Cost-effective Testing and Calibration of Low Cost MEMS Sensors for Integrated Positioning, Navigation and Mapping Systems

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SUMMARY

Integrated INS/GPS systems provide continuous positioning information in any environment. Accurate positioning information from GPS is used to provide frequent updates to the INS, while the GPS signal losses will be compensated for in real-time by using the short-term accuracy of the INS derived position and velocity. However, current integrated existing systems use high-end inertial sensors which are expensive and bulky. Hence, to reduce the cost of the integrated system, Micro-Electro-Mechanical System (MEMS) based inertial sensors are proposed. However, these light-weight and low-cost MEMS sensors suffer from various errors like turn-on biases or the scale factor drift errors which are negligible for navigation grade sensors. Moreover the performance characteristics of these sensors are highly depended on the environmental conditions, especially temperature variations. Hence there is a need for the development of accurate, reliable and efficient thermal models to decrease the effect of these errors that can potentially degrade the system performance. In this paper, the maximum noises affecting the MEMS sensors were analyzed and the effects of thermal variations on biases and scale factor errors were investigated. Utilizing these thermal effects, efficient thermal calibration model was proposed for ADI sensors. Effectiveness and validity of the proposed method was investigated through a kinematic vehicle test using integrated GPS and MEMS-based inertial measurement unit (IMU). Various intentionally introduced GPS signal outage periods were considered during data processing for evaluation of compensated data as compared to uncompensated data, with respect to a reference trajectory.

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1. INTRODUCTION

The current market of integrated positioning and navigation systems is clearly dominated by the Global Positioning System (GPS). The need for alternative positioning systems only arises as GPS does not work in all environments. One promising development is the emergence of Micro-Electro-Mechanical Systems (MEMS) technology. Since Inertial Navigation systems (INS) technology is capable of working in all environments where GPS has difficulties, MEMS inertial technology is used as a complement to GPS. MEMS-based INS systems provide accurate navigation data over short time intervals but suffer from accuracy degradation with time due to the combined effects of errors like noises, biases, drifts and scale factor instabilities (Nassar, 2006; Godha, 2006). These errors can be corrected using frequent updates from external sources like GPS derived position and velocity which forms the basis of integrated INS/GPS systems.

Inertial sensor errors can be divided into two parts: random and deterministic (systematic) (Nassar, 2002). In order to integrate MEMS inertial sensors with GPS, and to provide a continuous and reliable navigation solution, the characteristics of different error sources and the understanding of the stochastic variation of these errors are of significant importance (Park, 2004). The random errors include bias-drifts and/or scale factor drifts that correspond to the rate at which the error in inertial sensor accumulates with time (El-Sheimy, 2003). These random errors have to be modeled stochastically. The deterministic error sources include the bias and the scale factor errors which can be removed by specific calibration procedures in a laboratory environment. However, for low cost sensors such as the MEMS sensors, these errors are quite large and their repeatability is typically poor because of the environmental dependence, especially temperature, which makes frequent calibration a necessity (El-Diasty, 2006). More explicitly, the actual value of the bias and the scale factor varies from that obtained through calibration process due to the difference between the operational and calibration temperatures (Walid, 2005). Hence there is a need for development of accurate, reliable and efficient thermal models to be used for online and post processing applications. Since these errors get accumulated with time, the position accuracy degrades if these thermal variations for both accelerometer and gyroscope biases and scale factors are not modeled and compensated (Shcheglov et al, 2000).

This paper compare the performance of noise and temperature affected data for MEMS inertial sensors, with the comensated data using a newly developed model.

2. METHODOLOGY

2.1 Calibration Methods

Calibration is defined as the process of comparing instrument outputs with known reference information. Consequently, the coefficients are determined that force the output to agree with the reference information for any range of output values. In this study, we determined approximate biases and scale factor errors using a modified method described in (Titteron, 1997). The description of the modified method is beyond the scope of this paper.

2.2 Stochastic Modeling

The basic difference between deterministic and stochastic modeling is that in deterministic modeling, relationship has to be established between one or more inputs and one or more outputs, whereas in stochastic modeling, there may not be any direct relationship between input and output (Hou, 2004). A model is theorized as though the system is being excited by white noise, having the same output characteristics as the IMU under evaluation. Allan Variance method was used to characterize the various noise terms in the sensor signal as described in (Hou, 2004).

2.3 Methods of Thermal Testing

The purpose of thermal testing is to establish the variation of the basic sensor parameters, operating under different temperatures. The soak method was used in this paper that allows the IMU enclosed in the thermal chamber to stabilize at a pre-set temperatures.

