Review of Calibration Method of Strapdown Inertial Navigation System

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Abstract. Strapdown Inertial Navigation System (SINS) has been widely used in both civil and military fields, due to its low cost and flexibility. However, as a dead-reckoning method, SINS has an influential defect, which is the accumulation of error with time. In practice, the error can be significantly compensated by calibration. This paper focuses on calibration and aims to build the mathematical model of Inertial Measurement Unit (IMU). Through analyzing the two categories of calibration, this paper would note the new research direction in the future.

Introduction

In recent years, with the development of technology and the increase of requirements, inertial navigation has been widely used in both military and civil fields, because it is covert and less likely to be influenced by external conditions [1].

Comparing with the traditional Platform Inertial Navigational System, Strapdown Inertial Navigation System (SINS) has smaller size and weight, lower cost, higher reliability, and less problem in maintenance, so it has become a new research focus [2-4]. However, SINS is directly connected with the carrier, and it is considerably impacted by vibration. Therefore, its operation circumstance is adverse and may lead to loud signal noise. Moreover, as a dead-reckoning method, SINS has an inherent defect, which is the accumulation of error with time.

To ensure the high precision of navigation, it is significant to control the error with the support from both hardware and software [5]. In terms of hardware, the physical structure and techniques of traditional inertial device needs to be modified, and more advanced inertial sensor has to be developed. In light of software, the compensation of calibration can further increase the precision of inertial device in actual operation.

The Definition of Calibration

The theoretical base of calibration is system identification, whose purpose is to determine the parameters of the mathematical model for inertial instruments and inertial navigation system. After calibration, the output of inertial instruments can be compensated and the precision of SINS will be notably increased [6].

To summarize, calibration mainly refers to the following steps:

1) Build a mathematical model for the inertial instruments and ensure that the model is adapted to the application environment.
2) Provide a precise input into inertial instruments.
3) Record the output of inertial instruments.
4) Build the transfer function of inertial instruments and the correlation between input and output.
Mathematical Model of IMU

Inertial measurement unit (IMU) composes of three gyroscopes and three accelerometers. In this case, only the zero-order and first-order parameters of the IMU are considered. These parameters include zero offset, scale factor and installing-error angle.

The input-output model of gyroscopes can be written in following form:

\[
\begin{bmatrix}
N^g_x \\
N^g_y \\
N^g_z
\end{bmatrix} =
\begin{bmatrix}
S^g_x & 0 & 0 \\
0 & S^g_y & 0 \\
0 & 0 & S^g_z
\end{bmatrix}
\begin{bmatrix}
x^g \cdot x^b \\
y^g \cdot y^b \\
z^g \cdot z^b
\end{bmatrix}
\begin{bmatrix}
x^g \\
y^g \\
z^g
\end{bmatrix}
\begin{bmatrix}
x^b \\
y^b \\
z^b
\end{bmatrix}
+ \begin{bmatrix}
b^g_x \\
b^g_y \\
b^g_z
\end{bmatrix}
+ \begin{bmatrix}
\varepsilon^g_x \\
\varepsilon^g_y \\
\varepsilon^g_z
\end{bmatrix}
\]

(3.1)

Here, \( N^g \) is the pulse output of gyroscope per unit time, and \( S^g \) is the scale factor of the J-axis gyroscope. Matrix \( \begin{bmatrix}
x^g \cdot x^b & x^g \cdot y^b & x^g \cdot z^b \\
y^g \cdot x^b & y^g \cdot y^b & y^g \cdot z^b \\
z^g \cdot x^b & z^g \cdot y^b & z^g \cdot z^b
\end{bmatrix} \) stands for the installation relationship, and \( \omega^b \) is the input angular velocity. \( b^g \) refers to zero offset, and \( \varepsilon^g \) is the measurement noise of gyroscopes.

Similarly, the input-output model of accelerometers is:

\[
\begin{bmatrix}
N^a_x \\
N^a_y \\
N^a_z
\end{bmatrix} =
\begin{bmatrix}
S^a_x & 0 & 0 \\
0 & S^a_y & 0 \\
0 & 0 & S^a_z
\end{bmatrix}
\begin{bmatrix}
x^a \cdot x^b \\
y^a \cdot y^b \\
z^a \cdot z^b
\end{bmatrix}
\begin{bmatrix}
x^a \\
y^a \\
z^a
\end{bmatrix}
\begin{bmatrix}
x^b \\
y^b \\
z^b
\end{bmatrix}
+ \begin{bmatrix}
b^a_x \\
b^a_y \\
b^a_z
\end{bmatrix}
+ \begin{bmatrix}
\varepsilon^a_x \\
\varepsilon^a_y \\
\varepsilon^a_z
\end{bmatrix}
\]

(3.2)

In this model, \( N^a \) is the pulse output of accelerometers per unit time, and \( S^a \) is the scale factor of the J-axis accelerometers. Matrix \( \begin{bmatrix}
x^a \cdot x^b & x^a \cdot y^b & x^a \cdot z^b \\
y^a \cdot x^b & y^a \cdot y^b & y^a \cdot z^b \\
z^a \cdot x^b & z^a \cdot y^b & z^a \cdot z^b
\end{bmatrix} \) stands for the installation relationship, and \( f^b \) is the specific force. \( b^a \) refers to zero offset, and \( \varepsilon^a \) is the measurement noise of accelerometers.

The Categories of Calibration

Calibration methods have different categories according to various standard. Currently, there are two categories of methods to calibrate the inertial instruments [7,8]:

The Classic Method

Firstly, build the mathematical model based on the characteristics of inertial devices. Secondly, receive the input for reference through double-axis or triple-axis turntable. This method includes comparing the output of gyroscopes with earth rotation rate (or the sum of earth rotation rate and turntable rotation rate), and comparing the output of accelerometers with the local gravity. It poses different attitudes relative to earth axis (or gravity direction), normally using least square method to calculate the error of parameters. Since this method is simple, it is widely adopted in practice [9,10].

Filtering Method

Filtering method replaces turntable with digital platform of SINS to obtain the reference angle, and use the results of navigation solution to process data and to identify error by Filter. The filtering method decrease the requirements of turntable accuracy. It allows the turntable with lower precision to produce ideal results. Filtering method is suitable for systems with high precision, while its drawback is the complexity in calculation. Also, it is difficult to receive the analytical solution of Kalman filter algorithm, which is commonly used in filtering method. Those two defects restrict the application of this method in practice [11-13].
Conclusion

In conclusion, the techniques to enhance the accuracy of SINS calibration methods are evolved in both hardware and software. The development of hardware is based on the industrial technology, so it needs extensive investment and long development cycle. While the improvement of calibration method through software is more flexible and effective than through hardware [14-17].

There are three general trends in the development of calibration [18-22]:

1). Calibration will evolve into high precision, relying on the enhancement of technology in hardware and software.

2). When the requirement of accuracy is satisfied, it also leads to effective calibration by improving algorithms and procedures. To adapt to the fast-paced modern warfare, new calibration methods tend to simplify data processing, increase response speed, reduce time consumption, and meet the demands of operation environment.

3). Most calibration methods adopt linear processing techniques, thus the focus of future researches may turn to the non-linear techniques, and to choosing proper filtering methods to improve the accuracy and efficiency of calibration.

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