Polynomial Degree Determination for Temperature Dependent Error Compensation of Inertial Sensors

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***Abstract*—MEMS based Inertial Measurement Units, which include MEMS accelerometers and gyroscopes, have a wide range of applications due to their low cost, small size and low power consumption. IMU error should be reduced to the lowest level so as to minimize errors of navigation systems which use MEMS IMU. MEMS sensors have bias, scale factor as well as temperature change of these errors. In the error compensation algorithm, polynomials are used to compensate temperature dependent change of errors. The degree of polynomials, which are determined according to sensor characteristics, affect IMU performance. Therefore, optimum degree must be determined by various methods and studies. In this paper, temperature dependent errors of MEMS inertial sensors will be defined and how to determine degree of polynomial will be explained so as to compensate errors by the optimum way. Several simulation studies are supported with real sensor data.**

Keywords— inertial sesnsor; temperature characteristic of inertial sensor; temperature dependent error; polynomial degree; compensation

I. INTRODUCTION

In ancient times, people used various primitive methods like the length of shadow, direction of the polar star or behavior of animals to find their directions [6]. In the modern world, people can find their way with more advanced techniques. Position of any object can be determined with the satellites orbiting around the earth or inertial navigation systems. Inertial navigation is the process of establishing the position, velocity, attitude and heading of a vehicle using information derived from inertial sensors [1]. The major sensors in an inertial navigation system are the accelerometer and gyroscope. Accelerometer measures specific force, which is the acceleration due to all forces except for gravity. Gyroscope measures angular rate, which is used by the navigation processor to maintain the INS's attitude [2].

Inertial navigation systems are autonomous, which means they are self-contained so they don't need external references. When initial position and orientation are known, measurements are integrated once for gyroscopes and twice for accelerometers to provide orientation and position respectively [5].

IMU is the most important part of an inertial navigation system. IMU generally consists of three orthogonal gyroscopes, three orthogonal accelerometers and electronics which are required to operate sensors and processor. IMU processor performs unit conversion on the inertial sensor outputs and provides compensation for the known errors of the inertial sensors.

MEMS sensors are low-cost, low-power and small dimensioned units, but suffer from larger errors. These sensors exhibit high biases, scale factor variations, axis nonorthogonalities, drifts, and noise characteristics. These errors vary with time and so the precision of the measurements becomes corrupt [4]. The accuracy of navigation systems depends on the calibration of MEMS based IMU to remove deterministic errors like bias and scale factor error. The process of understanding the variation of these errors at different temperature points is another important step for improving performance of IMU and hence performance of navigation system [10].

The main objective of this article is to determine an optimum way in order to reduce temperature dependent errors of MEMS inertial sensors.

II. COMPENSATION ALGORITHM OF TEMPERATURE DEPENDENT ERRORS

Inertial sensors contain two main types of errors which are deterministic errors like scale factor, bias, misalignment and stochastic errors such as bias instability and scale factor instability. The calibration algorithms and the error compensation models are developed to improve the performance of inertial sensors [3]. Inertial sensor errors like bias and scale factor change with temperature. In the error compensation algorithm, polynomials should be used to compensate temperature dependent variation of errors. The degree of polynomials, which are determined according to sensor characteristics, affects sensor performance. In order to improve sensor performance, optimum degree of polynomials should be determined.

The deterministic error sources include bias and scale factor errors, which can be removed by performing specific calibration procedures in a laboratory environment. Calibration tests can be performed by using a two-axis rate table. Reference inputs can be applied to IMU or inertial sensors using this equipment. During static tests, data is collected while the sensor is at rest at various configurations

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between 1g and -1g. During dynamic tests, the rotation rate of the rate table is started from zero and is varied between desired maximum and minimum rates.

MEMS-based inertial sensor errors are temperature dependent. Therefore, same calibration procedure which is summarized in the previous paragraph is performed under different temperatures to determine temperature dependent behavior of these errors. In the scope of this study, same static and dynamic calibration procedure was processed at ten different temperature points ranging from −30 °C to 50 °C and inertial sensor and temperature data sets were collected during these test steps. Thermal tests were carried out in a rate table with integrated thermal chamber.

