A Survey of Error Analysis and Calibration Methods for MEMS Triaxial Accelerometers

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Abstract: MEMS accelerometers are widely used in various fields due to their small size and low cost, and have good application prospects. However, the low accuracy limits its range of applications. To ensure data accuracy and safety we need to calibrate MEMS accelerometers. Many authors have improved accelerometer accuracy by calculating calibration parameters, and a large number of published calibration methods have been confusing. In this context, this paper introduces these techniques and methods, analyzes and summarizes the main error models and calibration procedures, and provides useful suggestions. Finally, the content of the accelerometer calibration method needs to be overcome.

Keywords: MEMS, accelerometer, calibration, error analysis, accelerometer calibration.

1 Introduction

Compared with traditional sensors, MEMS-based (Microelectromechanical systems) sensors have the advantages of smaller size, lower cost, lower power consumption, etc., and are widely used in various fields such as smart mobile devices, computers, smart home management, robots, automobiles, and medical fields, therefore depicting good application prospects [Liu, Chen, Zhou et al. (2007); Liu and Liu (2018)].

Micro-acceleration sensors have been a hot research topic as an important branch of MEMS sensors. The so-called acceleration sensor refers to the use of sensitive mass inertial force or other means to sense the carrier's mechanical motion information and convert it into electrical quantity for measurement, which is the collective name of this type of inertial sensor [Dong, He and Guan (2014)]. Accelerometer readings can be directly used in biomechanics as well as in medical fields, especially motion recognition [Godfrey, Conway, Meagher et al. (2008)], attitude analysis. A

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typical application is to analyze the daily activities of the human body and apply it to the patient's adjuvant therapy. Sun used FES treatment equipment with MEMS accelerometer to rehabilitate stroke patients [Sun (2014)]. Accelerometers are often combined with gyroscopes to form an inertial measurement unit (IMU). The IMU has important application value in the navigation field and can be used to determine attitude and heading [Alandry, Latorre, Mailly et al. (2011)]. It can also be used to estimate the direction of the human body or its specific parts, including fall detection for the safety of the elderly, body movement and posture-oriented movement and analysis [Ahmed and Tahir (2017)]. In engineering applications, the use of MEMS-based accelerometers is well established. Some of these applications include vehicle condition monitoring, seismic wave detection, and condition monitoring of plant machinery. MEMS accelerometer can also be used in mobile devices and photographic devices. It can be used for screen orientation detection and image shake prevention. The accelerometer installed in the device will detect the shake of the device when capturing the image, which facilitates the post-processing of the image by the processor. Unlike engineering applications, medical and clinical applications of accelerometers are at an emerging stage. Wearable MEMS accelerometers can be used to detect physical activity and state of the person, which contributes to the development of preventive medicine [Roy, Mandal and Hanumaiah (2016)].

However, the accuracy of MEMS accelerometers is at a low level among similar sensors. Due to the wider application range of MEMS, in some special fields with high safety requirements, such as medical, military, and aerospace, these fields need to be highly Accurate sensor data has limited the use of MEMS sensors. With the increasing application of accelerometers, researchers have become more and more in-depth research on MEMS. How to improve the accuracy of MEMS accelerometers has become a hot topic and technical difficulty. Due to the fabrication and installation of the MEMS, the accelerometer has errors caused by non-orthogonal coordinate axis, zero offset and scale factor, which will further reduce the accuracy of the accelerometer. In order to ensure the accuracy of the sensor data and improve the use of the accelerometer, we need to calibrate the accelerometer. In addition, in addition to the error of the acceleration sensor itself, there are errors caused by measurement and inaccurate selection of the calibration algorithm model.

At present, accelerometer calibration methods are mainly divided into two categories, the difference is whether the accelerometer calibration depends on external precision calibration equipment. The first method achieves the calibration goal mainly by rotating on the turntable, centrifuge and other equipment or putting them in multiple positions. However, this method is economically expensive and difficult to implement. It is only suitable for calibration in the laboratory and is not suitable for various fields. Therefore, it is necessary to explore an error calibration and compensation method of an acceleration sensor that is simple and easy to implement. In recent years, researchers have proposed a variety of calibration and compensation methods. Choosing the right accelerometer calibration method may be confusing. This paper aims to introduce these techniques and methods and compare their advantages and limitations.

