A Novel MEMS Accelerometer-Based Nine-Position Calibration Algorithm

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Abstract

For the problem of the non-linear error and the crosstalk effect caused by the non-orthogonal axis of each axis in the six-position calibration algorithm of the accelerometer, a novel nine-position calibration algorithm based on MEMS accelerometer is proposed. The algorithm take consideration of non-linear factor and the electronic crosstalk effect of the accelerometer, reducing the non-linearity of the accelerometer and improving the stability of the accelerometer. The improved algorithm is tested on the 902E-1 biaxial turntable using an accelerometer calibrated by a nine-position calibration algorithm. The results show that the nine-position calibration algorithm based on MEMS accelerometer effectively solves the accelerometer nonlinear problem, and reduces the influence of the electronic crosstalk effect on the accelerometer. The error accuracy of the accelerometer is reduced from 0.0548g to 0.0081g. The optimized six-position calibration algorithm is proved the feasibility and effectiveness..

Keywords

Accelerometer, Calibration algorithm, Six-position calibration, Error accuracyr.

1. Introduction

Micro-electro-mechanical system is a new field of science and technology based on microelectronics technology combined with precision machinery technology, including micro-mechanical, micro-sensors, micro-actuators and signal processing and control circuits, until the interface, communication and power, and so on [1].

The development of micro-electro-mechanical systems and micro-fabrication techniques has led to the development of micro-inertial devices and micro inertia measurement unit technologies, leading to the generation of new generation gyroscope and accelerometer [2]. Among them, the use of silicon material to produce micro inertial devices not only makes the traditional inertial devices achieve miniaturization, but also contributes to sensitive devices and processing circuits fully integrated in the silicon chip. Because of silicon micro-processing technology and integrated technology compatibility, the true sense of the mechanical and electrical integration is achieved [3].

The inertial sensor realized by silicon as the base material is called the silicon micromechanical inertial sensor. Compared with the traditional inertial instrument, the silicon micromechanical inertia instrument has the characteristics of small volume, light weight, low cost, good reliability, low power consumption, large measuring range, and intelligent, and so on [4]. At present, the micro-mechanical inertia sensor in the micro-mechanical accelerometer performance indicators can be comparable with the traditional.

2. Six-position Salibration Algorithm for MEMS Accelerometer

2.1 Accelerometer Six-position Sompensation Sodel

Due to the accuracy difference of the accelerometer caused by production and installation, the system error of the accelerometer is generated [5]. Through the detailed analysis and theoretical calculation of the system error of the accelerometer, the error model is established. The model establishment block diagram is shown in Fig.1.

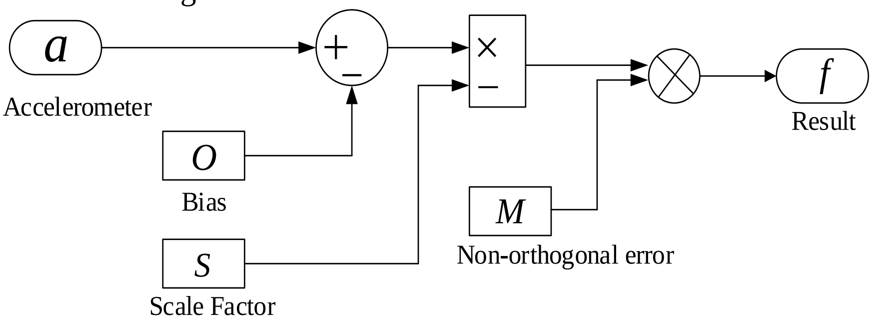


Fig.1 The six- position error model of MEMS inertial accelerometer

The PCB board error and manual error when the sensor are patched on the PCB board led the three axes of the sensor to be not sufficiently orthogonal in the three-dimensional space, which brings about systematic errors, called non-orthogonal errors. A bias is a fixed difference in the measured value from the theoretical value. Ideally, the scale factor is 1. However, because the integrated amplifier in the sensor is not completely symmetrical and the differences between the signal line on the PCB board cause inconsistency in the signal attenuation, scale factor from the system measures have a deviation from the theoretical value.