Data collecting at the temperature points as much as possible provides more reliable results to identify temperature dependent errors because the temperature characteristic of inertial sensor errors is nonlinear.

Temperature dependent bias and scale factor errors can be compensated with error compensation algorithms which are processed on IMU processor. Various degrees of polynomials can be used in error compensation algorithms. Different degree curve fit was used to calculate temperature variation polynomial coefficients. And the results from different degree of polynomials were compared.

III. Simulation and Experimental Results

Bias and scale factor errors were calculated for each calibration tests which were performed under different temperature.

The following figures present accelerometer bias error and residual error according to polynomial degrees. In plots, blue trace expresses calculated bias values acquired in different temperature conditions which were determined from real accelerometer test data and red trace expresses the polynomial curve fit with calculated temperature coefficients.

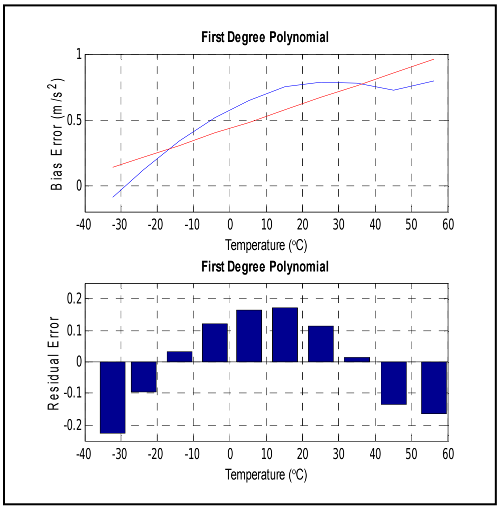

Fig. 1. First degree temperature polynomial of accelerometer bias error and residual error

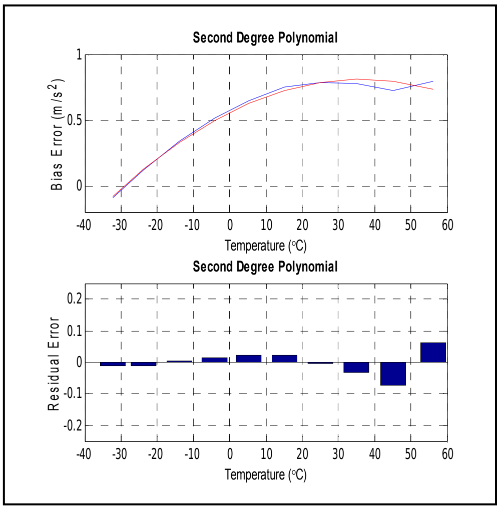

Fig. 2. Second degree temperature polynomial of accelerometer bias error and residual error

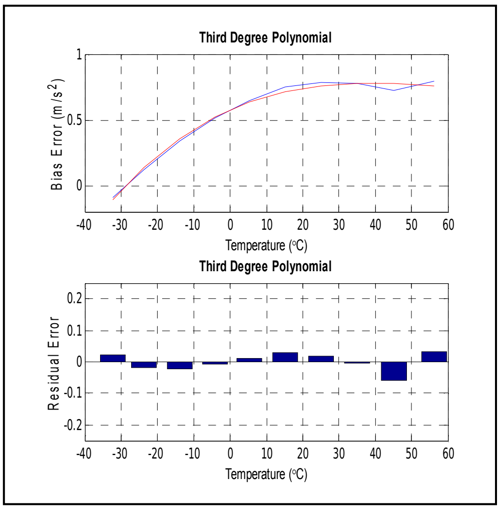

Fig. 3. Third degree temperature polynomial of accelerometer bias error and residual error

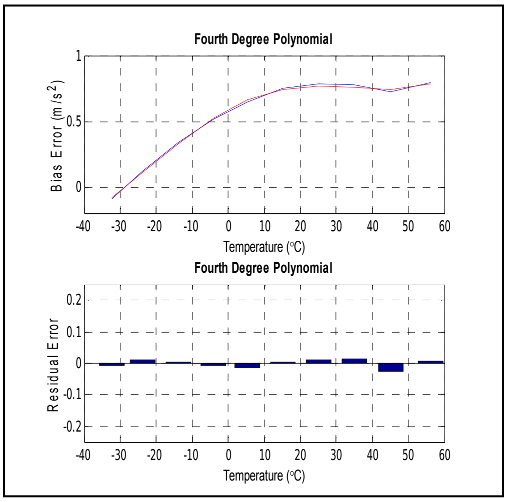

Fig. 4. Fourth degree temperature polynomial of accelerometer bias error and residual error

