Inertial Navigation Sensors

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ABSTRACT

For many navigation applications, improved accuracy/performance is not necessarily the most important issue, but meeting performance at reduced cost and size is. In particular, small navigation sensor size allows the introduction of guidance, navigation, and control into applications previously considered out of reach (e.g., artillery shells, guided bullets). Three major technologies have enabled advances in military and commercial capabilities: Ring Laser Gyros, Fiber Optic Gyros, and Micro-Electro-Mechanical Systems (MEMS) gyros and accelerometers. RLGs and FOGs are now mature technologies, although there are still technology advances underway for FOGs. MEMS is still a very active development area. Technology developments in these fields are described with specific emphasis on MEMS sensor design and performance. Some aspects of performance drivers are mentioned as they relate to specific sensors. Finally, predictions are made of the future applications of the various sensor technologies.

INTRODUCTION

The science of guidance, navigation, and control has been under development for over 100 years. Many exciting developments have taken place in that time, especially in the area of navigation sensors. (Ref. 1, 2, 3) Today, to understand fully the entire range of navigation sensors, one needs to know a wide range of sciences such as mechanical engineering, electronics, electro-optics, and atomic physics. The fact that an inertial (gyroscope or accelerometer) sensor's output drifts over time means that inertial navigation alone has an upper bound to mission accuracy. Therefore, various aiding/augmentation sensors have been tied into the inertial systems; e.g., GPS, velocity meters, seekers, star trackers, magnetometers, lidar, etc. The wide use of GPS aiding has greatly enhanced the role of traditional navigation sensors, and has been able to provide quick, inexpensive answers to the basic navigation solution. As long as GPS is available, other augmentation sensors are not generally required for an integrated INS/GPS system. In fact, many navigation missions can now be accomplished with GPS alone, with inertial sensors used only for stabilization and control. However, the vulnerability of GPS (e.g., to jamming, or in applications where GPS is unavailable (such as indoors or in tunnels and caves), or cannot be acquired quickly enough (such as very short-time-of-flight munitions)) means that other navigation sensors will always be required. The key driver for which system architecture to use is cost for mission performance, where cost includes not only purchase but also life cycle cost. Some mission applications are extremely size- and power-restricted, so that not all inertial technologies are competitive.

Sensors are often compared on the basis of certain performance factors, such as bias and scale-factor stability and repeatability or noise (e.g., random walk). Sensor selection is made difficult by the fact that many different sensor technologies offer a range of advantages and disadvantages while offering similar performance. Nearly all new applications are strapdown (rather than gimbaled) and this places significant performance demands upon the gyroscope (specifically: gyro scale-factor stability, maximum angular rate capability, minimum g-sensitivity, high BW). For many applications, improved accuracy/performance is not

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For many navigation applications, improved accuracy/performance is not necessarily the most important issue, but meeting performance at reduced cost and size is. In particular, small navigation sensor size allows the introduction of guidance, navigation, and control into applications previously considered out of reach (e.g., artillery shells, guided bullets). Three major technologies have enabled advances in military and commercial capabilities: Ring Laser Gyros, Fiber Optic Gyros, and Micro-Electro-Mechanical Systems (MEMS) gyros and accelerometers. RLGs and FOGs are now mature technologies, although there are still technology advances underway for FOGs. MEMS is still a very active development area. Technology developments in these fields are described with specific emphasis on MEMS sensor design and performance. Some aspects of performance drivers are mentioned as they relate to specific sensors. Finally, predictions are made of the future applications of the various sensor technologies.

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necessarily the driving issue, but meeting performance at reduced cost and size is. In particular, very small sensor size allows the introduction of Guidance, Navigation, and Control into applications previously considered out of reach (e.g., artillery shells, 30-mm bullets), and many of these newer applications will require production in much larger quantities at much lower cost. This paper discusses various ongoing gyroscope and accelerometer technology developments. Specific emphasis is given to the design and performance of MEMS sensors, which continues to be a very active development area.