The paper is organized as follows: Section II describes the acceleration calibration model, include the error analysis of the MEMS accelerometer and the parameter calibration model. Section III describes the error calibration method of the MEMS accelerometer. A summary is drawn in Section IV.

2 Accelerometer calibration model

There are three main sources of error in the application of MEMS accelerometer in various fields. The first is the system-level error, which is mainly caused by the approximation of the mathematical model. Because the mathematical model is not always perfect and reliable, in the process of calculation, it will cause errors in mathematical calculation of data. The second is the algorithm error, which is mainly the deviation caused by the data trade-off problem during the calibration process or during the use of the accelerometer data process (such as attitude solution). The third is the device error, also known as fixed error, which is mainly caused by the limited level of manufacturing technology. Fixed error mainly includes zero offset, non-orthogonality between proportional coefficient and axis. At the same time, in the process of using and installing sensors, the position offset will also form an error [Vaubhav, Rana and Kuber (2010); Petkov and Slavov (2010)].

As researchers continue to delve into the research, the errors caused by mathematical models and algorithms have been reduced a lot. Due to the small size of the MEMS, the accuracy is much smaller than some large-volume sensors. Therefore, the fixed error has a greater impact on the MEMS accelerometer with its own low accuracy. This section mainly analyzes and studies the errors of MEMS acceleration and calibration models.

2.1 MEMS accelerometer error analysis

It can be seen from the above that in the process of manufacturing and using MEMS accelerometer, various errors will inevitably occur, and the external environment (such as temperature) will also have a large impact. The fixed errors of MEMS accelerometers are as follows:

Zero Offset Error. The zero offset error means that when the MEMS accelerometer is at zero input, the output is not zero. As shown in Fig. 1. This is due to the precision of the process, and each unit is unique, their zero offset error is different, resulting in zero offset error is individual [Gao, Zhao and Zhang (2006)]. MEMS accelerometers are also affected by external environmental factors, which can be divided into random offsets and deterministic offsets. The most obvious is the temperature factor. When we calibrate the error, we need to separately model it and compensate for temperature drift.

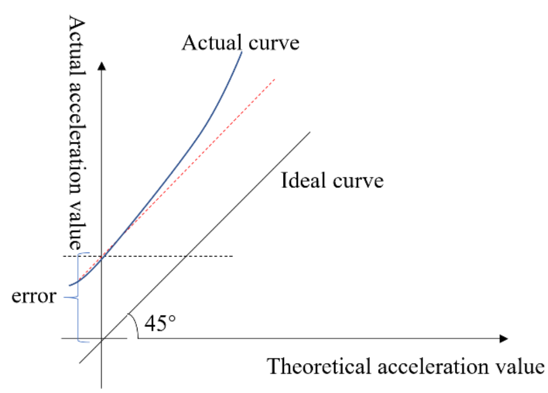

Figure 1: Zero offset error and the difference between an ideal curve and an actual curve

Scale Factor Error. The value output by the MEMS accelerometer is not a normal direct measurement value, and it needs to be numerically calculated with a scale factor to output the true value. This factor is called the scale factor. In field applications, the scale factor of the MEMS accelerometer is somewhat different from the parameters in the data sheet provided by the manufacturer, resulting in an error in the measurement of the acceleration. This error is called the scale factor error. That is, the scale factor of the accelerometer is the slope of the line drawn by its output data. In theory, the input-output proportional factor of linear accelerometer should be equal to 1, but in fact, the proportional factor will be affected by temperature, signal circuit, jitter and other reasons, resulting in the input-output proportional factor is not equal to 1, and the three axes of the MEMS accelerometer have different scaling factors. Assuming that the real scale factor of accelerometer is f_1 and the actual scale factor of accelerometer is f, there are the following formulas:

$$f = (1 + K_a) \cdot f_1 \tag{1}$$

In the formula, $K_a = [K_{ax} \quad K_{ay} \quad K_{az}]$, It is the scale factor error matrix of the MEMS accelerometer.

Among the error factors of MEMS accelerometers, scale factor errors account for a large proportion. Therefore, in the process of subsequent data calibration, we need to calculate the correct scale factor using the corresponding algorithm and accurately plot its slope map.

Triaxial Non-orthogonal Error. Because the orientation of the acceleration installation does not coincide with the coordinate system of the carrier, there exists a deviation angle between the measurement axis of the accelerometer and the coordinate system of the carrier, as shown in Fig. 2. This deviation angle results in that the coordinate system of the three-axis acceleration is not completely orthogonal. According to the related non-orthogonal transformation matrix theory, we need to calculate the calibration matrix according to the matrix model, and then calibrate the non-orthogonal error.