So the six-position compensation equation for the accelerometer is as follows:

$$\begin{bmatrix} A_x \\ A_y \\ A_z \end{bmatrix} = \begin{bmatrix} a_{x0} \\ a_{y0} \\ a_{z0} \end{bmatrix} + \begin{bmatrix} S_{ax} & K_{ax1} & K_{ax2} \\ K_{ay1} & S_{ay} & K_{ay2} \\ K_{az1} & K_{az2} & S_{az} \end{bmatrix} \cdot \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} + \begin{bmatrix} K_{ax3} & 0 & 0 \\ 0 & K_{ay3} & 0 \\ 0 & 0 & K_{az3} \end{bmatrix} \cdot \begin{bmatrix} a_x^2 \\ a_y^2 \\ a_z^2 \end{bmatrix} \tag{1}$$

where $A_x \sim A_z$ is the measured value of the accelerometer, whose unit is g; $a_{x0} \sim a_{z0}$ is the zero deviation of the accelerometer, whose unit is g; $S_{ax} \sim S_{az}$ is the accelerometer scale factor; $K_{ax1} \sim K_{az1}$ is the accelerometer installation error coefficient; $K_{ax2} \sim K_{az2}$ is the accelerometer installation error coefficient; $K_{ax3} \sim K_{az3}$ is the error factor of the accelerometer quadratic, whose unit is g^{-1}.

2.2 Accelerometer six-position calibration

According to the error model equation of the MEMS accelerometer, the six-position method is used to determine the error model coefficient of the acceleration sensor, so as to realize the compensation and calibration of the accelerometer error [6].

Table 1. The six-positions of each position of gravity acceleration

Position	Axis orientation			Gravitational acceleration/g		
	X axis	Y axis	Z axis	X axis	Y axis	Z axis
1	East	Heaven	South	0	-1	0
2	Western	Land	South	0	1	0
3	East	North	Heaven	0	0	-1
4	South	Western	Land	0	0	1
5	Land	East	South	1	0	0
6	Heaven	Western	South	-1	0	0

The six-position method according to the location shown in Tab.1, the sensor node stationary level is fixed on the dual-axis turntable, as shown in Fig.2. The static output data in six-positions of the three-axis accelerometer are measured respectively. According to Eq.1, the error coefficient of the three-axis accelerometer can be get. Then substituting it into the Eq.1, the corrected output data of three-axis acceleration is obtained. Whereas the six-position calibration model only considers the linear error of the three-axis accelerometer, without considering the non-linearity error and non-orthogonal crosstalk effects of the three-axis accelerometer in the tilt state,. Therefore, the nine-position calibration method is proposed for the above deficiencies.

Fig.2 The biaxial test turntable

3. Optimization of six-position error compensation model

3.1 Nine-position error compensation model

In the six-position error compensation model, the scale factor, zero bias, installation error coefficient and quadratic error of the three-axis accelerometer are calibrated. In the calculation process, the quadratic error factor is large and its general actual value is about 10^{-4}, so it can be ignored. When the three-axis accelerometer are calibrated in the six-position, only six orthogonal surfaces are calibrated without considering the non-linearity error and the crosstalk effect caused by non-orthogonal of the three-axis accelerometer in the tilted state. The nine-position error compensation model is shown in Fig.3.

