Research on practical calibration compensation method of MIMU

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Abstract. The Micro-inertial measurement unit (MIMU) is affected by the processing, installation and environment during its working process, which will produce large errors, resulting in low measurement precision, therefore, error calibration compensation is necessary. In this paper, a practical calibration compensation method of MIMU based on the error model of gyroscope and accelerometer was studied. The practical method uses a three-axis multi-functional turntable, which can provide high-precision angular rate and spatial position benchmark, to design the angular rate and six-position calibration scheme, and computes twenty-four error parameters of the MIMU, including zero bias, scale factor and installation error coefficient. The analysis of the experimental result shows that the precision of MIMU after calibration compensation can be improved by 1-2 orders of magnitude, which proves the effectiveness of the calibration compensation method.

1. Introduction

The Micro-inertial measurement unit (MIMU) can measure the angular velocity, angular position, acceleration and other motion information of the carrier. Compared with the traditional inertial devices, it has the advantages of small size, low cost, easy integration and mass production. At present, MIMU is widely used in the civil and military fields such as robots, smart phones, unmanned aerial vehicles (UAVs), weapon guidance and so on [1]. As the core device of MIMU, the performance of gyroscopes and accelerometers determines the measurement precision. However, due to the limitation of manufacturing and installation level, as well as the influence of working environment, there are many errors in the measurement output of MIMU inertial devices [2]. Therefore, the research on MIMU error calibration compensation can improve the performance and measurement accuracy of MIMU, which is of great significance.

MIMU error mainly includes system error and random error, in which system error is the main error source [2]. System error is deterministic error, which can be compensated by error calibration, while random error has randomness and cannot be calibrated accurately. In order to establish an accurate MIMU error model, it’s necessary to calibrate the zero bias, scale factor, installation error coefficient of the inertial device [1], [3]. For accelerometers, the separate calibration method is usually used, including 24-position, 12-position, 6-position and other methods [4]. Reference [5] introduced the six-position test method of micro-electro mechanical systems (MEMS) accelerometers in detail, which is simple and easily conducted. For gyroscopes, commonly used calibration method is angular rate method, and the turntable is used to provide precise angular rate for calibration, with good experimental results [6].

Different from the calibration of gyroscopes and accelerometers alone, this paper establishes the MIMU error and compensation model and designs the scheme of MIMU angular rate and static six-
position calibration. Twenty-four error parameters of ADIS16375 MIMU were calibrated through experiments based on a three-axis multi-function turntable, moreover, the validity of the calibration method was proved.

2. MIMU error model
The MIMU consists of three-axis gyroscope and accelerometer. Ideally, the three sensitive axes are perpendicular to each other in three-dimensional space, the structure composition is shown in Figure 1, where, $\omega_x, \omega_y, \omega_z$ represents the output of gyroscope, $a_x, a_y, a_z$ represents the output of accelerometer.

Actually, due to the influence of processing and installation, the axes of gyroscope and accelerometer aren’t completely orthogonal, there are zero bias, scale factor, non-orthogonal installation error, etc. In the following, the error models of gyroscope and accelerometer are introduced.

### 2.1. Error model of gyroscope
According to the error source and output characteristics of the gyroscope, the output error model of the MIMU gyroscope at room temperature is established without considering the influence of temperature changing [7], as shown in equation (1),

$$
\begin{bmatrix}
W_x \\
W_y \\
W_z
\end{bmatrix} =
\begin{bmatrix}
\omega_{x0} \\
\omega_{y0} \\
\omega_{z0}
\end{bmatrix} +
\begin{bmatrix}
L_{ox} & K_{oxy} & K_{oxz} \\
K_{oxy} & L_{oy} & K_{oyz} \\
K_{oxz} & K_{oyz} & L_{oz}
\end{bmatrix}
\begin{bmatrix}
\omega_x \\
\omega_y \\
\omega_z
\end{bmatrix}
$$

(1)

Where, $W_i (i = x, y, z)$ represents measured angular rate, $\omega_{io} (i = x, y, z)$ represents zero bias, $\omega_i (i = x, y, z)$ represents real angular rate, $K_{ij} (i, j = x, y, z, i \neq j)$ represents non-orthogonal installation error coefficient, $L_{io} (i = x, y, z)$ represents scale factor.