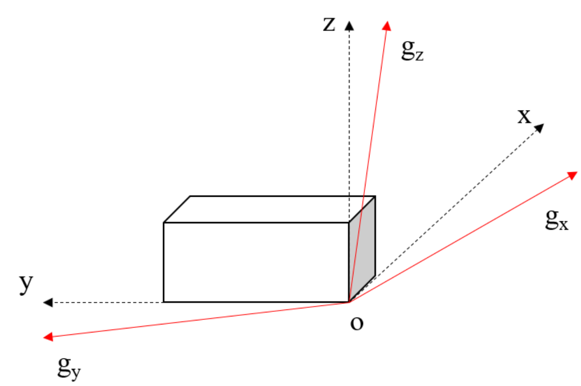

Figure 2: Triaxial non-orthogonal. The direction of acceleration installation does not coincide with the coordinate system of the carrier

As can be seen from Fig. 2, each axis of the MEMS accelerometer will have different deflection angles in the process of installation and use. The coordinate system installed does not coincide with the carrier coordinate system and does not form an orthogonal relationship. In order to calibrate the triaxial non-orthogonal error, we need to construct the installation error matrix and then perform mathematical modeling analysis. We first select an axis as a fixed axis, assuming that the fixed axis is in the desired position. Then the surface formed by the other two axes is rotated about the fixed axis, and the yaw angle can be measured. Similarly, the yaw angles of the other two fixed axes are measured.

We use *oxyz* in Fig. 2 as the standard coordinate system and $og_xg_yg_z$ as the non-orthogonal coordinate system of the actual accelerometer. We use the x, y, and z axes as the fixed axes, and the matrix uses the Euler angle method to obtain the following transformation matrix:

$$\omega_a = f(x) \cdot f(y) \cdot f(z) \tag{2}$$

expand Eq. (2) to get:

$$\omega_a = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & -\omega_{zx} \\ 0 & \omega_{yx} & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & \omega_{zy} \\ 0 & 1 & 0 \\ -\omega_{xy} & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & -\omega_{yz} & 0 \\ \omega_{xz} & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{3}$$

Finally, the installation error matrix of the MEMS accelerometer is obtained:

$$\omega_a = \begin{bmatrix} 1 & \omega_{xz} & -\omega_{xy} \\ -\omega_{yz} & 1 & \omega_{yx} \\ \omega_{zy} & -\omega_{zx} & 1 \end{bmatrix} \tag{4}$$

2.2 Parameter calibration model

Ideally, MEMS accelerometers must have the same sensitivity over their specified amplitude range, so when the external environment (such as temperature) is stable, the output model can be expressed as linearly related [Nez, Fradet, Laguillaumie et al. (2016)], and the measurement model is as follows:

$$a = k \cdot (a_m - d) \tag{5}$$

where *a* represents the actual acceleration value, *k* is the scale factor, a_{mx} is the acceleration value measured by the MEMS accelerometer, and *d* is the offset. The model of the MEMS triaxial accelerometer can be represented by a matrix:

$$\begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} = \begin{bmatrix} k_x & 0 & 0 \\ 0 & k_y & 0 \\ 0 & 0 & k_z \end{bmatrix} \cdot \left\{ \begin{bmatrix} a_{mx} \\ a_{my} \\ a_{mz} \end{bmatrix} - \begin{bmatrix} d_x \\ d_y \\ d_z \end{bmatrix} \right\} \tag{6}$$

The model contains six calibration parameters and the calculation is very simple. However, the model is based on the complete orthogonal assumption of the three axes of the accelerometer. From the above error analysis, it can be concluded that this model has certain drawbacks and cannot achieve a good calibration accuracy.

Since the acceleration installation direction does not coincide with the carrier's coordinate system, there are three-axis non-orthogonal errors, and many authors compensate the error between the accelerometer mounting axis and the orthogonal coordinate system by a matrix O [Syed, Aggarwal, Goodall et al. (2007)]. Make the model also need to multiply a compensation parameter:

$$O = \begin{bmatrix} 1 & 0 & 0 \\ -\beta_{yx} & 1 & 0 \\ \beta_{zx} & -\beta_{zy} & 1 \end{bmatrix} \tag{7}$$

Compared with the simple model above, this model has three more angle compensation parameters, but the model also has certain drawbacks. It is based on the fact that the one-dimensional accelerometer is only sensitive to the acceleration along the axis. Therefore, this model is not fully applicable to MEMS accelerometers, so we need to consider the sensitivity of the cross-axis when building the model.

