±2ppm Frequency Drift and 300x Reduction of Bias Drift of Commercial 6-Axis Inertial Measurement Units Using a Low-Power Oven-Control Micro Platform

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***Abstract*—The performance of a commercial 6-axis (3-axis accelerometer and 3-axis gyroscope) MEMS inertial measurement unit (IMU) has been improved by a factor of >300x by utilizing a low-power ovenized microsystem. The IMU is thermally isolated from the external ambient by mounting it on a custom-designed micro-machined glass platform and packaging it in vacuum. In the present study, a microcontroller and voltage-controlled current source are assembled together with the thermally-isolated packaged IMU on a printed circuit board. The entire system is thermal-cycled over a temperature span from -40°C to 85°C. Both temperature control (i.e., ovenization) and compensation are used to reduce bias drift due to temperature change. The measured frequency drift of the IMU is improved by a factor of 950x and stabilized to ±2ppm, and the bias drift of the IMU is reduced to 60 °/hr for one of the gyroscope axes, and 1.7 mg for one of the accelerometer axes.**

Keywords—accelerometer; gyroscope; temperature compensation; oven-control system; inertial measurement unit; hermetic package; bias drift;

I. INTRODUCTION

MEMS resonators and inertial measurement units (IMUs) have achieved significant improvement in their speed, accuracy, size, power, and cost over the past several years. These have been accomplished by improving the device structure, fabrication technology, packaging, interface circuits, and better understanding and design of the device. The overall accuracy and performance of these devices is affected by several parameters, of which temperature is the most difficult and challenging. Temperature-induced errors pose a number of problems for most sensors. In some cases, some of these errors can be compensated out using a variety of techniques. However, it has been shown that compensation alone is not sufficient to improve the performance (primarily bias stability) by more than a factor of about 10 or so. Temperature control is another technique where drift due to temperature variations can be significantly reduced. In this approach, the device is maintained at a nearly constant temperature through the use of a closed-loop feedback system, where a temperature sensor is used to measure changes in the external environment temperature, and a local heater is used to keep the device at a constant temperature, usually above the highest nominal environment temperature. In order to reduce power dissipation, the heater and the device being ovenized need to be well isolated from the surrounding environment. This is achieved by supporting the device, heater and temperature sensor on an isolation platform, which is thermally isolated from the external environment. Thermal isolation is dominated by solid conduction through tethers that mechanically attach the system to its package, and by conduction through the medium (typically a gas) surrounding the device. To minimize this gas conduction, the device and its isolation platform would be ideally packaged in a vacuum environment. This temperature control approach has been long used in oven-controlled crystal oscillators (OCXO), which provide much superior performance compared to their non-ovenized counterparts [1]. However, most existing OCXOs consume a significant amount of power since thermal isolation is somewhat compromised due to high solid and gas conduction. To reduce power consumption, several groups have developed integrated approaches to forming the isolation platform and vacuum packaging [2-6]. These approaches can be categorized into several areas, those which monolithically integrate the resonator (or sensor) and the isolation platform into a single device, and those where the device being controlled is hybrid-attached to the isolation platform [6]. While the former approach has the potential of reducing size and power dissipation, it is limited because the sensor of interest has to be fabricated and integrated with the oven control system using the same fabrication technology. The latter approach provides the design flexibility and modularity whereby any device can be mounted on a standard isolation platform and packaged in vacuum to reduce power dissipation, and achieve reasonably small size and good thermal isolation [6]. This paper reports detailed measurement results of a miniature ovenized inertial measurement system that utilizes a commercial off-the-shelf multi-axis IMU and a custom designed isolation platform [6] and vacuum package to significantly improve bias stability. The basic structure and fabrication technology for the isolation platform were presented in [6]. The ovenized system presented here is modular, and provides reduced power dissipation, and on-platform temperature sensing and heating.

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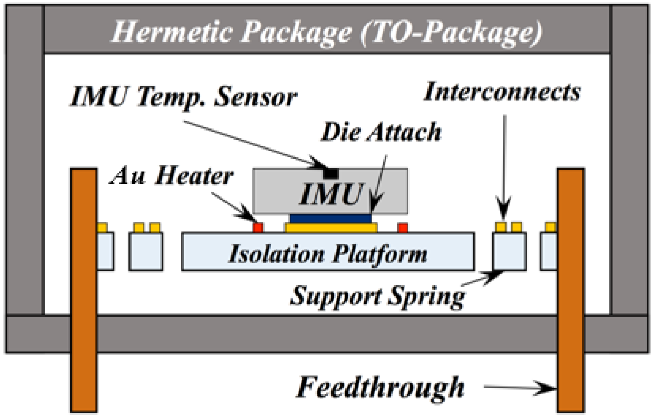

Fig. 1: System architecture and structure of the hermetically sealed and ovenized 6-axis commercial IMU.