3. EXPERIMENTAL SETUPS

3.1 Sensor Noise Estimation

Tests were conducted first to identify the major noise terms existing in the custom built MEMS unit called ADI MEMS IMU (three accelerometers and three gyroscopes) Sensor Triad (ADI) developed by the Mobile Multi-sensor Systems (MMSS) Group, The University of Calgary (El-Sheimy and Niu, 2005). Eighteen hours of static data, with sampling frequency of 100 Hz was collected from the ADI IMU at room temperature. The collected data was analyzed using Allan variance method to evaluate various random noise components.

3.2 Thermal Calibration

In this paper, ADI MEMS IMU was used for thermal. Fig. 1 shows the static test setup. The data was collected at the Inertial Lab at the University of Calgary, which is equipped with a thermal chamber. The temperature of the thermal chamber was varied from -25 to 70 ^{o}C in steps of 5 ^{o}C. A total of 20 different temperatures were considered in this experiment. At each temperature, the ADI IMUs were allowed to stabilize before recording data. The IMUs data were sampled at 100 Hz at different temperatures and was saved on a laptop via National Instrument 16-Bit A/D card to be used for post processing.

Figure 1: Thermal Test Setup

3.3 Thermal Variation Model

In order to compensate for these thermal drifts, a 3rd order polynomial was fitted to the calculated biases and scale factors to obtain a continuous global temperature compensation model. The modified equations for the bias and scale factor variation models are

$$b(t) = b(t_o) + c_1(t - t_o) + c_2(t - t_o)^2 + c_3(t - t_o)^3 \qquad (1)$$

$$S(t) = S(t_o) + d_1(t - t_o) + d_2(t - t_o)^2 + d_3(t - t_o)^3 \qquad (2)$$

where, t corresponds to individual temperature points and t_o is the room temperature (25 ^oC). $b(t_o)$ and $S(t_o)$ are the bias and scale factor values at room temperature, evaluated by 6 position calibration tests, while $b(t)$ and $S(t)$ are the evaluated bias and scale factor values for the each temperature point where temperature ranges from -25 ^oC to 70 ^oC. The polynomial coefficients are then evaluated by the least squares method and compensated in real time data to validate the proposed thermal model.

3.4 Trajectory and Reference

To evaluate the contribution of the calibration, kinematic data was collected in March 2005 by MMSS group using the ADI sensor triad, a higher grade IMU and GPS receivers. The

ADI IMU was mounted within a test vehicle with NovAtel OEM4 GPS receivers. The test trajectories include medium to good quality GPS signals. The quality of the position estimation is often evaluated by simulating a set of short-term GPS signal outages and by checking the position drifts during these GPS signal outages where the INS has to work as a stand-alone navigation system. To test the MEMS IMU performance with the developed thermal compensation model, some short-term (60 sec) GPS signal outages were simulated. Nine GPS signal outages were carefully picked to cover all typical dynamics of the land vehicle. The IMU position errors during GPS signal outages are obtained and then compared with the corresponding solution of the reference trajectory. This solution is acquired from the smoothed best estimate of the CIMU/DGPS data processing.

4. RESULTS AND DISCUSSIONS

The Allan Variance results can be found in (Hou, 2004) and therefore, will not be discussed here. The computed two dimensional North- East GPS trajectory for the compensated IMU data is shown in Fig. 2.