Through the above output error model, the error compensation model of gyroscope can be obtained, as shown in equation (2),

$$
\begin{bmatrix}
\omega_x \\
\omega_y \\
\omega_z
\end{bmatrix} =
\begin{bmatrix}
L_{ox} & K_{oxy} & K_{oxz} \\
K_{oxy} & L_{oy} & K_{oyz} \\
K_{oxz} & K_{oyz} & L_{oz}
\end{bmatrix}^{-1}
\begin{bmatrix}
W_x - \omega_{x0} \\
W_y - \omega_{y0} \\
W_z - \omega_{z0}
\end{bmatrix}
$$

(2)

### 2.2. Error model of accelerometer
For low precision MIMU accelerometer, the installation error coefficient related to secondary term can be ignored [7], the output error model of the MIMU accelerometer at room temperature is established without considering the influence of temperature changing [5], [8], as shown in equation (3),

$$
\begin{bmatrix}
A_x \\
A_y \\
A_z
\end{bmatrix} =
\begin{bmatrix}
a_{x0} \\
a_{y0} \\
a_{z0}
\end{bmatrix} +
\begin{bmatrix}
L_{ax} & K_{axy} & K_{axz} \\
K_{axy} & L_{ay} & K_{ayz} \\
K_{axz} & K_{ayz} & L_{az}
\end{bmatrix}
\begin{bmatrix}
a_x \\
a_y \\
a_z
\end{bmatrix}
$$

(3)
Where, \( A_i (i = x, y, z) \) represents measured specific force, \( a_{i0} (i = x, y, z) \) represents zero bias, \( a_i (i = x, y, z) \) represents real specific force, \( K_{aij} (i, j = x, y, z, i \neq j) \) represents non-orthogonal installation error coefficient, \( L_{ai} (i = x, y, z) \) represents scale factor.

Similarly, the accelerometer error compensation model can be obtained, as shown in equation (4).

\[
\begin{bmatrix}
    a_x \\
    a_y \\
    a_z
\end{bmatrix} =
\begin{bmatrix}
    L_{ax} & K_{axy} & K_{axz} \\
    K_{ayx} & L_{ay} & K_{ayz} \\
    K_{azx} & K_{azy} & L_{az}
\end{bmatrix}^{-1}
\begin{bmatrix}
    A_x - a_{x0} \\
    A_y - a_{y0} \\
    A_z - a_{z0}
\end{bmatrix}
\]  

(4)

3. MIMU calibration method arrangement

According to the output error and compensation model of MIMU gyroscope and accelerometer given above, designed the angular rate and static six-position calibration arrangement scheme. Fixed MIMU on the three-axis multi-functional turntable, making its three-axis coordinate system aligned and parallel to the turntable axis coordinate system, and using the high-precision angular rate and angular position excitation provided by turntable to calibrated the MIMU’s error parameters. The specific calibration arrangement schemes of error parameters are as follows.

3.1. Arrangement of gyroscope angle rate method

(a) Before experiment, aligning the MIMU with the turntable and powering the turntable and the MIMU sensor for 15 minutes to improve the stability of the collected data; (b) Making the three rotating axes of the turntable operate in 24 rotating speed modes of \( \pm 25 \, \text{°/s}, \pm 40 \, \text{°/s}, \pm 60 \, \text{°/s}, \pm 100 \, \text{°/s} \) (‘+’ for forward rotation, ‘-’ for reverse rotation). In each mode, collecting gyrooscope’s output data of 10s after the turntable rotates stably; (c) In each mode, the average value of gyro output data is expressed as the output value.

According to equation (1), the bias of gyroscope is obtained, as shown in equation (5),

\[
\omega_{i0} = (W_i + W_{-i}) / 2 \quad (i = x, y, z)
\]  

(5)

Where, \( W_i (i = x, y, z) \), \( W_{-i} (i = x, y, z) \) represents the measurement value of the gyroscope when the rotating axis of turntable is rotating forward and reversed respectively.