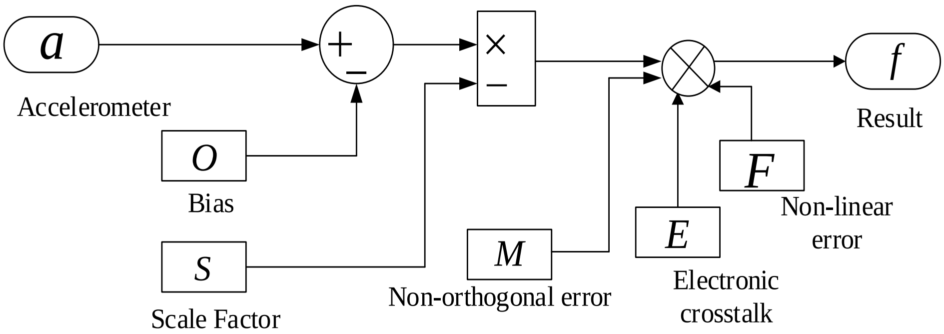


Fig.3 The nine-position error model of MEMS inertial accelerometer

In order to further optimize the accelerometer performance and improve the accuracy of accelerometer measurement, a nine-position error compensation model based on MEMS accelerometer is proposed. The nine-position error model expression is

$$= A = S(V - O) \tag{2}$$

where $V^T = \begin{bmatrix} v_x & v_y & v_z \end{bmatrix}$ represents the output data of the axes before the accelerometer is calibrated, whose unit is g; the accelerometer vector $A^T = \begin{bmatrix} A_x & A_y & A_z \end{bmatrix}$ is defined as the actual output of the accelerometer after the accelerometer calibration, whose unit is g, where

$$S=\begin{bmatrix} S_{xx} & S_{xy} & S_{xz} \\ S_{yx} & S_{yy} & S_{yz} \\ S_{zx} & S_{zy} & S_{zz} \end{bmatrix}, O=\begin{bmatrix} O_x \\ O_y \\ O_z \end{bmatrix} \tag{3}$$

where the matrices S and O represent scale factor and zero bias in the accelerometer. The diagonal elements of the matrices S represent the scale factors along the three axes. The other elements of the matrices S are called cross-axis factors, a description of the crosstalk effect caused by the non-orthogonal of the MEMS accelerometer [7-8]. In the ideal case, $S_{xy}=S_{yx}=S_{xz}=S_{zx}=S_{yz}=S_{zy}=0$. According to the chip data sheet, their error reaches 2% of the accelerometer measurement range in the actual situation, as reported in Tab.2.

3.2 Accelerometer nine-position calibration

Under the ideal static conditions, the modulus of accelerometer is equal to the gravitational acceleration g, that is

$$\sqrt{a_x^2+a_y^2+a_z^2}=g \tag{4}$$

In order to calculate the matrix S of nine independent parameters, the MEMS accelerometer is placed in nine different positions and remains stationary. The six- position has been described above, and the other three positions, listed as east-north-day, west-land-south and heaven–west-south, respectively, are obliquely fixed on the turntable with a certain angle, as show in Fig.4

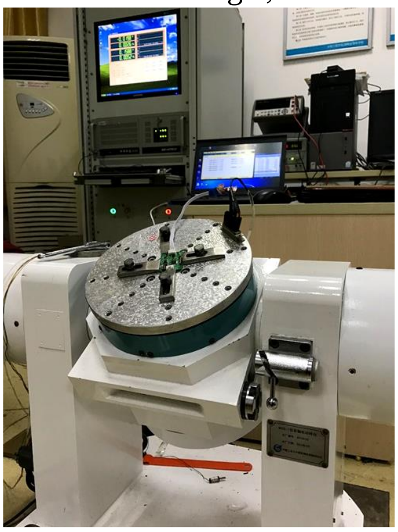


Fig.4 The data acquisition from accelerometer in tilt state

In this paper, Defining the square error of the MEMS accelerometer as e_k^2, which is the difference between the sum of the squares of the actual output of the accelerometer and the square of the earth's gravity acceleration at k-th , as follows:

$$\begin{aligned} e_k^2 &= a_x^2+a_y^2+a_z^2-g^2 \\ &= \sum_{i=x,y,z}\left\{\sum_{j=x,y,z}\left[S_{ij}\cdot\left(V_{j,k}-O_j\right)\right]^2\right\}-g^2 \end{aligned} \tag{5}$$

where $V_{j,k}$ is the output of j-th axis in the MEMS accelerometer at the time k-th , $S_{xy}=S_{yx}$, $S_{xz}=S_{zx}$, $S_{yz}=S_{zy}$. By accumulating the error e_k^2 of the MEMS accelerometer, the cumulative mean error E is obtained as

$$E=E\left(O_x \quad O_y \quad O_z \quad S_{xx} \quad S_{yy} \quad S_{zz} \quad S_{xy} \quad S_{xz} \quad S_{yz}\right)=\frac{\sum_{k=1}^{N}e_k^2}{N} \tag{6}$$

