NORTH-FINDING WITH 0.004 RADIAN PRECISION USING A SILICON MEMS QUADRUPLE MASS GYROSCOPE WITH Q-FACTOR OF 1 MILLION
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ABSTRACT
We demonstrate north-finding capability with a measured 4 milliradian (mrad) 1-σ uncertainty using an in-house developed vibratory silicon MEMS quadruple mass gyroscope (QMG). We instrumented a vacuum packaged QMG with isotropic Q-factor of 1.2 million and bias instability of 0.1 °/hr for azimuth detection by measuring the Earth’s rotation. Continuous rotation (“carouseling”) produced azimuth datapoints with uncertainty diminishing as the square root of the number of turns. Integration of 100 datapoints with normally distributed errors reduced uncertainty to 4 mrad, beyond the noise limit of the QMG. We also implemented self-calibration methods, including temperature compensation and discreet calibration methods, including temperature compensation and discreet turnover (“maytagging”) as potential alternatives to the carouseling.

INTRODUCTION
North-finding with single digit mrad precision is required for setting the initial orientation in the dead reckoning and targeting. Practical limitations of geodetic, celestial, magnetic, and GPS-based methods make high performance gyroscopes desired for true North finding (“gyrocompassing”). Although commercially available fiber optic, ring laser, and hemispherical resonator gyroscopes can be used for precision gyrocompassing, they are not perfectly suited for man-portable or handheld systems due to their size, weight and power (SWaP) characteristics. North-finding based on micromachined gyroscopes is an intriguing possibility, but silicon MEMS are yet to establish credibility in the high-precision domain [1]. gyrocompassing requires repeatable and stable measurements of extremely low angular rates (fractions of the Earth’s rate). For instance, a bias drift of only 1 °/hr leads to a 100 mrad azimuth uncertainty at a 45° latitude, which translates into a 9 m location error per each 100 m of dead reckoning or targeting.

Several approaches have been explored for the reduction of drift in MEMS gyroscopes, including carouseling [2,3] and maytagging [4]. Nevertheless, single digit mrad error is often assumed unattainable by MEMS technology. Our latest progress in the design, packaging and control electronics has enabled sub-degree per hour MEMS quadruple mass gyroscope (QMG) [3,5]. This paper reports the development and application of the high performance micromachined QMG for gyrocompassing.

NORTH-FINDING TEST-BED
The section describes a north-finding setup consisting of a QMG sensor, a tilt stage, and a rate table, Figure 1.

Sensor and Electronics
A stand-alone QMG [3] was fabricated using an in-house SOI process and vacuum sealed using the ceramic package level technology. The QMG sensor was mounted on a PCB with front-end amplifiers and installed on the 1291 Ideal Aerosmith rate table enclosed in a thermal chamber. All reported experiments were carried out using a custom PCB connected to a HF2 digital lock-in amplifier from the Zurich Instruments (ZI), providing control and signal conditioning for the QMG [3].

For the angular rate measurements, the drive-mode was operated closed loop; the sense-mode remained open loop. A PLL drive loop sustained oscillation at resonance and provided reference for signals demodulation. An automatic gain control (AGC) stabilized the amplitude of drive motion. Rotation was detected by demodulating the sense-mode signal. The rate measurements were performed at a 0.16 Hz separation between the drive- and the sense-mode frequencies.

Sensor Characterization
The mechanical characterization of the QMG sensor with a 2 kHz resonant frequency was performed by ring-
Temperature Self-Compensation

Most MEMS devices are sensitive to environmental fluctuations and require temperature compensation. For instance, high stability resonators employ secondary mode as a thermometer for self-compensation of primary mode drifts [6]. While the drive-mode of the QMG is controlled by PLL and AGC closed loops, the sense-mode mode is open loop and susceptible to temperature variations. The uncompensated temperature sensitivity of 1000 °C/ppm is customary for MEMS [7], and presents a challenge for the long-term measurements of the Earth's rate (15 °/hr).

Similarly to high stability resonators, we utilized the drive-mode frequency for a self-compensation of the gyro sense-mode drifts. A change in drive frequency (relative to the ovenized quartz reference) acted as an embedded thermometer free from thermal lag or hysteresis. The TCF of the QMG was determined using a 10−4°C resolution thermistor from GEC Instruments. The room temperature and frequency were recorded for 24 hr and analyzed using the Allan deviation.

