MULTI-DOF INERTIAL MEMS: FROM GAMING TO DEAD RECKONING

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ABSTRACT
This paper presents an overview of multi degrees-of-freedom (DOF) inertial MEMS in applications ranging from gaming to dead reckoning. Approaches to the implementation of high-performance inertial measurement units (IMU) are examined, focusing on challenges related to tri-axial gyroscope implementation. Benefits and tradeoffs of homogeneous multi-axis sensors are reviewed and contrasted with advances in single-chip integrated IMUs.

KEYWORDS
Inertial measurement unit (IMU), accelerometers, gyroscopes, magnetometers, degrees of freedom (DOF)

MULTI-DOF MOTION AND POSITION SENSING
The motion and position of an object in space can be accurately mapped through the use of a ten degrees-of-freedom (10-DOF) sensing microsystem comprising a three-axis accelerometer, a three-axis gyroscope, a three-axis magnetometer and a barometer. Accelerometers measure linear motion along the x, y, and z axes (axial acceleration), while gyroscopes measure rotation (angular velocity) around these axes [1]. Magnetometers provide heading information by measuring the earth magnetic field, whereas barometers measure atmospheric pressure to determine the relative altitude of an object. Such a motion and position measurement and processing unit can be used to enable dead reckoning for pedestrian and in-door navigation, and to improve the accuracy, speed and efficiency of outdoor navigation (in conjunction with GPS) especially in densely populated urban areas. 6-DOF inertial measurement units (IMU) consisting of accelerometers and gyroscopes are being deployed in a myriad of consumer, automotive and industrial applications such as gaming, image stabilization in digital cameras, user interfaces, electronic stability control in automobiles, and robotics. Single-chip tri-axial silicon accelerometers are now widely available in small form factors and at low cost [2-4]. Single-chip tri-axial gyroscopes have also become available [5-7], although with slightly larger form factors and higher prices. Single-package and single-chip 6-DOF IMUs have recently entered the market [8, 9], and will soon be followed by 9 and 10-DOF microsystems. However, MEMS gyroscopes are yet to break into the high-precision dead-reckoning applications; the noise and bias drift of these gyro result in fast-growing errors in computed orientation, which does not allow for extended periods of navigation.

In this paper, approaches to the implementation of high-performance tri-axial gyroscopes and IMUs will be reviewed. Given that gyroscope resolution and bias stability is the current bottleneck to achieve navigation grade performance, the paper is mostly focused on the implementation and scaling of tri-axial gyroscopes. The benefits of homogeneous multi-axis system-in-package (SiP) sensors are presented, followed by a discussion on the advances of single-chip or system-on-chip (SoC) IMU implementations. Lastly, future trends and challenges in multi-DOF systems are briefly examined.

HIGH FREQUENCY BAW GYROSCOPES
Low-frequency flexural-mode vibratory gyroscopes (Fig. 1) have been widely investigated over the past two decades. They rely on increases in mass and vibration amplitude for higher SNR. SEM of (top) a Class-I mode-matched tuning fork gyro (M³-TFG) [10], and (bottom) a Class-II multi-shell resonating star gyro (RSG) [11] are shown.

Figure 1. Low frequency (kHz) flexural mode gyroscopes rely on increases in mass and vibration amplitude for higher SNR. SEM of (top) a Class-I mode-matched tuning fork gyro (M³-TFG) [10], and (bottom) a Class-II multi-shell resonating star gyro (RSG) [11] are shown.

The fundamental mechanical noise equivalent rotation rate \( MNE\Omega \) of a resonant shell gyro scope is given by (1),

\[
MNE\Omega \equiv \frac{1}{2mA_o^{x_{drive}}\sqrt{\frac{4k_B T}{M_{eff} \omega_o Q_{eff}}} \sqrt{BW}}
\]

where \( k_B \) is the Boltzmann constant, \( T \) is the temperature and \( BW \) is the measurement bandwidth. The quantities \( m, A_o, M_{eff}, Q_{eff} \) are the mode shape number, angular gain,
effective mass and quality factor of the device, respectively; the parameter $x_{\text{drive}}$ represents the displacement amplitude of the drive resonance mode. It is clearly seen that if the frequency $\omega_d$ is scaled up from the conventional kHz range to MHz, noise levels can be significantly reduced without requiring large and massive structures, assuming one can still achieve high quality factors ($Q$) for operating frequencies in MHz.

