An analysis of the calibration method of accelerometer bias and scale factor

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Abstract. Accelerometer bias and scale factor are important parameters of the accelerometer. The accuracy of calibration of bias and scale factor will directly affect navigation accuracy. This paper studies the calibration of accelerometers under out-door conditions. In some applications, the inertial measurement unit (IMU) cannot rotate with any angle due to the restriction of equipment and site. The pitch and roll rotation range is -45° to 45°, and the yaw is -180° to 180°. In this paper, the bias and scale factor identification equations under different positions are derived based on the inertial navigation error equation. The results show that when the IMU rotates around the pitch axis, as long as there are three pitch positions, the bias and scale factor of the y-direction and z-direction accelerometers can be calibrated. When the IMU rotates 45° around the roll axis and then rotates 90° around the yaw axis, the x-direction accelerometer scale factor can be calibrated. If the bias and scale factor of the y-direction and z-direction accelerometer are known, the bias of the x-direction accelerometer can also be calibrated. Then, several simulations are conducted which are consistent with the theoretical results. At last, optimized calibration path is designed. Within 20 min, the calibration accuracy of bias is better than 5 mGal, and the calibration accuracy of scale factor is better than 5 ppm.

1. Introduction

Accelerometer bias and scale factor are important error sources in inertial navigation systems[1-3]. Ideally, if the input of accelerometers is zero, the output should also be zero. But in actual applications, the output of accelerometers is not zero, which is the accelerometer bias. The output of the accelerometer is a digital electrical signal that needs to be converted to velocity increment. The ratio of the velocity increment to the digital electrical signal is the accelerometer scale factor[4-5]. The bias and scale factor errors can affect the navigation accuracy badly, so the bias and scale factor need to be accurately calibrated.

Calibration methods mainly include discrete calibration and systematic calibration. Systematic calibration can meet the need of out-door calibration and becomes a research hotspot[6-7]. Yang Xiaoxia proposed a systematic calibration model, and analyzed the identification of inertial measurement unit (IMU) error parameters[8]. Shi Wenfeng designed a ten-position systematic calibration method to improve calibration accuracy[9]. Wang Zihui[10] proposed an eight-position systematic calibration method based on the two-axis turntable, which is superior to the traditional calibration method for both calibration time and navigation precision. These studies are based on the premise that the IMU can rotate to any position. In some applications, the IMU cannot rotate with any angle due to the restriction of equipment and site. The pitch and roll rotation range is -45° to 45°, and
the yaw is -180° to 180°. Due to the constraints of the rotational position, the rotational path needs to be redesigned for calibration.

This paper mainly studies the calibration of accelerometer bias and scale factor. The rest of the paper is organized as follows: section 2 conducts theoretical analysis based on inertial navigation error equation and proves the identification of accelerometer bias and scale factor; section 3 conducts simulations to verify the theoretical analysis and section 4 makes a conclusion of this paper.

2. Theoretical analysis

Ignoring the gravity error, the velocity error model of IMU can be written as follows[11-12]:

$$\delta \vec{V}^n = \vec{f}^{x} \times \vec{\phi} + C_{n}^{e} \delta \vec{f}^{b} - \left( 2 \vec{\omega}_{e}^{n} + \vec{\omega}_{n}^{b} \right) \times \delta \vec{V}^{n} - \left( 2 \delta \vec{\omega}^{e}_{e} + \delta \vec{\omega}^{n}_{n} \right) \times \vec{V}^{n}$$ (1)

Where $\vec{V}^{n}$ is the velocity of IMU; $\vec{\phi}$ is the attitude error of IMU; $\vec{f}^{x}$ and $\vec{f}^{b}$ are the specific force in the navigation frame ($n$-frame) and body frame ($b$-frame) respectively; $C_{n}^{e}$ is the direction cosine matrix from $b$-frame to $n$-frame; $\vec{\omega}_{e}^{n}$ is the angular velocity of the earth rotation in $n$-frame; $\vec{\omega}_{n}^{b}$ is the angular velocity of $n$-frame with respect to Earth-centric fixed frame ($e$-frame); $\delta \vec{\omega}^{e}_{e}$ and $\delta \vec{\omega}^{n}_{n}$ are the differential of $\vec{\omega}^{e}_{e}$ and $\vec{\omega}^{n}_{n}$ respectively.