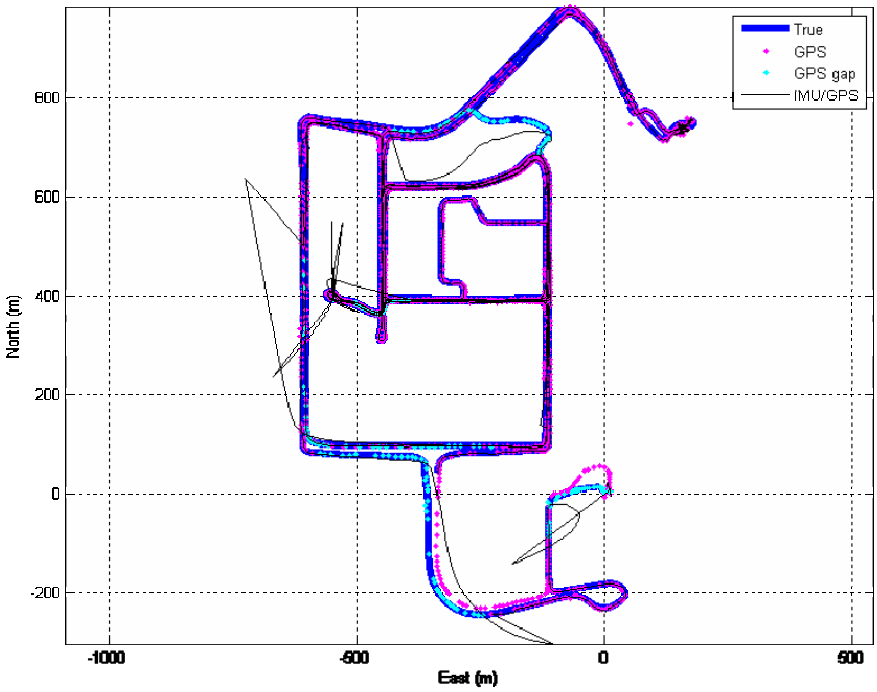

Figure 2: ADI IMU trajectory

The variations of biases and scale factors of Gyroscopes with increasing temperature were computed as shown in Fig. 3 and 4. Similarly, biases and scale factors for accelerometers X and Y at different temperatures were calculated.