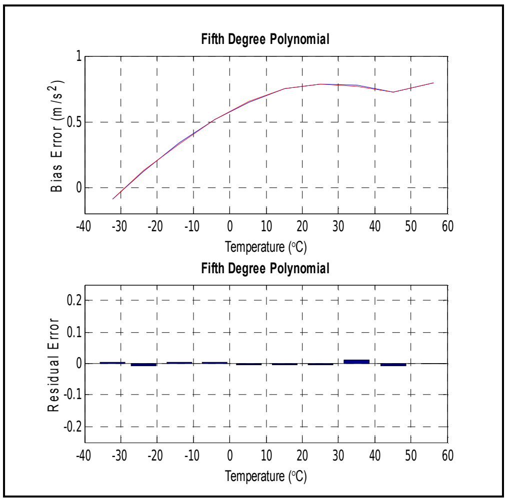

Fig. 5. Fifth degree temperature polynomial of accelerometer bias error and residual error

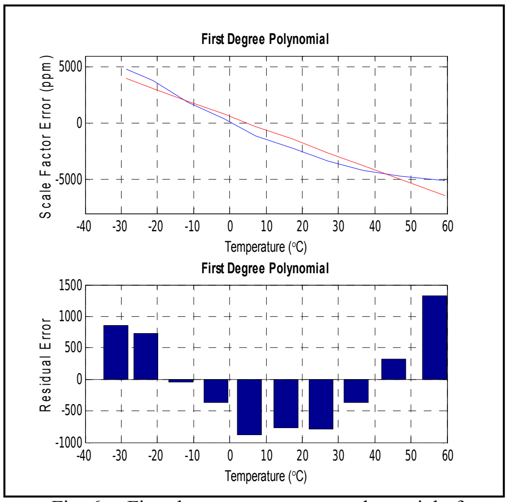

Fig. 6. First degree temperature polynomial of accelerometer scale factor error and residual error

Mean squared error, absolute maximum error and absolute minimum error according to polynomial degrees are given in Table I.

TABLE I. RESIDUAL ERROR ACCORDING TO POLYNOMIAL DEGREE

Residual Error	**Test Result According to Polynomial Degree**				
	First	***Second***	***Third***	***Fourth***	***Fifth***
Mean Squared Error (mg)	198.57	12.07	7.19	1.46	0.32
Absolute Maximum Error (mg)	17.56	6.35	3.19	1.53	1.17
Absolute Minimum Error (mg)	22.91	7.33	5.92	2.51	0.81

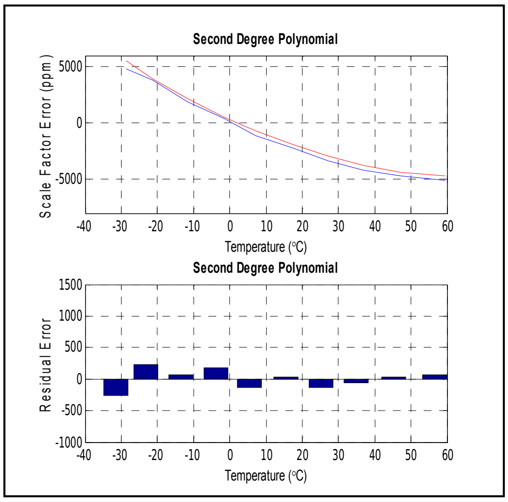

Fig. 7. Second degree temperature polynomial of accelerometer scale factor error and residual error

The following figures present accelerometer scale factor error and residual error according to polynomial degrees. In plots, blue trace expresses calculated scale factor values acquired in different temperature conditions which were determined from real accelerometer test data and red trace expresses the polynomial curve fit with calculated temperature variation polynomial coefficients.