II. VACUUM PACKAGED OVEVIZED SYSTEM FOR 6-AXIS IMU

Fig. 1 shows the diagram of the complete ovenization system for packaging commerical off-the-shelf six-axis IMU chips. The IMU chip is attached to an isolation platform using standard conductive expoxy. The IMU chip could also be surface mount attached to the platform. The platform is suported using several tethers that attach it to pins in a standard TO can package.

The isolation platform chip is fabricated from glass. A glass wafer is patterned and etched to form the complete platform. This platform consists of suspensions that support a suspended platform. These glass suspensions provide excellent mechanical support, very low thermal conductance, and a smooth surface where interconnect lines and thin-film sensor and heater can be formed [6]. A thin-film gold heater is formed under the area where the IMU die is attached. A thin-film temperature sensor is formed around the perimeter of the suspended platform. Electrical signals are carried between the devices on the suspended platform and the metal pins of the TO package using interconnect lines that are formed and passed through the suspensions. The entire system is capped using a metal package and sealed in vacuum for improved thermal isolation.

III. OVEN CONTROLLED SYSTEM

Fig. 2 shows the diagram of the complete low-power oven-control system. The hermetically-packaged and thermally-isolated IMU package shown in Fig. 1 is operated in a closed-loop system where both temperature compensation and temperature control through the ovenized system are provided to reduce bias drift against temperature variations. Temperature is measured using two sensors, one that is formed on the isolation platform, and one that is included in the IMU sensor package. The IMU temperature is obtained from an integrated temperature sensor included in the commercial IMU chip. The IMU output is compensated using data measured from an ambient temperature sensor. The sensor is maintained at a constant temperature using a heater on the platform, which is controlled through a PID controller and driven through a voltage-controlled current source (VCCS).

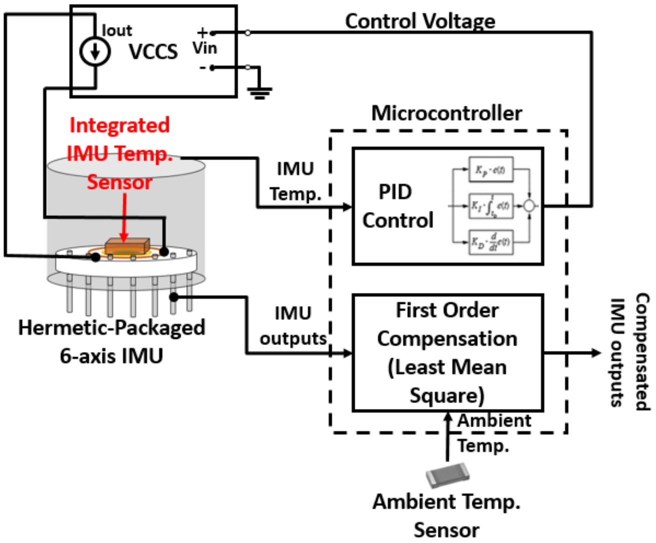

Fig. 2: Block Diagram of Low-Power Oven-Control System.

This combined temperature control and compensation scheme reduces IMU temperature-induced bias drifts. The details of the control and compensation approaches are discussed below.

A. PID controller

A Pproportional-integral-derivative (PID) controller utilizes proportional, integral and derivative control errors:

$$V = K_P T_E + K_I \int T_E \, dt + K_D \, dT_E/dt \tag{1}$$

where V is the controller output, T_E is the temperature error, and K_P, K_I, and K_D are P, I and D terms, respectively. The simple proportional control (P term) enables a faster start-up of the control system, while the integral control (I term) and derivative control (D term) are responsible for minimization of the final error and reduction of the overshoot, respectively. Selecting proper PID parameters for the system is important for a fast and stable control system.