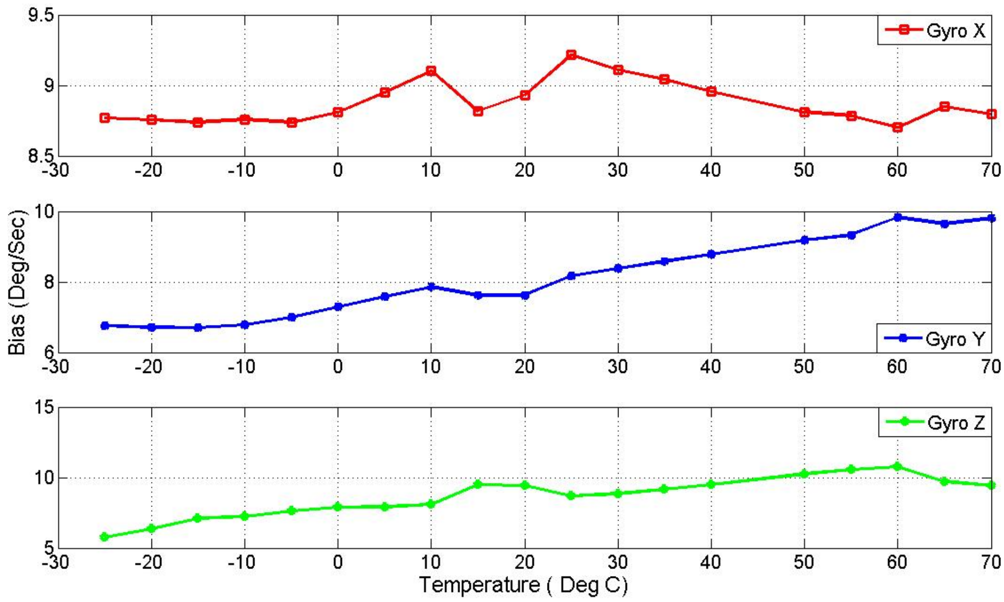

Figure 3: Variation of Gyroscope Biases with temperature

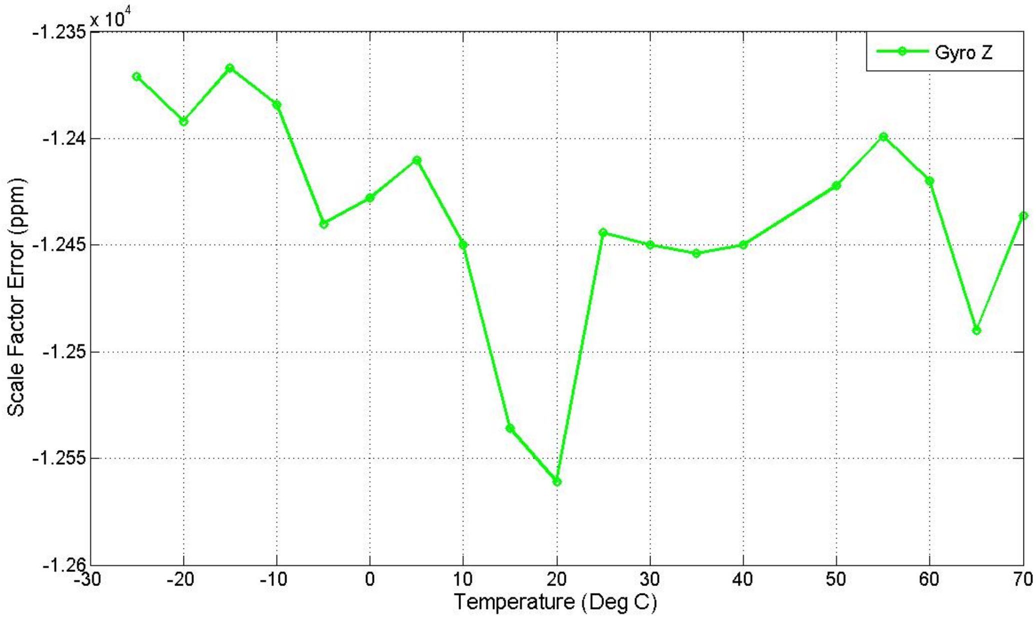

Figure 4: Variation of Gyroscope Scale Factor with temperature

These variations (Fig. 3-4) can lead to considerable errors in the measurements. For example, the thermal variation of accelerometer bias may reach about 0.94 m/s^2 for ADI MEMS sensors. This error, if not corrected or compensated, can lead to position errors of about four hundred meters in 30 sec and about 2 Km after 60 sec for standalone inertial navigation system. Similarly, the gyroscope biases (Fig. 3) can reach drifts of 5 degs/sec, over the whole temperature range, which gives position error of few Km after 30 sec for navigation with the standalone inertial system.

The comparison between the compensated and uncompensated data for similar GPS signal outages is listed in Table 1 which clearly indicates that position accuracy can be greatly improved by the compensation techniques presented in this paper.

Table 1: Obtained Position Errors during 60s GPS Outages

	Position Errors(m)		
IMU / Outage	ADI with SF and thermal compensation model		ADI without scale factor and thermal compensation models
#1	184.457		420.49
#2	147.0599		145.3
#3	142.9408		129.2
#4	58.8821		13.9
#5	178.0626		3951.2
#6	164.7154		1887.7
#7	107.4107		777.00
#8	133.6185		2546.2
#9	234.0778		1417.00
Mean	150.1361		1254.2

5. CONCLUSION

This paper investigated the effect of noise and temperature on the navigation accuracy of MEMS-based IMU in land vehicle navigation environments. Initially, uncompensated data used failed to converge due to large biases. By removing the biases before processing, the errors were very large (at the Kilometer range) as can be seen from Table 3. It is shown that the thermal variation of accelerometer bias may reach about 0.94 m/s^2 for ADI MEMS sensors and gyroscope drift can reach 5 degs/sec, over the temperature range from -25 ^oC to 70 ^oC. Hence if these thermal variations are not corrected or compensated, it can lead to very large position errors. To account for these thermal errors, a polynomial thermal model was proposed. The results were presented in the form of a real kinematics test. The compensation of the thermal errors through the proposed model reduced the positional errors from 1254 m to 150 m for MEMS-based stand alone navigation during 60 sec of simulated GPS signal outages.

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BIOGRAPHICAL NOTES

Ms. Priyanka Aggarwal is a PhD student in the Mobile Multi-Sensor Systems (MMSS) research group at University of Calgary. She obtained her BSc degree from the Department of Electronics and Communication Engineering, Kurukshetra Univerity from India in 2000. Her MSc degree is from the Department of Electrical and Computer Engineering, at University of Calgary in 2004. Her research interests include MEMS fabrication, multi-sensors data fusion and non-linear filtering approaches.

Ms. Zainab Syed is currently a Ph.D. student in the Department of Geomatics Engineering, University of Calgary, Canada. She is a member of the Mobile Multi-Sensor research team, where her research interest focuses on personal navigation system. Zainab holds an M.Sc. degree in Electrical and Computer Engineering, University of Calgary (2004). Her M.Sc. research was to automate the modeling for cardiac action potentials. Zainab obtained her B.Sc. degree from the Department of Geomatics Engineering, University of Calgary, in 2001.

Dr. Xiaoji Niu is a research scientist and a member of the Mobile Multi-Sensor Systems (MMSS) Research Group in the Department of Geomatics Engineering at the University of Calgary. He has a Ph.D. from the Department of Precision Instruments & Mechanology at Tsinghua University in China in 2002. He received B.Eng. degrees (with Honors) in both Mechanical Engineering and Electrical Engineering from Tsinghua University in 1997. His research interests focus on the low-cost GPS/INS integration technologies and micromachined (i.e. MEMS) inertial sensors and systems.

Dr. Naser El-Sheimy is a Professor in the Department of Geomatics Engineering at U of C and the leader of the MMSS research group. He holds a Canada Research Chair (CRC) in Mobile Multi-Sensor Systems. Dr. El- Sheimy is a member of the Canadian GEOIDE NCE research management committee. Currently, he is the chair of the International Federation of Surveyors (FIG) working group C5.3 on Integrated Positioning, Navigation and Mapping Systems, chair of the ISPRS WG on "Integrated Mobile Mapping Systems, and the Vice-Chair of the special study group for mobile multi-sensor systems of the IAG. Dr. El-Sheimy's research interests include multi-sensor systems, mobile mapping systems, real-time kinematic positioning and digital photogrammetry.

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