After the zero bias of the gyroscopic was determined, substituting the measured value of the gyroscope and the rotation rate provided by the turntable in the corresponding mode into the gyroscope error compensation model equation (2), the scale factor and non-orthogonal installation error coefficient of the gyroscopic can be calculated by the least square method.

3.2. Arrangement of accelerometer six-position method

(a) After completing the angular rate calibration of gyroscope, adjusting the position of the turntable in turn shown in Table 1; (b) Collecting the accelerometer’s output data of 10s at each position when turntable is stable, (c) Taking the average of measured data as the output specific force of the position.

| Position | Accelerometer axis orientation | Ideal specific force |
|----------|-------------------------------|----------------------|
| x-axis   | y-axis | z-axis | x-axis | y-axis | z-axis |
| 1 East    | Up    | South  | 0      | -g     | 0      |
| 2 East    | North | Up     | 0      | 0      | -g     |
| 3 Down    | East  | South  | g      | 0      | 0      |
| 4 West    | Down  | South  | 0      | g      | 0      |
| 5 Up      | West  | South  | -g     | 0      | 0      |
| 6 South   | West  | Down   | 0      | 0      | g      |
The output values of accelerometer’s x-axis, y-axis and z-axis in six positions are expressed as $A_{x_n} (n = 1 \sim 6)$, $A_{y_n} (n = 1 \sim 6)$, $A_{z_n} (n = 1 \sim 6)$ respectively. According to the error model equation (4), the equation groups of the three axes of the accelerometer in six positions can be obtained.

Taking x-axis for example, the equation group is as equation (6), the y-axis and z-axis are similar.

$$\begin{align*}
A_{x_1} &= a_{x_0} - K_{axy} \\
A_{x_4} &= a_{x_0} + K_{axy} \\
A_{x_2} &= a_{x_0} - K_{axz} \\
A_{x_6} &= a_{x_0} + K_{axz} \\
A_{x_3} &= a_{x_0} + L_{ax} \\
A_{x_5} &= a_{x_0} - L_{ax}
\end{align*}$$

(6)

Therefore, the bias, scale factor and installation error coefficient of the accelerometer can be calculated as shown in equation (7). Similarly, the y-axis and z-axis also can be got. Above all, the 12 error parameters of the accelerometer can be obtained.

$$\begin{align*}
\omega_{x_0} &= \frac{(A_{x_1} + A_{x_2} + A_{x_3} + A_{x_4} + A_{x_5} + A_{x_6})}{6} \\
L_{ax} &= \frac{(A_{x_3} - A_{x_5})}{2} \\
K_{axy} &= \frac{(A_{x_4} - A_{x_6})}{2} \\
K_{axz} &= \frac{(A_{x_6} - A_{x_2})}{2}
\end{align*}$$

(7)

4. Calibration experiment and model verification

4.1. Calibration experiment

According to the steps of the calibration method described above, using the three-axis multi-function turntable (as shown in Figure 2) to calibrate the model ADIS16375 MIMU (as shown in Figure 3), and verifying the validity of the calibration method. The experimental environment’s temperature is 22 °C, and the value of acceleration of gravity is 9.8022m/s².

![Figure 2. Three-axis multi-function turntable](image1)

![Figure 3. ADIS16375](image2)

The output data of gyroscope in 24 speed modes and accelerometer in 6 positions are collected, processing those data according to the calibration program written in MATLAB.

For the gyroscope, selecting the data collected by the three-axis turntable at the rate of $\pm 25$°/s, $\pm 40$°/s, $\pm 60$°/s, and calculating 12 error parameters of the gyroscope as shown in Table 2.