B. Voltage-Controlled Current Source (VCCS)

A voltage-controlled current source (VCCS) converts the output voltage produced by PID controller to a a costant current tht drives the heater on the suspended platform. Ideally, the VCCS should have the following input-output relationship:

$$I_{out} = g_m V_{in} \tag{2}$$

where I_{out} is the output current, g_m is the conversion gain, and V_{in} is the input control voltage. For improved control, the conversion gain, g_m, needs to be constant regardless of the load. Fig. 3 shows the circuit diagram of the VCCS used in

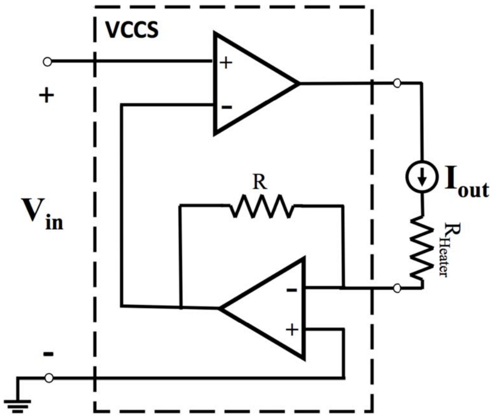

Fig. 3: Load-independent voltage-controlled current source (VCCS).

this system. It is easily shown that the relationship between the input voltage (in this case V_{in}) and the output current (in this case I_{out}) is given by:

$$I_{out} = V_{in}/R \tag{3}$$

Therefore, the heater current is independent of the heater resistance, as desired for an ideal VCCS.

C. Temperature Compensation

Since the commercial 6-axis IMU is packaged in an epoxy molding compound (EMC) typically used in plastic-molded packages, and since it is mounted on a glass suspension platform, it is expected that a significant temperature-induced stress due to the difference in coefficient of thermal expansion (CTE) between the EMC and glass platform exists, which in turn causes bias drift even at a constant temperature. These effects are repeatable, and can be removed to a first order using a compensation algorithm with the aid of an ambient temperature sensor. The equation used for this compensation is:

$$S_{comp} = S - (a_1 T_{amb} + a_2 P + a_3) \tag{4}$$

where S_{comp} and S are IMU outputs after and before compensation, respectively, T_{amb} is the ambient temperature, P is the power consumption, and a_1, a_2 and a_3 are compensation coefficients.

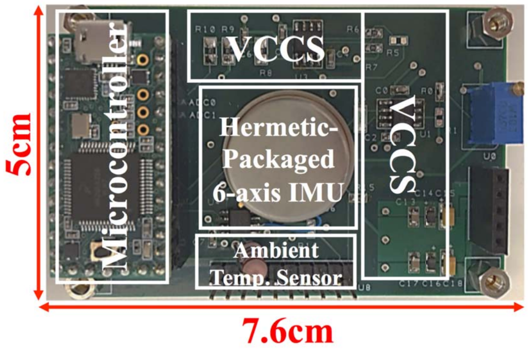

Fig. 4: Printed Circuit Board supporting the microcontroller, VCCS, and the hermetically-sealed and thermally-isolated IMU.

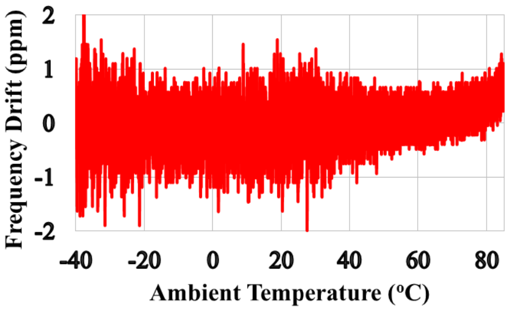

Fig. 5: Measured frequency drift of the oven-controlled IMU chip.

IV. EXPERIMENTAL RESULTS

A 32-bit microcontroller was used to implement the PID controller, first order compensation and communication with the 6-axis commercial IMU. The microcontroller, VCCS, and hermetically-packaged 6-axis IMU were asselmbled on a single printed circuit board, as shown in Fig. 4. The size of the entire system is 7.6cm x 5cm. The system was placed in an oven chamber for the thermal-cycle test. The temperature of the oven chamber was ramped from -40°C to 85°C at 1°C/min, and the IMU temperature was controlled to 92°C. Fig. 5 shows the measured real-time frequency drift of the x-axis gyroscope during the thermal-cycle test. The frequency drift of the IMU was originally about ±1900ppm, and was reduced to ±2ppm over the entire temperature span. Fig. 6 shows the bias errors of the 3-axis gyroscope without and with the oven-control system turned on. The bias drift for the x-axis gyroscope was reduced by a factor of 336 from 20,841°/hr to 62.08°/hr. Fig. 7 shows the bias errors of the 3-axis accelerometer without and with the oven-control system. The bias drift of the z-axis accelerometer was reduced from 173.5mg to 1.386mg, which is an improvement of 125x. Other axes of gyroscopes and accelerometers also showed large bias drift reduction of greater than 50x. The heater power consumption over the entire temperature span was less than 100mW.

