A New On-line Calibration Method Based on Three-axis MEMS Gyroscope

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Abstract

A new on-line calibration method based on three-axis Micro-Electro-Mechanical System (MEMS) gyroscope is designed, which processing the data by using Kalman filter and calibrating the installation error of the three-axis MEMS gyroscope in complex environment. The attitude angle updating for quaternion from the attitude instrument, which controlling the rotating system in real-time. Our experimental platform is constituted of the dual-axis electric rotary table and the attitude instrument which is developed independently by our scientific research team. The experimental results show that the maximum absolute error of the Z-axis data of the uncalibrated MEMS gyroscope is 2.7438 °/s, and the absolute error is higher than - 0.0024 °/s after calibrating which is improved by 1-2 orders of magnitude, that improved the measurement accuracy of MEMS gyroscope and enhanced the accuracy of the attitude instrument.

Keywords

MEMS gyroscope, Quaternion, Rotating system in real-time, On-line calibration.

1. Introduction

Inertial technology, combines classical mechanics and physics, can control the trajectory and movement posture, which promoted the automation system ^[1]. Micro-Electro-Mechanical System (MEMS) gyroscope is a new type of all-solid-state gyroscope ^[2-3]. Compared with the traditional mechanical gyroscope and optical gyroscope, MEMS gyroscope has many advantages such as small size, light weight, low cost, good reliability, large measuring range, easy to digitize and intelligent ^[4].

We proposed a novel on-line calibration method based on three-axis MEMS gyroscope. We compensate and calibrate the output data. The attitude angle is updated by quaternion, and on-line calibration is realized by operating the rotation control system. Compared with the two-position on-line calibration, the latitude information is undesired and the turntable is used only once, while the accuracy is higher than 1°.

The system consists of the attitude instrument (which integrates three-axis MEMS gyroscope, magnetometer and accelerometer) which is research and development from our laboratory, the 902E-1 biaxial electric turntable, the host computer and the RS232 serial cable as shown in Fig.1. According to the attitude angle of the attitude instrument, we use host computer to adjust the rotation control system to control the attitude instrument, then read the attitude information and adjust the rotation control system again.



Fig. 1 System architecture

The paper is organized as follows. Firstly, Kalman filter was designed to compensate the output data of the attitude instrument. Then the installation error of the three-axis MEMS gyroscope of the attitude instrument was calibrated, the initial attitude angle was determined by the magnetometer and accelerometer, and updated by quaternion. Finally, we operate the rotation control system to on-line calibration, which is decided by the three-axis MEMS gyroscope on-line calibration method.

2. Data filtering and installation error calibrating

2.1 Data filtering

Kalman filter is an optimal estimation method under the minimum covariance error, which has the advantages of small computation and high real-time performance. While taking the real-time and stability into account, it can improve the estimation accuracy of the future gyroscope continuously by using the variance parameters measured ^[7].

When the three-axis MEMS gyroscope raw data is processed with Kalman filter, (0, 0, 0) is used as the initial value of the state variable and the square of the original zero bias stability of the three-axis MEMS gyroscope is acted as the measured noise variance. We collected about 10 minutes static data of the three-axis MEMS gyroscope, then processing them by Kalman filter and the comparison of the data before and after filtering is shown in Fig. 2.



Fig. 2 The comparison of the data before and after filtering

Through the analysis of the raw data of the three-axis MEMS gyroscope processed by Kalman filter, it shows that the filtering effect is obvious. Therefore, the Kalman filter can effectively reduce the random noise and improve the measurement accuracy of the three-axis MEMS gyroscope, and improve the accuracy of the updated attitude instrument and provides a higher accuracy of on-line calibration ultimately for the program.

2.2 Installation error calibrating

There is an installation error between the attitude instrument and the three-axis MEMS gyroscope. The carrier coordinate system can be overlapped with the coordinate system of the three-axis MEMS gyroscope after three rotations^[8]. And the calibration model of the installation error of the three-axis MEMS gyroscope is:

$$\begin{pmatrix} \boldsymbol{\omega}_{xb} \\ \boldsymbol{\omega}_{yb} \\ \boldsymbol{\omega}_{zb} \end{pmatrix} = \begin{pmatrix} \boldsymbol{K}_{xx} & \boldsymbol{K}_{yx} & \boldsymbol{K}_{zx} \\ \boldsymbol{K}_{xy} & \boldsymbol{K}_{yy} & \boldsymbol{K}_{zy} \\ \boldsymbol{K}_{xz} & \boldsymbol{K}_{yz} & \boldsymbol{K}_{zz} \end{pmatrix}^{-1} \begin{pmatrix} \boldsymbol{\omega}_{xg} - \boldsymbol{\omega}_{x0} \\ \boldsymbol{\omega}_{yg} - \boldsymbol{\omega}_{y0} \\ \boldsymbol{\omega}_{zg} - \boldsymbol{\omega}_{z0} \end{pmatrix}$$
(1)