The accelerometer errors include accelerometer bias and scale factor error, so accelerometer errors can be written as follows:

$$\delta \vec{f}^{b} = \delta \vec{f}^{b} (\vec{V}^{b}) + \delta \vec{f}^{b} \left( \vec{\omega}^{e}_{e} \right) = \vec{V} + \begin{bmatrix} S_{ax} \\ S_{ay} \\ S_{az} \end{bmatrix} + \begin{bmatrix} f_{bx} \\ f_{by} \\ f_{bz} \end{bmatrix}$$ (2)

Where $\delta \vec{f}^{b} (\vec{V}^{b})$ is accelerometer bias; $\delta \vec{f}^{b} \left( \vec{\omega}^{e}_{e} \right)$ is accelerometer scale factor error. $\vec{\omega}_{e}^{n}$, $\vec{\omega}_{n}^{b}$, $\delta \vec{\omega}^{e}_{e}$ and $\delta \vec{\omega}^{n}_{n}$ can be expressed as follows:

$$\vec{\omega}_{e}^{b} = \begin{bmatrix} 0 & \omega_{e} \cos L & \omega_{e} \sin L \end{bmatrix}^{T}$$ (3)

$$\vec{\omega}_{n}^{b} = \begin{bmatrix} -V_{n} \\ V_{E} \\ V_{E} - R_{E} \sin L \end{bmatrix}$$ (4)

$$\delta \vec{\omega}^{e}_{e} = \begin{bmatrix} 0 & -\omega_{e} \sin L \delta L \\ 0 & \omega_{e} \cos L \delta L \end{bmatrix}$$ (5)

$$\delta \vec{\omega}^{n}_{n} = \begin{bmatrix} 0 & \frac{V_{N}}{R_{E} + h} \\ 0 & -\frac{V_{E}}{R_{E} + h} \\ 0 & \frac{V_{E} \sec^{2}L}{R_{E} + h} - \frac{V_{E} \tan L}{R_{E} + h} \end{bmatrix}$$ (6)

Substituting equations (2)-(6) into equation (1), we can obtain:
\[
\begin{bmatrix}
\partial V_E \\
\partial V_N \\
\partial V_U \\
\end{bmatrix} = \begin{bmatrix}
0 & 2(V_L \omega_x \cos L + V_N \omega_y \sin L) + \frac{V_V V_N}{(R_E + h)^2} L - \frac{V_V V_N}{(R_E + h)^2} \\
0 & -2V_L \omega_x \cos L - \frac{V_V^2}{(R_E + h)^2} L - \frac{V_V}{(R_E + h)^2} \\
0 & -2V_L \omega_x \sin L - \frac{V_V^2}{(R_E + h)^2} L - \frac{V_V}{(R_E + h)^2} \\
\end{bmatrix}
\]

During the calibration, the time of rotation is short. Ignoring the variety of velocity and position, we can obtain:

\[
\begin{bmatrix}
\partial V_E \\
\partial V_N \\
\partial V_U \\
\end{bmatrix} = \begin{bmatrix}
0 & -f_U & f_N \\
-f_N & 0 & f_E \\
-f_E & 0 & 0 \\
\end{bmatrix} \begin{bmatrix}
\varphi_E \\
\varphi_N \\
\varphi_U \\
\end{bmatrix} + \begin{bmatrix}
S_{ax} \\
S_{ay} \\
S_{az} \\
\end{bmatrix} \begin{bmatrix}
f^b_E \\
f^b_N \\
f^b_U \\
\end{bmatrix} + \begin{bmatrix}
S_{ax} \\
S_{ay} \\
S_{az} \\
\end{bmatrix} \begin{bmatrix}
f^b (0) \\
f^b (0) \\
f^b (0) \\
\end{bmatrix} + \delta \hat{\delta}^n \\
\]

(8)

Where \( \delta \hat{\delta}^n = C_b \delta \hat{\delta}^n \) is the error of accelerometer output in n-frame.

