} g_E^b \\ g_N^b \\ g_U^b \end{bmatrix} = \begin{bmatrix} g\cos\theta\sin\gamma \\ -g\sin\theta \\ -g\cos\theta\cos\gamma \end{bmatrix} \tag{2}$$

Where g_i^b are the local gravity vector in i axes for MIMS, $i = x, y, z$. The measurement value of accelerometers can be written as:

$$\bar{f}^b = \bar{g}^b + \delta\bar{f} = \begin{bmatrix} f_E^b \\ f_N^b \\ f_U^b \end{bmatrix} = \begin{bmatrix} g\cos\theta\sin\gamma + \delta f_E \\ -g\sin\theta + \delta f_N \\ -g\cos\theta\cos\gamma + \delta f_U \end{bmatrix} \tag{3}$$

Where δf_i is the bias error of accelerometers, f_i^b is the measured value in i axes, $i = x, y, z$. The bias error of accelerometers in three axes can be calculated as:

$$\delta f_N^b = -\frac{1}{n_c}\sum_{i=1}^{n_c} f_N^b + g\sin\theta; \delta f_E^b = \frac{1}{n_c}\sum_{i=1}^{n_c} f_E^b - g\cos\theta\cos\gamma; \delta f_U^b = \frac{1}{n_c}\sum_{i=1}^{n_c} f_U^b + g\cos\theta\cos\gamma \quad (4)$$

Where n_c is the number of accelerometer data.

4 THE CALIBRATION METHOD OF MEMS GYROSCOPES

According the initial pitch angular, θ, roll angular, γ and head angular, ψ, the local Earth rate $\boldsymbol{\omega}_{\mathbf{ie}}$, in both body frames, can be expressed as:

$$\bar{\Omega}^b = \begin{bmatrix} \cos\gamma\cos\psi - \sin\gamma\sin\theta\sin\psi & -\cos\gamma\sin\psi - \sin\gamma\sin\theta\cos\psi & -\sin\gamma\cos\theta \\ \cos\theta\sin\psi & \cos\theta\cos\psi & \sin\theta \\ \sin\gamma\cos\psi - \cos\gamma\sin\theta\sin\psi & -\sin\gamma\sin\psi - \cos\gamma\sin\theta\cos\psi & \cos\gamma\cos\theta \end{bmatrix} \begin{bmatrix} 0 \\ \omega_e\cos\phi \\ \omega_e\sin\phi \end{bmatrix} + \begin{bmatrix} \delta\omega_E \\ \delta\omega_N \\ \delta\omega_U \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} & T_{13} \\ T_{21} & T_{22} & T_{23} \\ T_{31} & T_{32} & T_{33} \end{bmatrix} \begin{bmatrix} 0 \\ \omega_e\cos\phi \\ \omega_e\sin\phi \end{bmatrix} + \begin{bmatrix} \delta\omega_E \\ \delta\omega_N \\ \delta\omega_U \end{bmatrix} \quad (5)$$

Where $\delta\omega_i$ is the bias error of gyroscope in i axes and can be obtained as:

$$\begin{bmatrix} \delta\omega_E \\ \delta\omega_N \\ \delta\omega_U \end{bmatrix} = \begin{bmatrix} -\frac{1}{n_d}\sum_{i=1}^{n_d}\omega_E^b \\ -\frac{1}{n_d}\sum_{i=1}^{n_d}\omega_N^b \\ -\frac{1}{n_d}\sum_{i=1}^{n_d}\omega_U^b \end{bmatrix} - \begin{bmatrix} T_{11} & T_{12} & T_{13} \\ T_{21} & T_{22} & T_{23} \\ T_{31} & T_{32} & T_{33} \end{bmatrix} \begin{bmatrix} 0 \\ \omega_e\cos\varphi \\ \omega_e\sin\varphi \end{bmatrix} \quad (6)$$

5 TEST AND EXPERIMENT OF MIMS

5.1 Calibration Experiment

In order to validate the proposed field self-calibration method, five groups calibration experiments are implemented using the three-axes turntable (attitude precise is 10") and the independently developed micro inertial measurement system. The calibration and compensation experiment results are shown in the Table 1 and Table 2.

