MEMS-IMU Error Modelling and Compensation by 3D turntable with temperature chamber

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Abstract—Under high dynamic and high temperature environments, the error model of the inertial measurement unit (IMU), which is the key sensor of the autonomous driving system, will be affected by temperature and input angular velocity. But the traditional error model of the IMU has the limitation that it cannot compensate with high precision under complex conditions. In this paper, the error model of the ADI16505 IMU is systematically observed at different temperatures and input angular velocity by using a three-axis turntable with a temperature chamber. The measured data objectively reflects the change of the IMU error model with temperature under dynamic angular velocity input. In this paper, an error model considering both temperature and input angular velocity is proposed. An error model was established with the correlation between temperature and angular velocity by the least square method and polynomial fitting. Finally, collecting data under the typical conditions of high temperature and low input angular velocity and compensating with this model. The average error observed on the six axes was reduced by more than 90%, and the feasibility of the optimized error model was verified.

Keywords—inertial measurement unit, error compensation, error model

I. Introduction

With the rapid development of Micro-Electro-Mechanical System(MEMS) technology, MEMS inertial measurement unit (IMU) has become a key component in the field of autopilot navigation and middle and low navigation. Research shows that small size, lightweight, low-cost, high-precision,and easy to integrate are important characteristics of MEMS inertial measurement units in mass production and multiple applications [1]. An inertial Measurement Unit (IMU) consists of an accelerometer, a gyroscope and an IMU processor. It can provide reliable position and velocity information by measuring and processing the output values of acceleration and angular velocity of the platform. Because the accuracy of output data is critical, compensating the error model of the IMU has become a research hot-spot in the field of inertial navigation systems in recent years.

The deterministic error model of the IMU includes the bias error, scale factor error and mutual coupling error of non-sensitive axis. To achieve the purpose of error compensation, the mathematical model of these errors needs to be established first. The deterministic errors can be compensated to improve IMU performance by calculating the collected output data under certain procedure on a three-axis turntable [2]. However, the performance of MEMS IMU will be seriously degraded when the temperature changes [3], so the traditional error model cannot be applied to every situation. For now, there are mainly two methods to eliminate the error caused by temperature. The first method is the temperature control method, based on processing technology and experimental methods [4-5]. This method has good stability and high precision, but it needs complicated design and expensive maintenance to keep the IMU working at a constant temperature. Another method, called the temperature compensation method, uses software technology and mathematical models to eliminate errors caused by temperature. Although the accuracy is slightly lower than that of the first method, the complexity and cost of the mathematical model are significantly reduced, which is more favored by scholars [6]. However, the temperature compensation method rarely considers the influence of the change in input angular velocity on the output data of the gyroscope, causing a reduction in the performance of the IMU.

The practical application conditions of the IMU include different inputs of angular velocity and temperature. But the traditional error model has limitations, especially under severe temperature conditions and highly dynamic autopilot navigation environments. Temperature and input angular velocity will cause different influences on every error parameter, so a more effective error model is urgently needed to obtain a better effect from compensation.

Therefore, this paper proposes a method to measure and compensate for IMU errors under controlled varies with both temperature and angular velocity input by a 3D turntable with a temperature chamber. Firstly, the proposed error model versus temperature and angular velocity input is mathematically expressed. Then, the coefficient matrices of the error model are calculated by the least square method and polynomial fitting. Finally, the optimized error model is used to predict and compensate the error parameters under every temperature and speed condition in the test range, optimizing the performance of the IMU considering various external conditions.

II. Analysis and Modeling of Error Parameter

The deterministic error of the MEMS inertial measurement unit is mainly affected by temperature, and the deterministic error of the gyroscope is also affected by angular velocity input. Due to the temperature sensitivity of materials in the production of MEMS inertial measurement units and the small size of the device, the change in temperature may cause the device to deform because of the heat [7]. In the working process, the device itself is affected by the rise in temperature and the thermal convection of the outside air, which causes its elastic coefficient, damping coefficient, and other detectable physical changes. It will lead to obvious nonlinear changes of each error parameter with the temperature. In addition, because of the non-linearity of gyroscope capacitance detection and the error of device structure machining, the effective signal is weak when the input angular velocity is low, which makes the non-linearity of the scale factor of the gyroscope more obvious [8].