The difference between the differential of velocity error before and after rotation can be expressed as follows[13]:

\[
\begin{aligned}
\partial V_E (T) - \partial V_E (0) &= -g \Delta \varphi_e + \Delta \delta f_e \\
\partial V_N (T) - \partial V_N (0) &= g \Delta \varphi_e + \Delta \delta f_e \\
\partial V_U (T) - \partial V_U (0) &= \Delta \delta f_u \\
\end{aligned}
\]

(9)

Where \( \partial V_E (T) , \partial V_N (T) \) and \( \partial V_U (T) \) are the east, north and vertical components of \( \partial \hat{\delta}^n \) after rotation; \( \partial V_E (0) , \partial V_N (0) \) and \( \partial V_U (0) \) are the east, north and vertical components of \( \partial \hat{\delta}^n \) before rotation; \( \Delta \hat{\phi} \) and \( \Delta \delta \hat{\delta}^n \) are the variety of \( \hat{\phi} \) and \( \delta \hat{\delta}^n \); \( \Delta \varphi_e \) and \( \Delta \varphi_u \) are the east and north components of \( \Delta \hat{\phi} \); \( \delta f_e \) and \( \delta f_u \) are the east and north components of \( \delta \hat{\delta}^n \); \( \Delta \delta f_u \) and \( \Delta \delta f_u \) are the east, north and vertical components of \( \Delta \delta \hat{\delta}^n \). In the case where the error of the gyro only includes bias, three components of \( \Delta \hat{\phi} \) are zero. \( \Delta \delta \hat{\delta}^n \) can be expressed as follows:

\[
\Delta \delta \hat{\delta}^n = C_b (T) \begin{bmatrix}
\begin{bmatrix} V_x^b \\ S_{ax} \end{bmatrix} + S_{ay} \begin{bmatrix} f^b_E (T) \\ S_{ax} \end{bmatrix} - C_b (0) \begin{bmatrix} V_x^b \\ S_{ay} \end{bmatrix} + S_{ay} \begin{bmatrix} f^b (0) \\ S_{ay} \end{bmatrix} \\
\begin{bmatrix} V_y^b \\ S_{ax} \end{bmatrix} + S_{ay} \begin{bmatrix} f^b_N (T) \\ S_{ay} \end{bmatrix} - C_b (0) \begin{bmatrix} V_y^b \\ S_{ay} \end{bmatrix} + S_{ay} \begin{bmatrix} f^b (0) \\ S_{ay} \end{bmatrix} \\
\begin{bmatrix} V_z^b \\ S_{ax} \end{bmatrix} + S_{ay} \begin{bmatrix} f^b_U (T) \\ S_{ay} \end{bmatrix} - C_b (0) \begin{bmatrix} V_z^b \\ S_{ay} \end{bmatrix} + S_{ay} \begin{bmatrix} f^b (0) \\ S_{ay} \end{bmatrix} \\
\end{bmatrix}
\end{bmatrix}
\]

(10)
Where $\tilde{f}^b(T)$ is the output of accelerometer after rotation; $\tilde{f}^b(0)$ is the output of accelerometer before rotation; $f^x_b(T)$, $f^y_b(T)$ and $f^z_b(T)$ are the x, y and z components of $\tilde{f}^b(T)$; $f^x_b(0)$, $f^y_b(0)$ and $f^z_b(0)$ are the x, y and z components of $\tilde{f}^b(0)$. During the calibration, velocity error can be obtained by Kalman filter. From equation (9), when three components of $\Delta \phi$ are zero, three components of $\Delta \delta f^b$ can be regarded as known parameters. So we can establish equation at the different rotational positions, and analyze the identification of the accelerometer bias and scale factor.