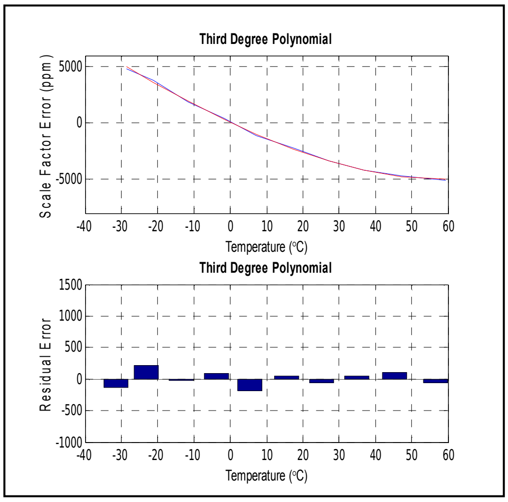

Fig. 8. Third degree temperature polynomial of accelerometer scale factor error and residual error

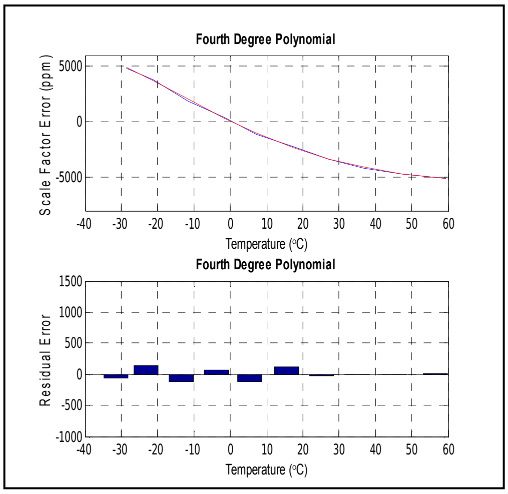

Fig. 9. Fourth degree temperature polynomial of accelerometer scale factor error and residual error

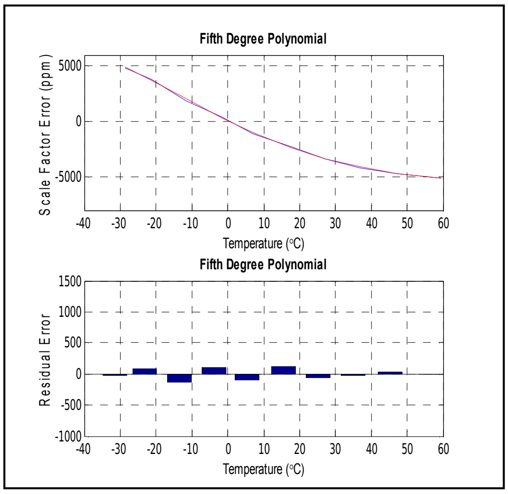

Fig. 10. Fifth degree temperature polynomial of accelerometer scale factor error and residual error

Mean squared error, absolute maximum error and absolute minimum error according to polynomial degrees are given in Table II.

TABLE II. RESIDUAL ERROR ACCORDING TO POLYNOMIAL DEGREE

Residual Error	**Test Result According to Polynomial Degree**				
	First	***Second***	***Third***	***Fourth***	***Fifth***
Mean Squared Error (ppm)	541882	19942	12429	7142	6314
Absolute Maximum Error (ppm)	1323	224	209	133	115
Absolute Minimum Error (ppm)	888	256	185	122	124

Accelerometer and gyroscope have the same behavior so test results were given accelerometer bias and scale factor errors variation versus temperature.

IV. CONCLUSION

This study suggests various degrees of polynomials for sensor error compensation algorithms. Therefore, temperature dependence of the IMU or sensor performance can be reduced. The first degree polynomial results aren't sufficient, difference between the bias/scale factor errors and the fitted bias/scale factor errors are large. In the third, fourth and fifth degree polynomials, fitted bias/scale factor errors are very close. Therefore, the differences between the real bias/scale factor errors and the fitted bias/scale factor errors are small.

There is a trade-off between processing load and effects of residual error in the system. High degree polynomial causes more processing load. However, usage of high degree polynomial gives better performance. Selection of the polynomial's degree can be determined by evaluating flight time and maximum acceleration, angular rate and capacity of the processor.

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