Compared with the simple model above, this model adds three angle compensation parameters, but the model also has certain drawbacks. It is based on the fact that the one-dimensional accelerometer is only sensitive to the acceleration along the axis. Therefore, this model is not fully applicable to MEMS accelerometers, so we need to consider the sensitivity of the cross-axis when building the model. Through the error analysis above, we have derived the non-orthogonal error matrix of the MEMS accelerometer, so the final accelerometer parameter calibration model is:

$$\begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} = \begin{bmatrix} 1 & \omega_{xz} & -\omega_{xy} \\ -\omega_{yz} & 1 & \omega_{yx} \\ \omega_{zy} & -\omega_{zx} & 1 \end{bmatrix} \cdot \begin{bmatrix} k_x & 0 & 0 \\ 0 & k_y & 0 \\ 0 & 0 & k_z \end{bmatrix} \cdot \left\{ \begin{bmatrix} a_{mx} \\ a_{my} \\ a_{mz} \end{bmatrix} - \begin{bmatrix} d_x \\ d_y \\ d_z \end{bmatrix} \right\} \tag{8}$$

Table 1: Definition of the related parameters

Parameters	Explanation
a-frame	The non-orthogonal frame denoted by the accelerometers' sensitivity axes
b-frame	The orthogonal reference frame related to triaxial accelerometers
$a_{0,i}$	The non-orthogonal transformation from b-frame to a-frame
ka,i	The scale factor of the i-axis accelerometer
λ	The misalignments of triaxial accelerometers
T_b^a	The non-orthogonal transformation from b-frame to a-frame
f^b	The representation of the specific force in b-frame
$f^{2,b}$	The squared representation of the specific force in b-frame
$v_{a,i}$	The measurement noise of the i-axis accelerometer

For the above models, all are linear models. Since MEMS accelerometers are also affected by white noise and temperature drift, linear models are not always suitable for various application environments. The researchers also proposed nonlinear models with square coefficients [Wei, Khosla and Riviere (2007); Yang, Wu, Wu et al. (2012)]:

$$A = k_a T_b^a f^b + a_0 + k_2 f^{2,b} + v_a \tag{9}$$

and some related parameters definitions are listed in Tab. 1, the corresponding parameters in Eq. (9) take the following forms:

$$A = \begin{bmatrix} A_x \\ A_y \\ A_z \end{bmatrix}, k_a = \begin{bmatrix} k_{a,x} & 0 & 0 \\ 0 & k_{a,y} & 0 \\ 0 & 0 & k_{a,z} \end{bmatrix}, T_b^a = \begin{bmatrix} 1 & 0 & 0 \\ \lambda_{yx} & \lambda_{yy} & 0 \\ \lambda_{zx} & \lambda_{zy} & \lambda_{zz} \end{bmatrix} \tag{10}$$

$$f^b = \begin{bmatrix} f_x^b \\ f_y^b \\ f_z^b \end{bmatrix}, a_{0=} \begin{bmatrix} a_{0.x} \\ a_{0,y} \\ a_{0,z} \end{bmatrix}, v_a = \begin{bmatrix} v_{0.x} \\ v_{0,y} \\ v_{0,z} \end{bmatrix} \tag{11}$$

where $f^{2,b} = \left[(f_x^b)^2 \quad (f_y^b)^2 \quad (f_z^b)^2 \right]^T$, $k_2 = diag([k_{2,x} \quad k_{2,y} \quad k_{2,z}])$.

Above, we introduce the parameter calibration model of the MEMS accelerometer, including the commonly used linear model and the less used non-linear model. Next, we will introduce calibration methods for these models.

3 Error calibration method for MEMS accelerometer

At present, accelerometer calibration methods are mainly divided into two categories. One is precise calibration using high-precision external equipment (such as turntable [Zhang, Wu, Wu et al. (2010)]). It can calibrate installation error, mainly proportional factor and zero offset. This method is only applicable to laboratory calibration. Another method is to use the collected acceleration data and use different algorithms to process the data.