2.1. Rotating around pitch-axis

The pitch of IMU is $45^\circ$ at the initial moment and initial attitude is $[45^\circ, 0^\circ, 0^\circ]$. Then, IMU rotates around pitch-axis with $-45^\circ$ and the attitude becomes $[0^\circ, 0^\circ, 0^\circ]$. $C^w_o(T)$, $C^w_o(0)$, $\tilde{f}^b(T)$ and $\tilde{f}^b(0)$ can be expressed as follows:

\[
C^w_o(T) = \begin{bmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 1
\end{bmatrix}
\]  

(11)

\[
C^w_o(0) = \begin{bmatrix}
1 & 0 & 0 \\
0 & 1/\sqrt{2} & -1/\sqrt{2} \\
0 & 1/\sqrt{2} & 1/\sqrt{2}
\end{bmatrix}
\]  

(12)

\[
\tilde{f}^b(T) = \begin{bmatrix}
0 \\
0 \\
g
\end{bmatrix}
\]  

(13)

\[
\tilde{f}^b(0) = \begin{bmatrix}
0 \\
g/\sqrt{2} \\
g/\sqrt{2}
\end{bmatrix}
\]  

(14)

Substituting equations (11)-(14) into equation (10), we can obtain:

\[
\Delta \delta f^b = \begin{bmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 1
\end{bmatrix} \begin{bmatrix}
V^b_x \\
V^b_y \\
V^b_z + \left(S_{ac}g + V^b_z\right)
\end{bmatrix} = \begin{bmatrix}
1 & 0 & 0 \\
0 & 1/\sqrt{2} & -1/\sqrt{2} \\
0 & 1/\sqrt{2} & 1/\sqrt{2}
\end{bmatrix} \begin{bmatrix}
V^b_x \\
V^b_y \\
S_{ac}g/\sqrt{2} + V^b_z
\end{bmatrix}
\]  

(15)

$\Delta \delta f^b$ can be obtained from the Kalman filter. From equation (15), $V^b_z$ can be calculated. When the attitude is $[0^\circ, 0^\circ, 0^\circ]$, the error of the z-direction accelerometer is $S_{ac}g + V^b_z$, which can be obtained from the Kalman filter. So $S_{ac}$ can be calculated.

The pitch of IMU is $45^\circ$ at the initial moment and initial attitude is $[45^\circ, 0^\circ, 0^\circ]$. Then IMU rotates around pitch-axis with $-90^\circ$ and the attitude becomes $[-45^\circ, 0^\circ, 0^\circ]$. $C^w_o(T)$, $C^w_o(0)$, $\tilde{f}^c(T)$ and $\tilde{f}^c(0)$ can be expressed as follows:

\[
C^w_o(T) = \begin{bmatrix}
1 & 0 & 0 \\
0 & 1/\sqrt{2} & 1/\sqrt{2} \\
0 & -1/\sqrt{2} & 1/\sqrt{2}
\end{bmatrix}
\]  

(16)
\[
C_v^\alpha(0) = \begin{bmatrix}
1 & 0 & 0 \\
0 & 1/\sqrt{2} & -1/\sqrt{2} \\
0 & 1/\sqrt{2} & 1/\sqrt{2}
\end{bmatrix}
\] (17)

\[
\hat{f}_v^\alpha(T) = \begin{bmatrix}
0 \\
-\frac{g}{\sqrt{2}} \\
g/\sqrt{2}
\end{bmatrix}
\] (18)

\[
\hat{f}_v^\alpha(0) = \begin{bmatrix}
0 \\
g/\sqrt{2} \\
g/\sqrt{2}
\end{bmatrix}
\] (19)