The temperature self-compensation using the drive-mode frequency as thermometer improved the QMG bias sensitivity to below 0.5 °/hr°C uncertainty, Figure 5, attesting feasibility of the long-term stable measurements required for the north-finding.

NORTH-FINDING BY MAYTAGGING

This section presents 2-point gyrocompassing results.

Basic Principles

The true North orientation (as opposed to the magnetic North) is found by observing the horizontal (tangential) component of the Earth's rotation vector. Since MEMS gyroscopes may exhibit long-term drift (not induced by temperature), a bias compensation is required for north-finding. A 2-point gyrocompassing [4] mitigates additive bias errors through differential azimuth measurement. The azimuth detection is accomplished by the ±180° turning (maytagging) of the gyroscope sensitive axis. The outputs of the gyroscope aligned to a local vertical level during maytagging are:

\[
\omega(0) = \Omega_x \cos \alpha + b, \tag{1}
\]

\[
\omega(180) = -\Omega_x \cos \alpha + b. \tag{2}
\]
Experimental Results

The North direction was detected by changing the rotation vector. The horizontal component was observed after orienting the QMG sensitive axis parallel to the local horizontal plane, as shown in Figure 1. A rate table was used to position the gyroscope in the local horizontal plane.

Error Propagation

The maytagging approach assumes constant bias during the 2-point gyrocompassing. The uncompensated bias \( \delta \) propagates to a differential azimuth measurement:

\[
\delta(0) - \delta(180) = 2\Omega_E \cos \alpha + \delta_b,
\]

and corrupts calculation of the true azimuth value \( \alpha \): \n
\[
\alpha = \arccos \left( \frac{\cos \alpha + \delta_b}{2\Omega_E} \right) = \alpha - \delta_b / (2\Omega_E |\sin \alpha|). \tag{4}
\]

The equation suggests error reduction for angles \( \alpha = \pm 90^\circ \). In other words, best precision is achieved by maytagging in the East-West direction (as opposed to North-South).

Figure 6: Measured projection of Earth’s rate as function of azimuth using the differential maytagging approach. Gyro output is 12.6°/hr (Irvine, CA) if pointing North.

Figure 7: Azimuth histogram with normal distribution fit after temperature self-compensation, showing a 40 mrad error of East-West maytagging. Inset: raw histogram.

Figure 8: Azimuth error (1-\( N \)) as a function of number of filtered measurements using Fig. 7 data. Error scales down as 44 mrad/\( \sqrt{N} \), resulting in 8 mrad after \( N = 30 \).

NORTH-FINDING BY CAROUSELING

In this section we evaluate the carouseling approach for the bias compensated north-finding [2]. In contrast to the discreet maytagging, the carouseling requires continuous rotation of the gyroscope sensitive axis. The technique relies on modulation of the constant Earth’s rate to separate bias, scale factor, and temperature errors.

The QMG sensor mounted on a rate table was rotated in local horizontal plane with 1°/s rate. This resulted in periodic rotation of the QMG sensitive axis and modulation of the Earth’s constant rate with a 6 min period. Figure 9 shows a QMG output from a carouseling run. As expected, the sinusoidal variation was maximum,

\[
\Omega_E - \delta \approx \Omega_E + \delta \tag{3}
\]
Figure 9: QMG output produced by the Earth's rotation (12.6°/hr at 33° latitude) during a 1°/s carouseling, generating amplitude modulation with a 6 min period.

Figure 10: Histogram of 400 azimuth datapoints with normal distribution fits obtained by the carouseling, showing convergence of uncertainty from 37 to 3 mrad.

Figure 11: Azimuth uncertainty as a function of number of filtered measurements from Fig. 10 data. A 4 mrad uncertainty is achieved by filtering of N = 100 points.

CONCLUSIONS

We demonstrated a silicon MEMS quadruple mass gyroscope with 0.1°/hr bias instability and 1.2 million Q-factor, capable of north-finding with 4 mrad precision. Carouseling and maytagging methods were implemented for true North detection using the Earth's rotation. Both methods produced an azimuth estimation with uncertainty σ diminishing as the square root of the number N of turns, σ(N) = 40 mrad/√N. The carouseling was robust to bias and scale factor changes, but required precise continuous rotation. The maytagging relied on 180° turns, but required temperature calibration. These results clearly show feasibility of silicon inertial MEMS for precision north-finding, currently limited to high resolution macro gyroscopes or magnetic compasses. The ongoing work is expected to reduce north-finding time down to a minute.

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