Taking the scale factor of the gyroscope as an example, when the angular velocity input angular velocity is from -100 °/s to +100 °/s and the temperature is set at 20 °C and 50 °C, the scale factor of the three axes of the gyroscope will change significantly, as shown in Fig. 1. Therefore, the influence of temperature and input angular velocity on error compensation cannot be ignored. The method of modelling and compensation of errors needs improvement and optimization under the high dynamic conditions.

Taking the scale factor of the MEMS gyroscope as an example, which can be described as a function of temperature T and input angular velocity ω:

$$K_g = f(T, \omega) \tag{1}$$

To compensate for the scale factor, (1) can be changed into the following form by the polynomial fitting method:

$$K_g = \begin{bmatrix} 1 & \omega & \cdots & \omega^m \end{bmatrix} \cdot P \cdot \begin{bmatrix} 1 & T & \cdots & T^n \end{bmatrix}^T \tag{2}$$

In the (2), P is the coefficient matrix, which consisted of C_{mn}:

$$P = \begin{bmatrix} c_{11} & c_{12} & \cdots & c_{1n} \\ c_{21} & c_{22} & \cdots & c_{2n} \\ \vdots & \vdots & & \vdots \\ c_{m1} & c_{m2} & \cdots & c_{mn} \end{bmatrix} \tag{3}$$

The relationship between the scale factor and temperature and the input angular velocity is analyzed based on the calibration data obtained from the experiment. Then coefficient matrix P can be calculated by substituting the calibration data into (2) with appropriate orders m and n.

The error model of the accelerometer and the bias error of the gyroscope are only affected by temperature in the calibration process, so the formula used in polynomial fitting is different from (2). For the scale factor error of the accelerometer, the fitting polynomial of the error parameter is [6]:

$$K_a = x_0 + x_1 \times T + x_2 \times T^2 + \cdots + x_n T^n \tag{4}$$

In the traditional multi-position static measurement and multi-velocity dynamic measurement [2], the influence of temperature and input angular velocity on each error parameter cannot be ignored, so the error models of the accelerometer and gyroscope after considering temperature and angular velocity input are as follows:

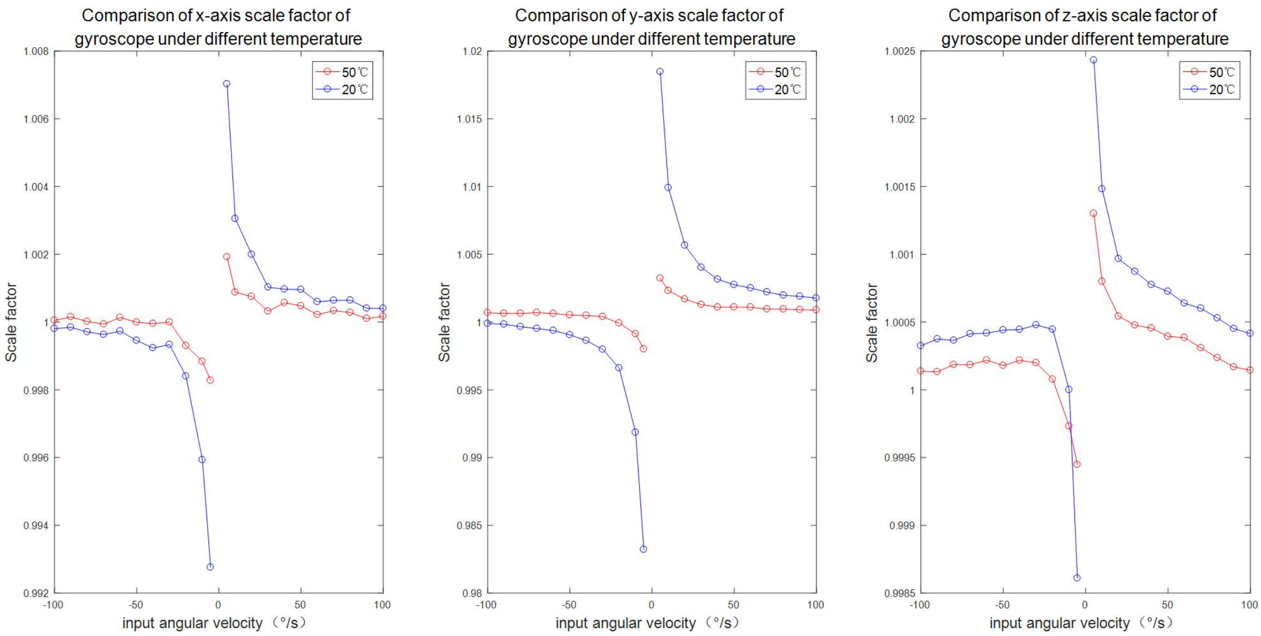

Fig. 1. Comparison of three-axis scale factor of gyroscope under different temperature

$$\begin{bmatrix} A_x \\ A_y \\ A_z \end{bmatrix} = \begin{bmatrix} K_{ax}(T) & S_{axy}(T) & S_{axz}(T) \\ S_{ayx}(T) & K_{ay}(T) & S_{ayz}(T) \\ S_{azx}(T) & S_{azy}(T) & K_{az}(T) \end{bmatrix} \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} + \begin{bmatrix} b_{ax}(T) \\ b_{ay}(T) \\ b_{az}(T) \end{bmatrix} \quad (5)$$

Where: A_x, A_y, A_z denote the output of the accelerometer; a_x, a_y, a_z denote real input of the turntable; K_{ax}, K_{ay}, K_{az} denote the scaling factor of the accelerometer; $S_{axy}, S_{axz}, S_{ayx}, S_{ayz}, S_{azx}, S_{azy}$ denote the mutual coupling errors of non-sensitive axes of the accelerometer; B_{ax}, B_{ay}, B_{az} denote the bias of the accelerometer.

$$\begin{bmatrix} W_x \\ W_y \\ W_z \end{bmatrix} = \begin{bmatrix} K_{gx}(\omega, T) & S_{gxy}(\omega, T) & S_{gxz}(\omega, T) \\ S_{gyx}(\omega, T) & K_{gy}(\omega, T) & S_{gyz}(\omega, T) \\ S_{gzx}(\omega, T) & S_{gzy}(\omega, T) & K_{gz}(\omega, T) \end{bmatrix} \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} + \begin{bmatrix} b_{gx}(T) \\ b_{gy}(T) \\ b_{gz}(T) \end{bmatrix} \quad (6)$$

Where: W_x, W_y, W_z denote the output of the gyroscope; $\omega_x, \omega_y, \omega_z$ denote the real input of the turntable; K_{gx}, K_{gy}, K_{gz} denote the scale factor of the gyroscope; $S_{gxy}, S_{gxz}, S_{gyx}, S_{gyz}, S_{gzx}, S_{gzy}$ denote the mutual coupling errors of non-sensitive axes of the gyroscopes; B_{gx}, B_{gy}, B_{gz} denote the bias of the gyroscope.

III. MEASUREMENT AND PROCESSING OF DATA

3.1 Experimental Equipment

The experimental equipment adopts a high-precision three-axis turntable (JDZT340E). The precision of the turntable is less than 3". The model of the inertial measurement unit is ADI16505. The temperature range of the self-made temperature chamber is 20 °C~55 °C. And the precision of temperature control is ± 1 °C. This equipment can complete the calibration experiment of the MEMS inertial measurement unit.

3.2 Data Acquisition

Data is collected at the temperature between 20 °C to 55 °C with 5 °C step.

In the multi-position static test method [2], 12 positions are selected, which can effectively eliminate the influence of misalignment between the turntable and north and angular velocity of earth rotation in the IMU. Then, after the collected data is averaged to eliminate the influence of noise, the bias error, scale factor, and mutual coupling error of the non-sensitive axis of the accelerometer can be calculated by the least square method, and the bias error of the gyroscope can also be calculated.