Substituting equations (16)-(19) into equation (10), we can obtain:

\[
\Delta \delta f^\alpha = \begin{bmatrix}
1 & 0 & 0 \\
0 & 1/\sqrt{2} & 1/\sqrt{2} \\
0 & -1/\sqrt{2} & 1/\sqrt{2}
\end{bmatrix}
\begin{bmatrix}
\nu^\alpha_x \\
-\gamma_{m\alpha} g / [\sqrt{2} + \nu^\alpha_y] \\
\gamma_{m\alpha} g / [\sqrt{2} + \nu^\alpha_z]
\end{bmatrix}
\begin{bmatrix}
1 & 0 & 0 \\
0 & 1/\sqrt{2} & -1/\sqrt{2} \\
0 & 1/\sqrt{2} & 1/\sqrt{2}
\end{bmatrix}
\begin{bmatrix}
\nu^\alpha_x \\
\gamma_{m\alpha} g / [\sqrt{2} + \nu^\alpha_y] \\
\gamma_{m\alpha} g / [\sqrt{2} + \nu^\alpha_z]
\end{bmatrix}
\]
\[
= \begin{bmatrix}
0 \\
-\gamma_{m\alpha} g + (\gamma_{m\alpha} g + \sqrt{2} \nu^\alpha_z) \\
-\sqrt{2} \nu^\alpha_z
\end{bmatrix}
\] (20)

From equation (20), \( \nu^\alpha_x \) can be calculated. According to equation (15), if \( \nu^\alpha_y \) and \( \gamma_{m\alpha} \) are known, \( \gamma_{m\alpha} \) can be calculated. Therefore, when the IMU rotates around the pitch axis, as long as there are three different pitch positions, \( \nu^\alpha_y \), \( \nu^\alpha_z \), \( \gamma_{m\alpha} \) and \( \gamma_{m\alpha} \) can be calculated. In these cases, the bias and scale factor of the y-direction and z-direction accelerometers can be calibrated.

2.2. Rotating around roll-axis and yaw-axis

The identification of the bias and scale factor of the y-direction and z-direction accelerometer has been analyzed in Section 2.1. The rotational path is designed to calibrate the bias and scale factor of the x-direction accelerometer in this section.

The roll of IMU is 45° at the initial moment and initial attitude is [0°, 45°, 0°]. Then IMU rotates around yaw-axis with 90° and the attitude becomes [0°, 45°, 90°]. \( C_v^\alpha(T) \), \( C_v^\alpha(0) \), \( \hat{f}_v^\alpha(T) \) and \( \hat{f}_v^\alpha(0) \) can be expressed as follows:

\[
C_v^\alpha(T) = \begin{bmatrix}
0 & -1 & 0 \\
1/\sqrt{2} & 0 & -1/\sqrt{2} \\
1/\sqrt{2} & 0 & 1/\sqrt{2}
\end{bmatrix}
\] (21)

\[
C_v^\alpha(0) = \begin{bmatrix}
1/\sqrt{2} & 0 & 1/\sqrt{2} \\
0 & 1 & 0 \\
-1/\sqrt{2} & 0 & 1/\sqrt{2}
\end{bmatrix}
\] (22)

\[
\hat{f}_v^\alpha(T) = \begin{bmatrix}
0 \\
g/\sqrt{2} \\
g/\sqrt{2}
\end{bmatrix}
\] (23)
Substituting equations (21)-(24) into equation (10), we can obtain:

\[
\Delta \delta \hat{f}^b = \begin{bmatrix} 0 & -1 & 0 \\ 1/\sqrt{2} & 0 & -1/\sqrt{2} \\ 1/\sqrt{2} & 0 & 1/\sqrt{2} \end{bmatrix} \begin{bmatrix} \hat{V}^b_x \\ S_{aw} g / \sqrt{2} + \hat{V}^b_y \\ S_{aw} g / \sqrt{2} + \hat{V}^b_z \end{bmatrix} - \begin{bmatrix} 1/\sqrt{2} & 0 & 1/\sqrt{2} \\ 0 & 1 & 0 \\ -1/\sqrt{2} & 0 & 1/\sqrt{2} \end{bmatrix} \begin{bmatrix} -S_{aw} g / \sqrt{2} + \hat{V}^b_x \\ \hat{V}^b_y \\ S_{aw} g / \sqrt{2} + \hat{V}^b_z \end{bmatrix}
\]

\[
= \begin{bmatrix} S_{aw} g / 2 - S_{aw} g / \sqrt{2} - S_{aw} g / 2 - \hat{V}^b_y / \sqrt{2} - \hat{V}^b_z / \sqrt{2} \\ -S_{aw} g / 2 + \hat{V}^b_y / \sqrt{2} - \hat{V}^b_z / \sqrt{2} \\ -S_{aw} g / 2 \end{bmatrix}
\]