The installation error of the three-axis MEMS gyroscope can be calibrated by (1), where ω_{xg} , ω_{yg} , ω_{zg} are the measurements of the three-axis MEMS gyroscope, ω_{xb} , ω_{yb} , ω_{zb} are the input angular rate. We

can use K_{ij} (i = x, y, z; j = x, y, z) as the ratio of the angular rate which is detected by j-axis to the input angular rate when the *i*-axis has an input angular rate. ω_{x0} , ω_{y0} , ω_{z0} represent the zero bias of the three axes of the gyroscope respectively. We considered them as fixed zero bias to facilitate the calibration of the installation error because they are very small [9]. We can get the calibration matrix as follows:

$$\begin{pmatrix} \omega_{xb} \\ \omega_{yb} \\ \omega_{zb} \end{pmatrix} = \begin{pmatrix} 0.05628079 & 1.0794006e-05 & 0.00071179 \\ 0.00046929 & 0.02025715 & 0.00037781 \\ 0.00022129 & 0.00027298 & 0.05610513 \end{pmatrix}^{-1}$$

$$\begin{pmatrix} \omega_{xg} + 22.67454166 \\ \omega_{yg} - 100.7170000 \\ \omega_{zg} + 44.60041666 \end{pmatrix}$$

$$(2)$$

3. An on-line calibration algorithm of the three-axis MEMS gyroscope

We set the coordinate of the E-N-S (east, north and sky) as the navigation coordinate system(n) followed by X-axis, Y-axis, Z-axis and the carrier coordinate system(b) followed by x-axis, y-axis, z-axis which are respectively coincidence with the installation coordinate system of the attitude instrument. The conversion matrix of the carrier coordinate system to the navigation coordinate system is C_b^n , and the angles of the attitude instrument around the x-axis, y-axis rotating are pitch β , roll γ and heading α , which are the angles between the n and b.

The quaternion and its differential equation are used to solve the conversion matrix. The attitude angle information can be updated in real time through the angular rate of the three axes of the MEMS gyroscope and the four state quantities, and that is convenient to operate , easy to implement and extensive to apply [10,11].

The differential equation of the quaternion as follows:

$$\dot{Q} = \frac{1}{2} Q \otimes W , \quad \dot{Q}(t_0) = \dot{Q}_0$$
(3)

Where Q is the attitude quaternion, and $Q = q_0 + q_1 i + q_2 j + q_3 k$, q_0 , q_1 , q_2 , q_3 are real numbers; and t_0 is the initial moment of movement of the attitude instrument, Q_0 is the quaternion of the initial moment of the attitude angles of the attitude instrument as (γ, β, α) .

Where *w* is the angular rate quaternion of the attitude instrument in the carrier coordinate system, \otimes is the multiplication sign of quaternion, the matrix form of differential equation as follows:

$$\dot{Q} = \begin{bmatrix} \dot{q}_0 \\ \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 0 & -\omega_1 & -\omega_2 & -\omega_3 \\ \omega_1 & 0 & \omega_3 & -\omega_2 \\ \omega_2 & -\omega_3 & 0 & \omega_1 \\ \omega_3 & \omega_2 & -\omega_1 & 0 \end{bmatrix} \cdot \begin{bmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \end{bmatrix} = \frac{1}{2} \Omega(\omega) \dot{Q}$$
(4)

Where $\omega_i(i=1,2,3)$ is the angular rate component of the three-axis MEMS gyroscope on the x, y, and z axes of the carrier coordinate system, $\Omega(\omega)$ is an anti-symmetric matrix of 4×4 .

Normally, we assume that the values of the MEMS gyroscope are constant during the sampling time T, the discretized quaternion attitude updated formula becomes:

$$\dot{Q}_{k+1} = \exp(\frac{1}{2}\Omega(\omega)T_s)\dot{Q}_k = (I\cos\frac{\Delta\theta}{2} + \Omega(\omega)T_s\frac{\sin\frac{\Delta\theta}{2}}{\Delta\theta})\dot{Q}_k$$
(5)