Lötters et al. [Lötters, Schipper, Veltink et al. (1998)] proposed the original idea of performing an accelerometer calibration in use. This type of method is based on a theorem that the acceleration modulus in all directions is always equal to the local gravitational acceleration:

$$a_x + a_y + a_z = G^2 \tag{12}$$

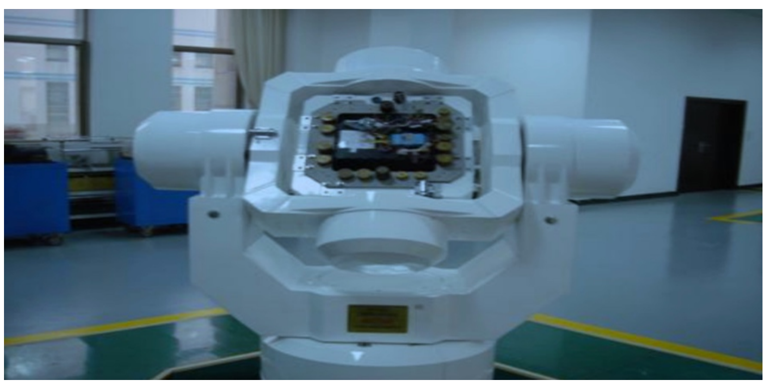

Figure 3: Calibration turntable (from Zhang et al. [Zhang, Wu, Wu et al. (2010)])

The most classic algorithm is the 6-position method. This method ensures that the coordinate system of the accelerometer coincides with the carrier coordinate system by means of high-precision equipment, and then performs vertical up and down tests along the coordinate axis of the accelerometer, as shown in Fig. 4. A total of 6 positions, so called the 6-position method.

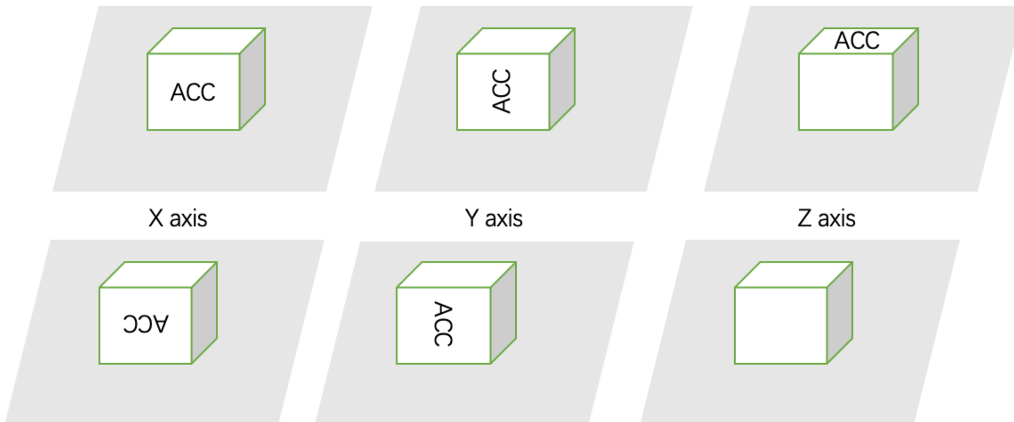

Figure 4: 6-position method (from Lötters et al. [Lötters, Schipper, Veltink et al. (1998)])

After collecting 6 real values, we use the least square error to determine the calibration parameters:

$$\underset{6\times 1}{\begin{bmatrix}\varepsilon_1\\ \vdots\\ \varepsilon_6\end{bmatrix}}=\underset{6\times 3}{\begin{bmatrix}a_{x1} & a_{y1} & a_{z1}\\ \vdots & \vdots & \vdots\\ a_{x6} & a_{y6} & a_6\end{bmatrix}}\underset{3\times 1}{\begin{bmatrix}k_x\\ k_y\\ k_z\end{bmatrix}}-\underset{6\times 1}{\begin{bmatrix}g^2\\ \vdots\\ g^2\end{bmatrix}} \tag{13}$$

where a is the measured value of each axis of the accelerometer, and k is the error calibration parameter, and the error is:

$$\varepsilon_{sum}=\sum_{i=1}^{6}\varepsilon_i \tag{14}$$

This method is simple to operate, but requires high precision, high cost and time consuming. From the perspective of adaptability, it is only suitable for calibration in the laboratory and cannot be applied to various fields. In response to this problem, some scholars have proposed the optimization of nine-position calibration algorithm. Based on the traditional six-position calibration algorithm of accelerometer, the non-linear error of accelerometer and the crosstalk effect caused by non-orthogonality between axes are considered. Gauss-Newton non-linear optimization method is used to calculate the scale factor, zero offset and non-orthogonal error, and the accelerometer is calibrated and compensated [Liu, Li, Di et al. (2018)].