From equation (25), \( S_{aw} \) can be calculated. When \( \hat{V}^b_x \), \( \hat{V}^b_y \), \( S_{aw} \) and \( S_{aw} \) are known, \( \hat{V}^b_z \) can also be calculated.

### 3. Simulation

Section 2 conducts theoretical analysis and demonstrates the effect of the different rotational paths on accelerometer calibration. This section conducts simulation to verify the theoretical analysis. The accelerometer scale factor is set to 100 ppm and other specific parameters are set in Table 1:

| Error items | Bias instability | Random walk |
|-------------|------------------|-------------|
| IMU         | Gyros            | 0.003°/h    | 0.0005°/√s |
|             | Accelerometers   | 20 mGal     | 20 mGal/√s |

#### 3.1. Rotating around pitch-axis

It can be seen from section 2.1 that when IMU rotates around the pitch-axis, as long as there are three pitch positions, the bias and scale factor of the y-direction and z-direction accelerometers can be calibrated. This section conducts simulation to verify the theoretical result. The rotational path and the results of calibration are shown in Figures 1-3.
Figure 3. Accelerometer scale factor

It can be seen from Figures. 2-3 that the bias and scale factor of the x-direction and y-direction accelerometers are calibrated within 20 min, which is consistent with the theoretical analysis. The calibration error of the bias is less than 5 mGal, and the calibration error of the scale factor is less than 5 ppm.

3.2. Rotating around roll-axis and yaw-axis

As known in section 2.2, when the IMU rotates 45° around the roll axis and then rotates 90° around the yaw axis, the x-direction accelerometer scale factor can be calibrated. This section conducts simulation to verify the theoretical result. The rotational path and the results of calibration are shown in Figures. 4-6.

Figure 4. Attitude of IMU
Figure 5. Bias of accelerometers
Figure 6. Accelerometer scale factor

It can be seen from Figure. 6 that the x-direction accelerometer scale factor can be calibrated, which is consistent with the theoretical analysis. The calibration error of the x-direction accelerometer
scale factor is less than 5 ppm, while the calibration error of the x-direction accelerometer bias is large. The bias needs to be calibrated in conjunction with the rotational path in section 3.1.

3.3. Optimizing rotational path

In sections 3.1 and 3.2, we conduct simulations to verify previous theoretical analysis. In this section, we combine the calibration methods of sections 3.1 and 3.2 and optimize them to calibrate the accelerometers. The rotational path and the results of calibration are shown in Figures. 7-9.

![Figure 7. Attitude of IMU](image)

![Figure 8. Bias of accelerometers](image)

**Figure 7. Attitude of IMU**

**Figure 8. Bias of accelerometers**

![Figure 9. Accelerometer scale factor](image)

**Figure 9. Accelerometer scale factor**

It can be seen from Figures. 8-9 that the bias and scale factor of the accelerometers are calibrated within 20 min. The calibration error of the bias is less than 5 mGal, and the calibration error of the scale factor is less than 5 ppm. Therefore, the rotational path is effective.

4. Conclusion

This paper mainly studies the calibration of accelerometer bias and scale factor in the case that the rotation is limited. The analysis shows: when the IMU rotates around the pitch axis, as long as there are three different pitch positions, the bias and scale factor of the y-direction and z-direction accelerometers can be calibrated. When the IMU rotates 45° around the roll axis and then rotates 90° around the yaw axis, the x-direction accelerometer scale factor can be calibrated. Then, several simulations are conducted to verify the theoretical results. The simulation results agree well with theoretical results. At last, optimized rotational path is designed. And the rotational path is effective for calibration.

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