**Table 2. 12 error parameters of gyroscope**

| Axis | Bias (°/s) | Scale factor | Installation error coefficient |
|------|-----------|--------------|-------------------------------|
| x    | $\omega_{x_0} = -0.1645$ | $L_{ax} = 1.0012$ | $K_{axy} = 0.0028$ | $K_{axz} = -0.0026$ |
| y    | $\omega_{y_0} = 0.0956$ | $L_{ay} = 1.0004$ | $K_{myx} = -0.0029$ | $K_{myy} = 0.0028$ |
| z    | $\omega_{z_0} = -0.0199$ | $L_{az} = 0.9997$ | $K_{mzx} = 0.0022$ | $K_{mzy} = -0.0027$ |

The specific error compensation model of this type of MIMU gyroscope can be represented as equation (8) according to the error parameters shown in Table 2.
\[
\begin{bmatrix}
\omega_x \\
\omega_y \\
\omega_z
\end{bmatrix}
= \begin{bmatrix}
1.0012 & 0.0028 & -0.0026 \\
-0.0029 & 1.0004 & 0.0028 \\
0.0022 & -0.0027 & 0.9997
\end{bmatrix}^{-1}
\begin{bmatrix}
W_x + 0.1645 \\
W_y - 0.0956 \\
W_z + 0.0199
\end{bmatrix}
\]

(8)

For the accelerometer, selecting the data collected by the turntable at six static positions, and calculating 12 error parameters of the accelerometer as shown in Table 3,

### Table 3. 12 error parameters of accelerometer

| Axis | Bias (°/s) | Scale factor | Installation error coefficient |
|------|------------|--------------|-------------------------------|
| x    | \(a_{x0} = -0.0055\) | \(L_{ax} = 0.9994\) | \(K_{axy} = 0.0007\), \(K_{axz} = -0.0038\) |
| y    | \(a_{y0} = 0.0170\) | \(L_{ay} = 0.9985\) | \(K_{ayx} = -0.001\), \(K_{ayz} = -0.0003\) |
| z    | \(a_{z0} = 0.0270\) | \(L_{az} = 0.9990\) | \(K_{azx} = 0.0021\), \(K_{azy} = -0.0024\) |

The specific error compensation model of this type of MIMU accelerometer can be represented as equation (9) by the error parameters shown in Table 3.

\[
\begin{bmatrix}
a_x \\
a_y \\
a_z
\end{bmatrix}
= \begin{bmatrix}
0.9994 & 0.0007 & -0.0038 \\
-0.001 & 0.9985 & -0.0003 \\
0.0021 & -0.0024 & 0.999
\end{bmatrix}^{-1}
\begin{bmatrix}
A_x + 0.0055 \\
A_y - 0.017 \\
A_z - 0.027
\end{bmatrix}
\]

(9)

### 4.2. Model verification

The 24 error parameters of ADIS16375 MIMU gyroscope and accelerometer are obtained by calibration experiment. The precision of the error model and the effectiveness of the angular rate method are verified in the following.

#### 4.2.1. Verification of gyroscope error model.

Putting the measured data collected by the gyroscope in the rate mode of ±100 °/s into the model equation (8) for error compensation, and comparing the data before and after compensation with the angular rate provided by the turntable. If the data after compensation is closer to the angular rate value provided by the turntable, indicating that the gyroscope calibration method is effective. The measured and compensated data of gyroscope shown in Table 4.

### Table 4. Measured and compensated data of gyroscope under turntable three-axis rotation ±100 °/s

| Rotation mode | x-axis(°/s) | y-axis(°/s) | z-axis(°/s) |
|---------------|------------|------------|------------|
|               | Measured   | Compensated| Measured   | Compensated| Measured   | Compensated |
| x (+)         | 99.9579    | 100.0036   | -0.1890    | 0.0102     | 0.2215     | 0.0174      |
| y (+)         | 0.1153     | -0.0012    | 100.1204   | 99.9857    | -0.2862    | 0.0032      |
| z (+)         | -0.4381    | -0.0089    | 0.3555     | -0.0152    | 99.9522    | 100.0062    |
| x (-)         | -100.2883  | -100.0050  | 0.4001     | 0.0097     | -0.2673    | -0.0235     |
| y (-)         | -0.4608    | -0.0152    | -99.9420   | -99.9984   | 0.2450     | -0.0046     |
| z (-)         | 0.1280     | 0.0278     | -0.1605    | 0.0192     | -100.0165  | -100.0309   |

Note: (+) (-) indicates forward and reverse rotation of turntable respectively.