The above equation is a nonlinear equation for the accelerometer parameters S and O. When the cumulative mean square error E of the accelerometer is minimized, the sensor parameters are determined [9]. The Gauss-Newton nonlinear optimization method is used to calculate the parameter. The method is an iterative optimization program that guarantees the second convergence. According to the sensor chip manual to determine an initial estimate, the iterative update equation is

$$x^{t+1} = x^t - \alpha \cdot H^{-1}(x^t) \cdot J(x^t) \tag{7}$$

where x^t is the unknown vector of the t-th iteration, containing nine variables:

$$x^t = [x_1, \ \cdots, \ x_9] = \begin{bmatrix} O_x & O_y & O_z & S_{xx} & S_{yy} & S_{zz} & S_{xy} & S_{xz} & S_{yz} \end{bmatrix}^t$$

where $J\left(x^t\right)$ and $H\left(x^t\right)$ are the Jacobian matrices and the Hessian matrices of the error E respectively, defined as follows:

$$J(x^t) = \left[\frac{\partial E}{\partial x_1}, \cdots, \frac{\partial E}{\partial x_9}\right], \quad H(x^t) = \left\{h_{ij} = \frac{\partial^2 E}{\partial x_i \partial x_j}\right\} \tag{8}$$

where α is a damping coefficient less than 1 and is calculated by a linear search procedure at each iteration[9].The iteration is stopped when the following convergence criterion is satisfied:

$$\max\left\{\left|\frac{x_l^t - x_l^{t-1}}{(x_l^t + x_l^{t-1})/2}\right|\right\} < \varepsilon \tag{9}$$

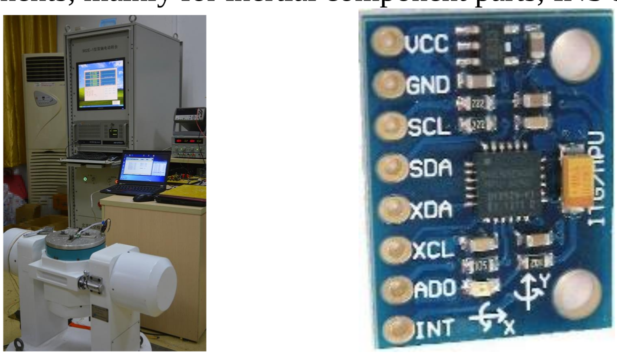
According to experience, the ε is a threshold, is usually set to 1.6×10^{-6}. Through nine iterations, the parameters can meet the experimental requirements.The final values of the parameters are determined. Through Eq.5 and Eq.6 to determine the accuracy of the parameters [10]

4. Experiment process and result analysis

4.1 Experiment platform

In order to verify whether the nine-position error compensation model can accurately reflect the output characteristics of the accelerometer, the MPU6050 and 902E-1 high-precision dual-axis turntable will be used as the experimental platform, as shown in Fig.5.

The 902E-1 type biaxial test table mainly consists of two parts, such as mechanical bed and monitoring system components, mainly for inertial component parts, INS static test and calibration.



(a) Biaxial test turntable (b) MPU6050 test module

Fig.5 902E-1 biaxial test turntable

The MPU6050 integrated MEMS three-axis gyroscope, MEMS three-axis accelerometer and built-in data motion processor. The operating voltage is from 2.375v to 3.46V. The related characteristics of MPU6050 are shown in Tab.2.