After considering accelerometer zero offset, proportional error, non-orthogonal error, installation error, and measurement noise, Lu et al. [Lu, Liu and He (2016)] proposed an accelerometer correction algorithm based on maximum likelihood estimation. On this basis, the error model is established, and then the acceleration correction problem is transformed into the maximum likelihood estimation problem of the calibration parameters. The iterative initial value is calculated using the conventional least squares method. Through numerical simulation and actual test verification, it can obtain higher accuracy of calibration parameter estimation, which can be used for offline calibration of MEMS accelerometer.

Next, in order to solve the limitations of matrix inversion in traditional methods, some scholars put forward the application of genetic algorithm and particle swarm optimization algorithm in the research of accelerometer calibration. However, particle swarm optimization (PSO) and genetic algorithm (GA) will be premature and fall into the trap in the later stage of accelerometer calibration optimization. Local optimal problems. Zhong et al. applied the adaptive covariance matrix evolution strategy (CMAES) algorithm to the rapid calibration of accelerometers, and the calibration accuracy was greatly improved [Zhong, Zhang and Du (2018)].

Table 2: Comparison of calibration methods

Calibration parameters	Local-level frame	Six-Position Static	Rate Test	the Newly Proposed Method
Bias	YES	YES	NO	YES
Scale Factor	YES	YES	NO	YES
Non-orthogonality	YES	NO	NO	YES

Sahebjameyan Jafari et al. [Jafari, Sahebjameyan, Moshiri et al. (2015)]. Use double Kalman filtering method to estimate the error parameters of MEMS acceleration. Predictive error minimization (PEM) is used to build the model randomly. At the same time, the influence of offset instability and random walk noise on the calibrated Kalman filter is modelled to reduce the offset estimation. Trapezoidal calibration curves are used to motivate different definite error parameters of accelerometer. The algorithm is complex and needs different filter parameters for different sensors.

Batista et al. [Batista, Silvestre, Oliveira et al. (2011)] proposed an offline accelerometer calibration that provides a biased dynamic filtering solution that derives a time-varying Kalman filter for online dynamic bias and gravity estimation. The deviation estimate, scale factor, cross-coupling factor and quadratic coefficient are calculated. Using the attitude relative measurement provided by the motion rate meter (MRT), this method does not require a priori knowledge of the gravity vector. Shin et al. proposed a new inertial navigation system calibration method. Since most of the current inertial navigation system calibration techniques require calibration equipment or complex calculation algorithms, these methods must ensure that the accelerometer axes are aligned with the local horizontal frame. The main advantage of this new calibration method is that it does not require any expensive auxiliary calibration equipment [Shin and El-Sheimy (2002)]. Deviations, scale factors and non-orthogonal parameters can be determined in a common adjustment using this method. Since the developed model is basically independent of the position of the accelerometer to be calibrated, the effect of field calibration can be achieved. Tab. 2 the new development method is compared to other calibration methods. Error parameter calibration is more accurate than common calibration methods such as the six-position static method.

4 Summary

With the rapid development of micro-motor technology, the application range of MEMS accelerometers is getting larger and larger. Scholars have tried different methods for error calibration and compensation of MEMS accelerometers. The proposed calibration and compensation methods are diverse for different application scenarios, sensor configurations, and operating environments. Starting from error analysis, several error models of MEMS accelerometer are introduced in this paper. The calibration method of MEMS accelerometer is summarized. Using precise external equipment can achieve the best accuracy, but due to equipment limitations, it is not convenient for calibration outside the laboratory. Most of the improved multi-position calibration methods do not need turntable, so the accuracy will be reduced, so the calibration needs robust algorithm. Researchers use different algorithms to correct the accelerometer, and the accuracy of accelerometer calibration has been greatly improved. MEMS accelerometer will be affected by many factors, and sometimes it will have obvious nonlinear characteristics. In addition, the interaction of environmental factors and dynamic changes will have different effects on accelerometers. It can be predicted that the calibration of accelerometers in complex environment has the characteristics of non-linearity and dynamic, which will be quite different from conventional calibration. How to calibrate the accelerometer in the complex environment is an important direction of the development of accelerometer calibration technology.

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