In Table 4, compared with the ±100 °/s angular rate excitation provided by the turntable, the error of measured and compensated can be got. For example, in the x(+)-mode, the measured error of gyroscope’s x-axis is -0.042 °/s, after compensation is 0.004 °/s, in the y(+)-mode, the measured error of gyroscope’s y-axis is 0.12 °/s, after compensation is -0.014 °/s, in the z(+) mode, the measured error of gyroscope’s z-axis is -0.048 °/s, after compensation is 0.006 °/s, the turntable reverse is similar. It can be seen that the error of the gyroscope after compensation is reduced by 1-2 orders of magnitude.
Taking the measured and compensated data of gyroscope under the turntable three axes forward rotation 100 °/s mode respectively for example, drawing for comparative analysis, as shown in Figure 4-6. The blue and red curves in the diagrams represent the measured and compensated data respectively.

Figure 4. Three-axis output of gyroscope under turntable x-axis forward rotation 100 °/s

Figure 5. Three-axis output of gyroscope under turntable y-axis forward rotation 100 °/s

Figure 6. Three-axis output of gyroscope under turntable z-axis forward rotation 100 °/s

Figure 4-6 shows the visual comparison curve between the measured and after compensation date of the gyroscope’s three axes. It can be seen that the measured value after calibration compensation is closer to the speed benchmark provided by the turntable, which proves that the angle rate method is effective.

4.2.2. Verification of accelerometer error model.
The accuracy of the error model and the validity of the six-position method are verified by comparing the measured and compensated attitude angle errors.

Adjusting turntable to the 6th position in Table 1. (a) Rotating the x-axis of turntable, turning the y-axis from 30° to 80°, stopping turntable every 10° rotation and collecting the accelerometer output data for 10s after the turntable is stable, which can be calculated the pitch; (b) Rotating the y-axis of turntable, turning the x-axis from 30° to 80°, stopping turntable every 10° rotation and collecting the accelerometer output data for 10s after the turntable is stable, which can be calculated the roll.
Through the model equation (9) to compensate the measured data, compared the attitude calculated by measured and compensated data with reference attitude provided by turntable. The calculated attitude angle, mean and variance of attitude angle error are shown in Table 5 and Table 6 respectively.

| Turntable angle (°) | Measured (°) | Compensate (°) |
|---------------------|--------------|----------------|
| Pitch               |              |                |
| 30                  | 30.1248      | 29.9747        |
| 40                  | 40.1166      | 40.0029        |
| 50                  | 50.1044      | 50.0310        |
| 60                  | 60.0791      | 60.0435        |
| 70                  | 70.0706      | 70.0675        |
| 80                  | 80.0582      | 80.0800        |
| Roll                |              |                |
| 30                  | 29.7456      | 29.9421        |
| 40                  | 39.7364      | 39.9730        |
| 50                  | 49.7214      | 49.9929        |
| 60                  | 59.7095      | 60.0070        |
| 70                  | 69.7073      | 70.0190        |
| 80                  | 79.7035      | 80.0156        |

| Pitch error         | 0.0697        | 0.0250         | -0.2096        | -0.0063        |
| Roll error          | 0.0024        | 0.0014         | 0.0169         | 0.0006         |

It can be seen from Table 6 that the mean and variance of attitude angle error calculated by the compensated data is smaller than the measured, which proves the model and method are effective.

5. Conclusion
In order to reduce the influence of the deterministic error on the MIMU and improve the measurement precision, this paper uses the structure and error model of the MIMU gyroscope and accelerometer for reference, designing the angular rate and static six-position calibration scheme, and using a three-axis multi-function turntable to carry out the calibration compensation experiment of the ADIS16375 MIMU. Through analysis of experimental data, the following conclusions are drawn: this calibration compensation method is simple, effective and easy to operate, after calibration and compensation, the precision of MIMU inertial devices has been improved by 1-2 orders of magnitude. But the precision of MIMU inertial devices is also affected by temperature, this paper doesn’t consider the impact of temperature changing, so that the error model has limitations.

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