Table 2. MPU6050's performance table

accelerometer sensitivity			
parameter	conditions	value	units
full-scale range	ACCEL_FS=0	±2	g
	ACCEL_FS=1	±4	g
	ACCEL_FS=2	±8	g
	ACCEL_FS=3	±16	g
sensitivity scale factor	ACCEL_FS=0	16384	LSB/g
	ACCEL_FS=1	8192	LSB/g
	ACCEL_FS=2	4096	LSB/g
	ACCEL_FS=3	2048	LSB/g
nonlinearity	best fit straight line	±0.5	%
cross-axis sensitivity	—	±2	%
initial tolerance	component-level, all axes	±25	mg
	board-level, all axes	±50	

4.2 Experimental process

The nine-position error compensation model of the MEMS accelerometer is tested as follows:

Step 1: The MPU6050 to be tested in the axial vertical is fixed on the dual-axis turntable. First, the axial to be tested in the sensor node are fixed on the dual-axis turntable, as shown in Fig. 2.

Step 2: The sensor node is connected and preheated for one minute. The output at the location of the accelerometer is saved in serial assistant of the host computer. The sampling frequency of set as 50Hz and the sampling time is three minutes.

Step 3: The sensor node is de-energized and cooled for 30 seconds at room temperature. Then repeat the step 1 and step 2 to collect the output data form another position in the accelerometer, until the accelerometer data in nine positions are collected successfully.

Step 4: Finally, the data acquisition is completed. Turn off the sensor power and cut off the dual-axis turntable's power supply. The experiment is completed.

4.3 Analysis of results

The collected static data from the MEMS nine-position accelerometer is shown in Fig.6. The values of the axes in the accelerometer that did not perform error compensation when acquiring the six-position calibration are shown in Tab.3.

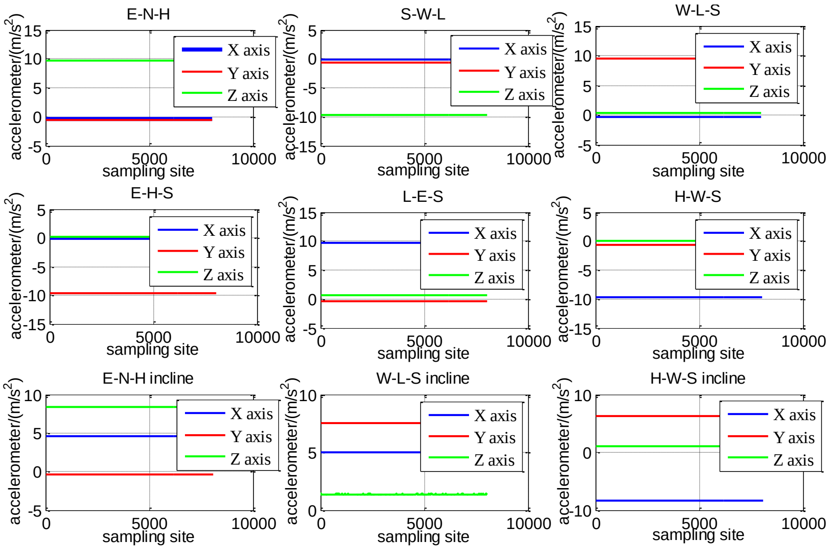


Fig.6 the data from the nine-position in MEMS accelerometer

Table 3.The uncalibrated values acquired from the accelerometer's six-position /g

Position	X axis acceleration	Y axis acceleration	Z axis acceleration
E-H-S	-0.2471	-9.6218	0.1834
E-N-H	-0.4171	0.5134	-9.6974
L-E-S	9.4642	-0.0457	0.6515
S-W-L	-0.1419	-0.0866	9.7245
H-W-S	-9.6899	-0.0654	-0.1465
W-L-S	-0.0327	9.5436	-0.3122

The collected value of each position in the accelerometer is taken into the accelerometer six position and the nine position error model. So the error parameter can be obtained. In the case that the error parameters are taken into the respective compensation model, the corrected output value of the accelerometer is obtained. The data from the six-position in the MEMS accelerometer and the data calibrated by nine-position accelerometer are compared, as shown in Tab.4

Table 4. The data comparison from six-position and nine-position calibration of MEMS accelerometer/g