Table 1 The fast self-calibration experiment results of accelerometers

Number	The real attitudes（°）	The initial bias error（g）	The calibrated bias error（g）
1	$\theta = 0, \gamma = 0$	$\delta f_E^b = -0.0012$ $\delta f_N^b = 6.928\times10^{-4}$ $\delta f_U^b = -5.1506\times10^{-4}$	$\delta f_E^b = -8.16639\times10^{-5}$ $\delta f_N^b = 5.01250\times10^{-5}$ $f_U^b = -4.5908\times10^{-9}$
2	$\theta = 0, \gamma = 5$	$\delta f_E^b = -5.5739\times10^{-4}$ $\delta f_N^b =$ -0.0010068 $\delta f_U^b = 3.4809\times10^{-4}$	$\delta f_E^b = 9.036\times10^{-5}$ $\delta f_N^b = 3.1608\times10^{-5}$ $f_U^b = -7.91\times10^{-6}$
3	$\theta = 0, \gamma = -5$	$\delta f_E^b = 2.1593\times10^{-4}$ $\delta f_N^b =$ -0.0022118 $f_U^b = 1.2953\times10^{-3}$	$\delta f_E^b = 2.8914\times10^{-5}$ $\delta f_N^b =$ -1.5568×10^{-5} $f_U^b = 2.5291\times10^{-6}$
4	$\theta = 5, \gamma = 0$	$\delta f_E^b = 0.0024125$ $\delta f_N^b = 0.0021596$ $f_U^b = 8.9809\times10^{-4}$	$\delta f_E^b =$ -8.1354×10^{-5} $\delta f_N^b = 4.9918\times10^{-5}$ $f_U^b = 4.3627\times10^{-6}$
5	$\theta = -5, \gamma = 0$	$\delta f_E^b = 0.0017076$ $\delta f_N^b = 5.5211\times10^{-4}$ $f_U^b = 2.7490\times10^{-3}$	$\delta f_E^b = 1.7039\times10^{-6}$ $\delta f_N^b = 3.3974\times10^{-5}$ $f_U^b = -2.9729\times10^{-6}$

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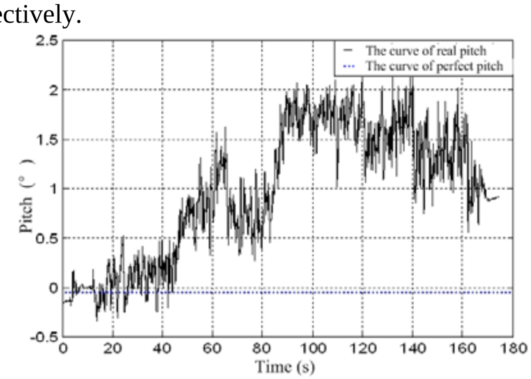
Table 2 The fast self-calibration experiment results of gyroscopes

Number	The real attitudes（°）	The initial bias error（°/h）	The calibrated bias error（°/h）
1	$\theta = 0, \gamma = 0$	$\delta\omega_E^b = 66.294; \delta\omega_N^b = 68.3424; \delta\omega_U^b = 60.1932$	$< 15° / h$
2	$\theta = 0, \gamma = 5$	$\delta\omega_E^b = -89.532; \delta\omega_N^b = -98.564; \delta\omega_U^b = -72.196$	$< 15° / h$
3	$\theta = 0, \gamma = -5$	$\delta\omega_E^b = 60.294; \delta\omega_N^b = 124.657; \delta\omega_U^b = 108.289$	$< 15° / h$
4	$\theta = 5, \gamma = 0$	$\delta\omega_E^b = 162.234; \delta\omega_N^b = 169.563; \delta\omega_U^b = 98.289$	$< 15° / h$
5	$\theta = -5, \gamma = 0$	$\delta\omega_E^b = -131.544; \delta\omega_N^b = 100.800; \delta\omega_U^b = -79.265$	$< 15° / h$