High-frequency and high-$Q$ bulk acoustic wave (BAW) modes of a disk resonator (Fig. 2) can be used to sense rotation around a normal axis [12]. If two of these high-$Q$ modes have identical frequencies, the device is said to be in a mode-matched condition, yielding $Q$-times higher rotation sensitivity as compared to moving-mass architectures that use a single resonance mode [5-7]. In turn, this allows operating the gyroscope as either a large bandwidth angular rate sensor, or a whole-angle mode unit capable of providing direct angle measurement [13].

In order to excite the acoustic modes of a disk resonator, large electrostatic forces are needed, which require strong capacitive coupling. This can be obtained by using high aspect-ratio narrow capacitive gaps [14]. Fig. 2 shows a 600µm diameter solid-state single crystalline silicon disk gyroscope implemented in a thick SOI substrate (30-60µm) with deep sub-micron capacitive gaps (100-200nm). The device has a degenerate secondary elliptical bulk mode at ~10MHz with a $Q \sim 20,000$ in low vacuum, attaining a large open-loop bandwidth of ~250Hz albeit the high $Q$, which is due to the megahertz operation of the gyro. In contrast, low frequency mode-matched gyros [10, 11] need high vacuum (<10mTorr) to achieve similar level of $Q$s, and yield much smaller open-loop $BW$ (<1Hz).

The electromechanical sensitivity $S_z$ of a mode-matched gyro is given by (2), where $A_{\text{cap}}, V_p$, and $g_o$ are the capacitive transduction area, DC polarization voltage, and rest capacitive gap, respectively.

$$S_z = \frac{I_{\text{out}}}{\Omega_z} \equiv \frac{2m\epsilon_0 A_{\text{cap}}Q_{\text{eff}}V_p}{g_o^2} x_{\text{drive}}$$

(2)

This shows that, in addition to their increased bandwidth, reduced Brownian noise and small form factor, the sensitivity of BAW gyros is independent of the frequency $\omega_d$, as long as the values of $x_{\text{drive}}$, and $Q$ remain constant. In reality, the vibration amplitude $x_{\text{drive}}$ is inversely proportional to $\omega_d^2$ (3) and will have to drop to less than 50nm in MHz, but this dependence can be counteracted either by increasing the drive voltage $V_p$ or decreasing the gap size $g_o$.

$$x_{\text{drive}} \equiv \frac{\epsilon_0 A_{\text{cap}}Q_{\text{drive}}V_p}{M_{\text{eff}} g_o^2} v_{\text{sin}}$$

(3)

High $Q$ is needed to improve noise and sensitivity and reduce operating voltages. Given their large stiffness, BAW structures are less susceptible to air damping as compared to flexural devices. Since thermo-elastic damping can be negligible for a solid disk operating in a vacuum (<10mTorr) to achieve similar open-loop bandwidth of ~ 250Hz albeit the high $Q$s, and yield much smaller open-loop $BW$ (<1Hz). The SOI substrate (30-60µm) is used to fabricate a disk gyroscope implemented in a thick SOI substrate (30-60µm) with deep sub-micron capacitive gaps (100-200nm). The device has a degenerate secondary elliptical bulk mode at ~10MHz with a $Q \sim 20,000$ in low vacuum, attaining a large open-loop bandwidth of ~250Hz albeit the high $Q$, which is due to the megahertz operation of the gyro. In contrast, low frequency mode-matched gyros [10, 11] need high vacuum (<10mTorr) to achieve similar level of $Q$s, and yield much smaller open-loop $BW$ (<1Hz).

The electrical noise equivalent rotation rate ($ENQE$) of a gyroscope is directly proportional to the electronics input referred spot noise $I_a$, and inversely proportional to the electromechanical sensitivity (4).

$$ENQE = \frac{I_a}{S_z} \sqrt{BW}$$

(4)

Therefore, interface ICs with low input referred current noise at MHz are needed to achieve navigation grade performance [16].

The large stiffness of BAW devices also provides a wide dynamic range of operation. In motion sensing, there are applications that have varying requirements for the upper and lower detection range. For example, consider gaming where the sensors have to be able to detect dramatic motions like swinging a tennis racket or a golf club and at the same time detect fine touch motions like putting. The term dynamic range refers to the ratio of the largest detectable signal (in linear range) to the smallest detectable signal. The dynamic range of the BAW gyro is given by (5), where the measurement bandwidth $BW$ is assumed to be the device resonance bandwidth $\omega_d/(4Q_{\text{eff}})$. A wide dynamic range in a low-noise gyro is highly desirable as it allows the use of a single device with a high level of stability in a broader array of applications, ranging from gaming to navigation.
HOMOGENEOUS TRI-AXIAL GYROS & IMU

Through 3D assembly of identical single-axis sensors into a single package, SiP implementations of homogeneous tri-axial gyros, IMUs and magnetometers with high level of uniformity in sensitivity, noise, and dynamic range can be realized. Signal coupling and cross-axis sensitivity are also much reduced as compared to single proof-mass or mechanically-coupled designs, given that single-axis sensors can be designed to provide high common-mode rejection ratios and high attenuation of unwanted signals.