Position	Six-position calibration			Nine-position calibration		
	X axis	Y axis	Z axis	X axis	Y axis	Z axis
E-H-S	-0.0031	-9.7334	-0.0094	0.0023	-9.7912	-0.0038
E-N-H	-0.0039	0.0024	-9.7674	0.0035	0.0025	-9.7989
L-E-S	9.7142	-0.0127	-0.0075	9.7952	-0.0049	-0.0031
S-W-L	-0.0319	-0.0086	9.7445	-0.0142	-0.0032	9.7935
H-W-S	-9.7389	-0.0454	-0.0054	-9.7813	-0.0114	-0.0034
W-L-S	-0.0324	9.7023	-0.0622	-0.0087	9.7934	-0.0042

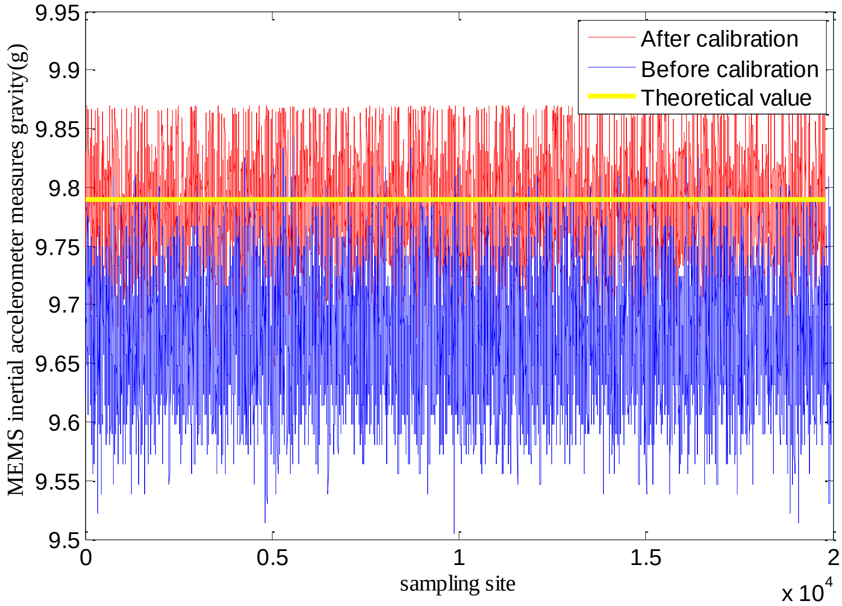


Fig.7 Acquisition calibration data after accelerometer nine position

As can be seen from Tab.3 and Tab.4, through the six-position and nine-position calibration model, both the six-position and nine-position calibration model can improve the accuracy of the accelerometer. The data of the six-position sensitive axis differs from the theoretical mean value by 5.48×10^{-2}, while the data of the nine-position sensitive axis differs from the theoretical mean value by

8.1×10^{-3}. The accuracy is improved by an order of magnitude. In the fig.7, we can get the conclusion that the measured value of the accelerometer after nine-position calibrations is closer to the true theoretical value. The nine-position data of another two axes is closer to the theoretical value than the six-position, which reduces the error caused by the nonlinear error and the crosstalk effect. Experimental results show that the nine-position correction method for the MEMS accelerometer can further optimize the accelerometer's performance.

5. Conclusion

Based on the six-position calibration algorithm of the accelerometer, due to the nonlinear error of the accelerometer and the crosstalk effect caused by the non-orthogonal axis of the accelerometer considered, an improved acceleration error compensation model is proposed. At the same time, the six-position calibration is optimized, thus the accelerometer nine position calibration method is presented. The experimental results show that the optimized six-position error compensation model and calibration method can effectively reduce the non-linearity of the accelerometer and the influence of the electronic crosstalk effect on the accelerometer. The measured value of the accelerometer is closer to the theoretical value. The error precision of the accelerometer is from 0.0548g to 0.0081g. So the feasibility and effectiveness of the optimized six-position calibration algorithm are demonstrated.

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