V. CONCLUSION

An oven-control system for a commercial 6-axis IMU (3-aixs gyroscopes and 3-axis accelerometers) is presented. With the ambient temperature change of 125°C, from -40°C to 85°C, the resonant frequency drift of the gyroscope was reduced from ±1900ppm to ±2ppm, which is 950x of improvement. During the same thermal-cycle tests, the bias drift of the gyroscope X-axis was reduced from 20,841°/hr to 62.08°/hr, a reduction of 336x. Similarly, the bias drift of the accelerometer Z-axis showed an improvement of a factor of 125x, from 173.5mg to 1.386mg. Other axes also showed significant bias drift reductions by more than a factor of 50x. The heater power consumption was less than 100mW for the entire temperature span, and the size of the entire system is 7.6cm x 5cm.

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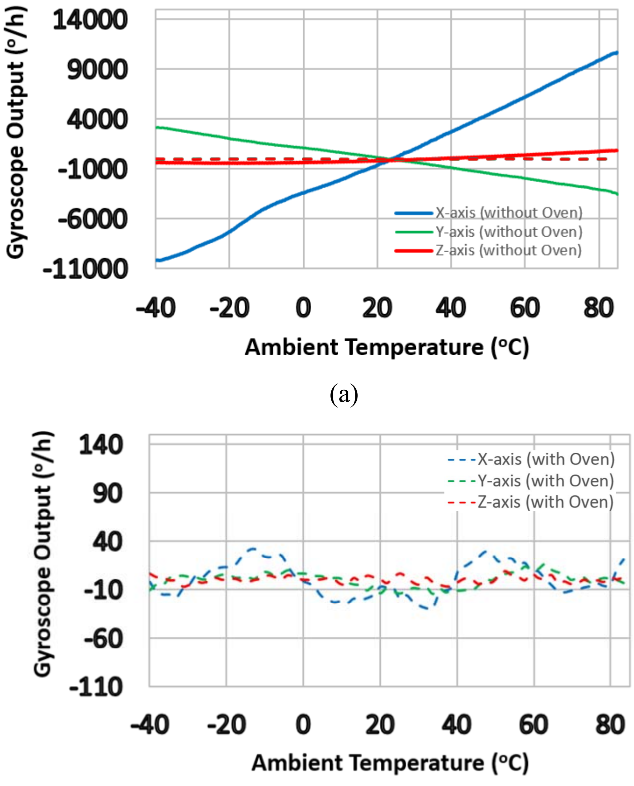

(a)

(b)

Fig. 6: Measured gyroscope output (a) without, and (b) with oven-control.

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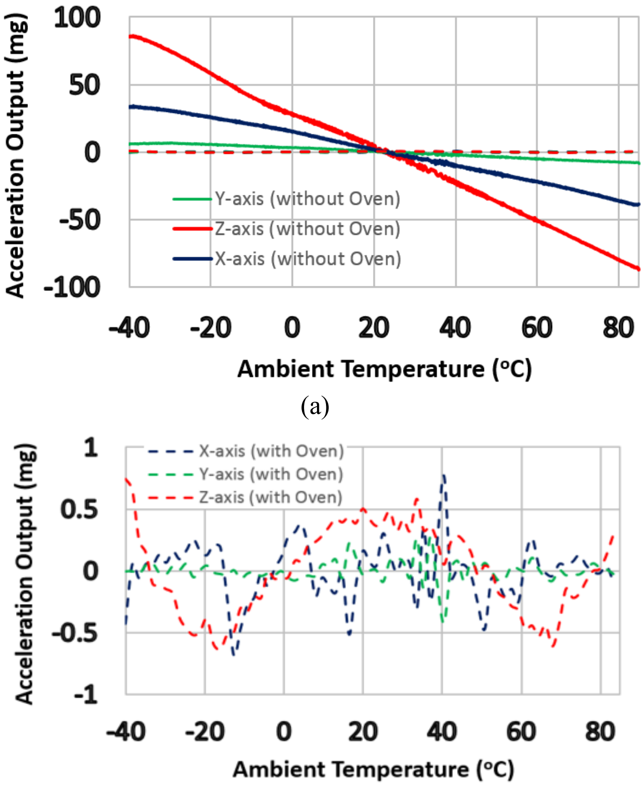

(a)

(b)

Fig. 7: Measured accelerometer output (a) without, and (b) with oven-control.

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