Where $\Delta \theta = T_s \sqrt{\omega_1^2 + \omega_2^2 + \omega_3^2}$, $k = 0, 1, \dots$. In the actual solution, $\cos \frac{\Delta \theta}{2}$ and $\sin \frac{\Delta \theta}{2}$ must be expanded in the accordance with series and took the finite term, then we get the first order approximation algorithm of quaternion [12]:

$$\dot{Q}_{k+1} = (I + \frac{\Omega(\omega)T_s}{2})\dot{Q}_k \tag{6}$$

Therefore, the updated quaternion can be obtained by knowing $q_0 \ge q_1 \ge q_2 \ge q_3$, and the angular rate of the MEMS gyroscope and the attitude matrix can be got from the relationship between the attitude quaternion and the conversion matrix:

$$C_{n}^{b} = \begin{bmatrix} q_{0}^{2} + q_{1}^{2} - q_{2}^{2} - q_{3}^{2} & 2(q_{1}q_{2} + q_{0}q_{3}) & 2(q_{1}q_{3} - q_{0}q_{2}) \\ 2(q_{1}q_{2} - q_{0}q_{3}) & q_{0}^{2} - q_{1}^{2} + q_{2}^{2} - q_{3}^{2} & 2(q_{2}q_{3} + q_{0}q_{1}) \\ 2(q_{1}q_{3} + q_{0}q_{2}) & 2(q_{2}q_{3} - q_{0}q_{1}) & q_{0}^{2} - q_{1}^{2} - q_{2}^{2} + q_{3}^{2} \end{bmatrix}$$
(7)

The updated attitude matrix C_n^b is obtained from the updated quaternion, we compare it with the rotation matrix of the Euler angle to obtain the updated attitude angle information:

$$\gamma' = \arctan(-\frac{2(q_1q_3 - q_0q_2)}{q_0^2 - q_1^2 - q_2^2 + q_3^2})$$

$$\beta' = \arcsin(2(q_2q_3 + q_0q_1))$$

$$\alpha' = \arctan(-\frac{2(q_1q_2 - q_0q_3)}{q_0^2 - q_1^2 + q_2^2 - q_3^2})$$
(8)

Through the process of the above data, including the installation of error calibration and the quaternion solution of attitude angles, we proposed a rotary calibration program to achieve the online north-seeking based on three-axis MEMS gyroscope. In the process of operation, firstly, filtering the data of the three-axis MEMS gyroscope and calibrating the installation error when we ensure the rotation control system stays at the stop state. Next, according to the data of three-axis MEMS gyroscope the attitude angle is updated and sent to the host computer to monitor by the interface RS232 in real-time.

4. Experimental results

We put the -100 °/s ~ +100 °/s measured data of the MEMS gyroscope Z axis into the formula (2) to get the value after calibration, and the calibrated and uncalibrated data are shown in Tab. 1.

Input	Before calibration	After calibration	Before calibration error	After calibration error
-100	-97.2562	-100.0052	2.7438	-0.0052
-80	-78.9821	-80.0624	1.0179	-0.0624
-60	-59.1321	-60.0451	0.8679	-0.0451
-40	-38.6261	-40.0405	1.3739	-0.0405
-20	-17.2652	-19.9959	2.7348	0.0041
-10	-9.1515	-10.0024	0.8485	-0.0024
10	9.7265	10.0168	-0.2735	0.0168
20	18.6247	20.0025	-1.3753	0.0025
40	39.1675	40.0068	-0.8325	0.0068
60	59.1564	60.0054	-0.8436	0.0054
80	79.4298	79.9926	-0.5702	-0.0074
100	98.4871	100.0098	-1.5129	0.0098

Tab. 1 The comparison of Z axis data before and after calibrating (Unit: °/s)

As it can be seen from Tab. 1, at the angular rate of -100 °/s ~ + 100 °/s, the absolute error of the Z-axis data of the MEMS gyroscope increasing with the increasing of the angular rate, and the installation error reaches maximum at the angular rate of \pm 100 °/s. The maximum absolute error of

the Z-axis data of the uncalibrated MEMS gyroscope is 2.7438 °/s, and the absolute error is higher than -0.0024 °/s after calibrating which is improved by 1-2 orders of magnitude, that improved the measurement accuracy of MEMS gyroscope and enhanced the accuracy of the attitude instrument.

5. Conclusions

A new on-line calibration method based on three-axis MEMS gyroscope has been proposed. The heading angle information of the attitude instrument is updated in real-time by using the three-axis MEMS gyroscope data which has be filtered and installation error calibrated. The maximum absolute error of the Z-axis data of the uncalibrated MEMS gyroscope is 2.7438 °/s, and the absolute error is higher than -0.0024 °/s after calibrating which is improved by 1-2 orders of magnitude, that improved the measurement accuracy of MEMS gyroscope and enhanced the accuracy of the attitude instrument.

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