In the multi-velocity dynamic test method, the x-axis, y-axis, and z-axis of the IMU coincide with the sky direction of the geographical coordinate system in turn. In the range of input angular velocity between -100 °/s ~+100 °/s, data is collected every 10 °/s in this range. After averaging and the least square calculation, the bias error and scale factor of the gyroscope can be calculated.

Fig. 2. Three axis turntable and self-made temperature chamber

3.3 Data Fitting and Error Compensation

Firstly, the calculated error parameters of the accelerometer and the bias error of the gyroscope are polynomial fitted with temperature. And the scale factor and mutual coupling error of insensitive axis of the gyroscope are polynomially fitted with temperature and input angular velocity, so that the polynomial fitting coefficient matrix of every error parameter can be calculated.

Then, the calculated error parameters are used to compensate the output data of the accelerometer and gyroscope, and the compensation effect indicator is as follows:

$$E = \frac{\varepsilon - \varepsilon_1}{\varepsilon} \times 100\% \quad (7)$$

Where: ε denotes the mean error of the output of the accelerometer or gyroscope before compensation; ε_1 denotes the mean error of the accelerometer or gyroscope after compensation

IV. TEST RESULTS AND ANALYSIS

First, verify whether different temperatures and input angular velocity have an influence on the compensation effect of the accelerometer and gyroscope. The comparison diagram of the compensation effect is as follows:

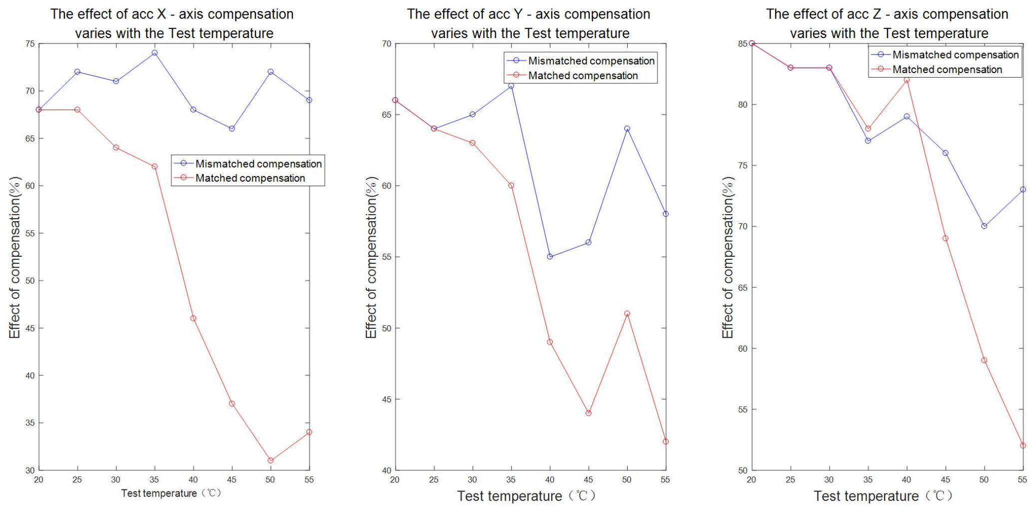

Fig. 3 Accelerometer compensation effect varies with temperature

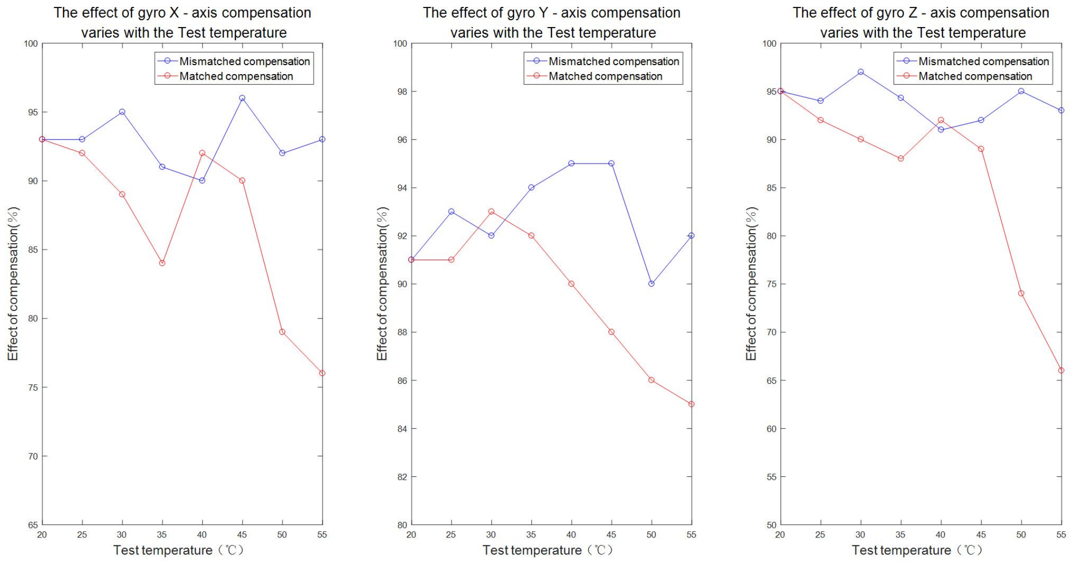

Fig. 4 Gyroscope compensation effect varies with temperature

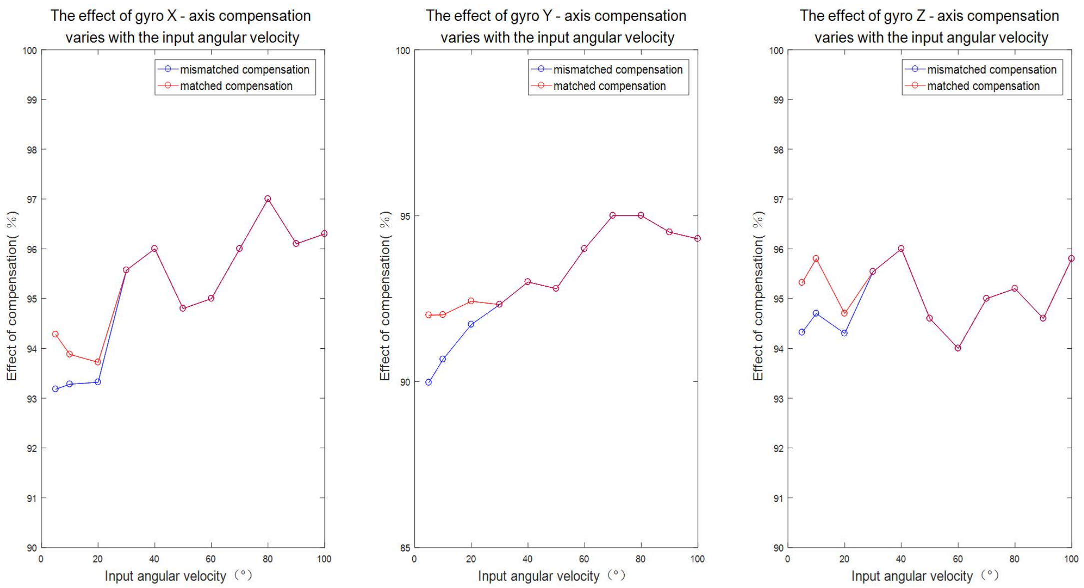

Fig. 5 Gyroscope compensation effect varies with input angular velocity

In Figs. 3, 4 and 5, method of mismatched compensation uses error parameters calculated at indoor temperature (20 °C) or 30 °/s input angular velocity to compensate for output data. The method of matched compensation uses error parameters calculated at the current temperature or input angular velocity to compensate the output data.

From Figs. 3 and 4, it can be known that when the temperature is higher than 40 °C, the influence of temperature on error compensation is very significant. From Fig. 5, it can be seen that although the input angular velocity below 30 °/s will have a certain influence on the scale factor and the mutual coupling errors of non-sensitive axes of the gyroscope, it will have little influence on the compensation effect.