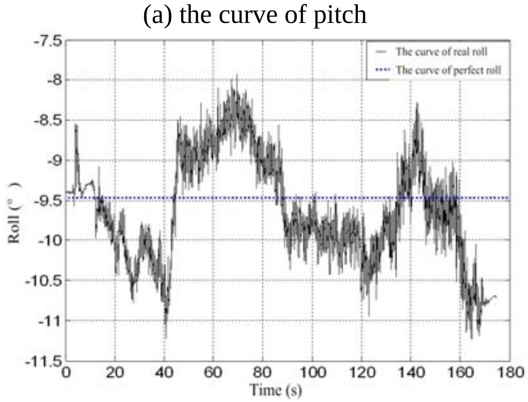
Table 1 shown that calibrated bias errors of accelerometers are reduced to 5.680×10-5g, 3.650×10-5g and 3.502×10-6g from1.219×10-3g, 1.324×10-3g and 1.161×10-3g. From the Table 2, we can known that the calibrated bias errors of gyroscopes are reduced to be less than 15°/h from 101.980°/h (East), 112.385°/h(North) and 83.646°/h(Up), respectively. The proposed method is helpful to further improving the precise of gyroscopes and accelerometers.

5.2 Vehicle Experiments

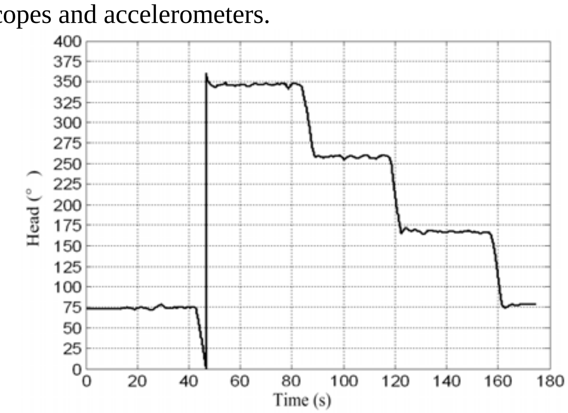
The MIMS are fixed in an experimental vehicle with initial roll angular $\gamma = 9.52°$ .The vehicle is driven along layout route for 180 seconds. According to the proposed method, the bias errors of gyroscopes and accelerometers in three axes can be calibrated and compensated, then, the initial attitude can be fined. The experiment results implemented by the proposed method are shown in Fig.1. The experiment results shown that inertial measurement pitch, roll and head angular error are about 2°,1.5° and 5° in 180 second, respectively.



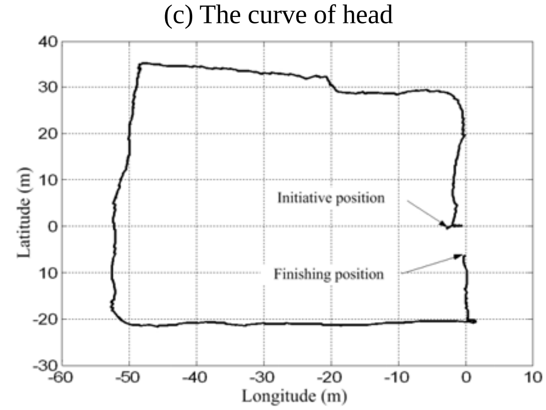
(a) the curve of pitch



(b) the curve of roll



(c) The curve of head



(d) the position curve of inertial navigation

Fig.1 the experiment results of proposed method

6 SUMMARY

The Micro Inertial Measurement System (MIMS) is important equipment for micro aircraft and robot. The MEMS gyro and accelerometer biases calibration are an effective way to reduce measurement error. In according to error mathematical model of MIMS, the bias error of MEMS gyroscopes and accelerometers can be fast calibrated in field, using the information provided by electrolytic gradienter and magnetic compass. A series of calibration and vehicle experiments are implemented, and the results verify the precision and practicability of the proposed method.

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