For example, in the case of BAW gyros, the response to linear acceleration is highly reduced due to the large stiffness of the solid disk. Hence, for a homogeneous 3-axis system, the cross-axis sensitivity is only dependent on the accuracy of the package level alignment of each individual sensor rather than on the structure itself. Each individual BAW gyro can be wafer-level packaged (as shown in Fig. 3) using silicon-gold eutectic bond with through-silicon-via (TSV) interconnects (Fig. 2). The use of the TSV process in combination with a small size BAW gyro provides a reduced form-factor that permits the vertical placement of die into a low-profile package. Fig. 4 shows a homogeneous tri-axial BAW gyroscope package with orthogonally mounted single-axis sensors for yaw, pitch and roll detection, being commercialized by Qualtré. By using small diameter disk gyros, a package thickness (height) of less than 1mm can be realized. A small high-performance single-axis accelerometer can be integrated with the BAW gyro on the same die to create a homogeneous SiP IMU.

SINGLE-CHIP IMU

The increased demand for small size, low cost, and low power IMUs has broadened the interest in the development of multi-DOF sensors integrated on a single die. Advances in fabrication techniques combined with innovative design have enabled the realization of these devices with some sacrifice in performance [13].

Fig. 5 shows a high frequency (~1MHz) hollow-disk gyroscope for pitch and roll detection [18]. If the structure is excited into an in-plane resonance mode (Fig. 6 left), the Coriolis force generated due to rotation along the X or Y axes couples the energy into out-of-plane modes (Fig. 6 right) with amplitudes proportional to the rotation rate. These displacements can then be transduced into electrical signals using top electrodes arranged around the hollow-disk. In addition, the wide and round central area, which is commonly utilized as a fixed support and DC polarization voltage electrode, can in fact be used to plug-in a small-size yaw BAW disk gyro to obtain a compact 3-axis rate sensor.

In a similar way, a single proof-mass 3-axis accelerometer was implemented to achieve a 6-DOF system. Figure 7 shows a SEM view of the structure [19]. The design consists of a single proof-mass supported at its center by tethers arranged in a cross-shape configuration that allows the structure to move freely when subjected to an applied acceleration. When the stimulus is along the X...
or Y-axis, the mass swings like pendulum causing a differential change in capacitance between the proof mass and two pairs of fixed electrodes placed right on top of the mass. If the acceleration is along the Z-axis, the mass deflects vertically, generating an equal change in capacitance in all four electrodes.

![Image of accelerometer](image)

**Figure 7.** Top SEM view of single proof-mass tri-axial accelerometer. Inset shows cross-sectional view of device [19].

![Image of accelerometer](image)

**Figure 8.** Integration of 3-axis accelerometers and 3-axis BAW gyros using HARPSS™ for single chip IMU.

Both the three-axis gyroscope and the three-axis accelerometer were simultaneously fabricated on a common 40µm silicon-on-insulator (SOI) substrate using a modified version of the HARPSS™ process. Fig. 8 shows a view of a functional IMU wafer. Since the high Q of high-frequency gyros can be maintained at low vacuum, the tri-axial HARPSS accelerometer of Fig. 7 with small gaps (200nm) can operate in stable conditions when co-packaged with the gyros. Despite the significant advancements towards single-chip IMU, there still exist several challenges to be overcome to achieve navigation grade performance, including reduction of noise and sensitivity to linear vibration, temperature variation, and package stress.

**CONCLUSIONS**

Three decades of advances in fabrication, design and packaging of inertial MEMS have led to a fast growing market where single-package multi-axis accelerometers and gyroscopes are being produced in high volumes and at low cost. Performance of current devices suffices the requirements of low to medium performance applications ranging from gaming to automotive. Improvements in terms of size and power consumption are still required in these applications, but more focus is being placed in the development of multi-DOF integrated microsystems for high-end applications. In particular, dead reckoning remains a key application that requires stable high-precision tri-axial gyros. The integration of sensors including IMUs, magnetometers and barometers is necessary to achieve short to medium range navigation. Since IMUs can only provide position and orientation information of an object relative to an initial point and angle, magnetic and pressure sensors are necessary to specify the initial heading value and altitude of an object in the absence of GPS, as well as to correct gyro errors periodically.

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**REFERENCES**


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