Then, the original data measured by the multi-position static method is used to calibrate the error of the accelerometer. Because the whole test is in a static state, the only influencing factor is the change of temperature. Taking the scaling factor error of X-axis of the accelerometer as an example, the fitting image of this error and temperature is shown in Fig. 6.

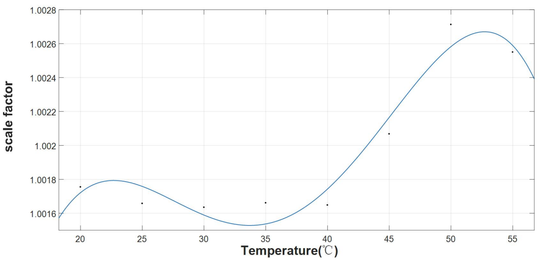

Fig. 6 Fitting diagram of scale factor X-axis of accelerometer and temperature

According to the fitting image, the fitting number of the polynomial is 4,and the obtained fitting polynomial is:

$$K_{ax} = 0 \times T^4 + 0 \times T^3 - 0.0001 \times T^2 + 0.0020 \times T + 0.9867 \tag{8}$$

Using the same method to analyze and fit the error of bias and non-sensitive axis mutual coupling of accelerometer. It is found that when the temperature is higher than 40 °C,the error parameters will change in different degrees. But there is no obvious change trend.

Then, the original data obtained by the multi-rate dynamic measurement method is used for calibration of the error of the gyroscope, and the influencing factors are input angular velocity and temperature. The scale factor of X-axis of the gyroscope is selected for polynomial fitting with temperature and angular velocity when rotating counterclockwise. And the fitting image is shown in Fig. 7.

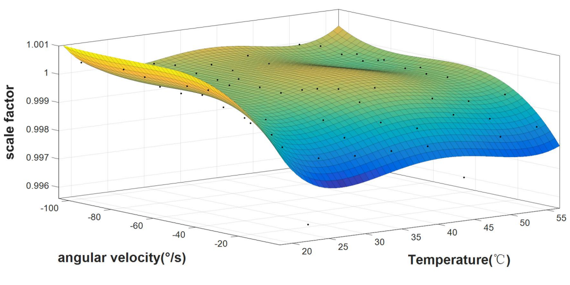

Fig. 7 Fitting diagram of scale factor of X-axis of gyroscope with temperature and angular velocity

By fitting the image,the fitting times m=3 and n=4 are selected,and the fitting polynomial is:

$$P_{gx-} = \begin{bmatrix} 1.03 & -0.003651 & 0.0001475 & -2.538e-06 & 1.581e-08 \\ -4.929e-05 & -4.358e-06 & 9.842e-08 & -7.259e-10 & 0 \\ -1.032e-06 & -2.589e-08 & 1.971e-10 & 0 & 0 \\ -5.215e-09 & -8.217e-11 & 0 & 0 & 0 \end{bmatrix} \tag{9}$$

After calculating the fitting polynomial of all error parameters, the error parameters of the accelerometer and gyroscope can be predicted at any input angular velocity and temperature in the test range. Finally, to verify the error model, a set of data is collected under the condition of 47 °C with an input angular velocity of Y axis of -5 °/s. With the error model of the accelerometer and gyroscope in (9), the compensation effect indicator is 92.2%, while the compensation effect indicator is 81.7% by using the mis-matched error model calculated at indoor temperature (20 °C) and input angular velocity of 20 °/s.

V. Conclusion.

In order to solve the problem that temperature and input angular velocity will affect the error parameters of the MEMS inertial measurement unit, the error model of the IMU is measured and compensated by the temperature chamber and 3D turntable. Not only is the influence of temperature considered, but also the angular velocity input is measured and compensated. The contributions are as follows:(1) The limitation of the traditional error model in a complex environment is solved by polynomial fitting. (2) Improved compensation accuracy. At the randomly selected test points of high temperature and low input angular velocity, the compensation effect indicator reaches 92.2%. The feasibility and effectiveness of the optimized error model have been verified. (3) Predefined error parameters. In the range of temperature and angular velocity, the optimized error model can be used to compensate the error model at any point in the range with high efficiency and accuracy.

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