INERTIAL SENSOR TECHNOLOGIES

In recent years, three major technologies in inertial sensing have enabled advances in military and commercial capabilities. These are the Ring Laser Gyro (since ~1975), Fiber Optic Gyros (since ~1985), and MEMS (since ~1995). The Ring Laser Gyro (RLG) moved into a market dominated by spinning mass gyros (such as rate gyros, single-degree-of-freedom integrating gyros, and dynamically (or dry) tuned gyros) because it is ideal for strapdown navigation. The RLG was thus an enabling technology for high dynamic environmental military applications. Fiber Optic Gyros (FOGs) were developed primarily as a lower-cost alternative to RLGs, with expectations of leveraging technology advances from the telecommunications industry. FOGs are now matching RLGs in performance and cost, and are very competitive in many military and commercial applications. However, apart from the potential of reducing the cost, the IFOG has not really enabled the emergence of any new military capabilities beyond those already serviced by RLGs. High performance navigation grade (0.01 deg/h and 25 micro g) RLG and FOG IMUs are still expensive (>50k$) and relatively large (>100 cu in). Efforts to reduce size and cost resulted in the development of small-path-length RLGs and short-fiber-length FOGs. These did enable new military capabilities such as guided munitions (e.g., JDAM) and UAVs (e.g., Predator). However, as with all optical gyros, significant size reduction resulted in performance degradation even though cost reduction was achieved, so that these IMUs are around tactical grade quality (1 deg/h, 1 milli g).

MEMS inertial sensors have shown themselves to be an extreme enabling technology for new applications. Their small size, extreme ruggedness, and potential for very low-cost and weight means that numerous new applications (e.g., guided artillery shells, personal navigation) have been, and will be, able to utilize inertial guidance systems; a situation that was unthinkable before MEMS. However MEMS has struggled to reach tactical grade quality, and is only now reaching that performance.

Optical Gyros

Ring Laser Gyros (RLGs)

Although the **Ring Laser Gyro** was first demonstrated in a square configuration in 1963, it wasn't until the late 1970s and 1980s that RLG systems came into common use as strapdown inertial navigators. The RLG has excellent scale-factor stability and linearity, negligible sensitivity to acceleration, digital output, fast turn-on, excellent stability and repeatability across dormancy, and no moving parts. The RLG's performance is very repeatable under temperature variations so that a temperature compensation algorithm effectively eliminates temperature sensitivity errors. It is superior to spinning mass gyros in strapdown applications, and is an exceptional device for high-dynamic environments. The RLG is an open-loop integrating gyro i.e., its output is delta angle. However, taking samples over set time periods also provides angular rate information. Backscatter from the mirrors causes the two counter-propagating waves to lock frequencies at very low input rates, known as lock-in. This can be overcome by introducing a frequency bias by means of a piezo-electric drive which dithers the RLG at several hundred hertz about its input axis.

The **Ring Laser Gyro** is basically a mature technology, and most development efforts involve continued cost reduction, rather than efforts at performance gains. The Honeywell H-764G Embedded GPS/INS, which is based on GG1320 RLGs, is a 1-nautical-mile/hour navigator that has been installed on over 50 different aircraft types. Many ship navigation systems are being replaced with the Honeywell Mk45 RLG navigator. Northrop Grumman's (Litton's) ZLG™ (Zero-Lock™ Laser Gyro) is a four-mirror device that avoids lock-in by using a Faraday rotator and a bent light path to provide a four-beam multi-oscillator. The ZLG™ is thus two laser gyros in one, sharing identical optical paths, which reduces ARW uncertainty. The ZLG™ is used in Northrop Grumman's LN100G navigation system.

Efforts to reduce size and cost resulted in developments of small-path-length RLGs. Honeywell's 1308 and Kearfott's T-16 small-path-length systems have been widely used. As an example, the 1308 RLG system is used in JDAM. Kearfott's MRLG (monolithic RLG) systems comprise three RLGs in one block for size reduction; the T-10 three-axis RLG being approximately the size of a golf ball. There are some efforts to put RLGs on a chip, but performance is not expected to be any better than tactical grade. An example of miniaturization is the development of semiconductor ring lasers with a diameter of 3 mm. In general, small size RLGs will continue to operate in tactical grade applications

Fiber Optic Gyros (FOGs)

In the 1970s, development of the Fiber Optic Gyro was started. The motivation was that the FOG was potentially less expensive and easier to build than the RLG, and might be more accurate. In 1976, IFOG feasibility was demonstrated when an interference pattern (Sagnac effect) was discerned from light traveling CW and CCW around an optical fiber at the University of Utah.

The **Interferometric Fiber-Optic Gyro (IFOG)** defines its light path by a wound coil of optical fibers in place of the RLG's mirrors and optical cavity. The IFOG has an external broadband light source (e.g., super-luminescent diode, doped fiber) that launches light into the fiber coil, which can be from 100m to 3km in length. Light from the optical source passes through a power splitter and into an integrated optics circuit which splits the light into counter-propagating beams and then recombines them after they have traveled through the fiber coil. The recombined beam then retraces its path to the optical detector. The open-loop IFOG is not an integrating gyro like the RLG, and the phase-angle output from the detector is proportional to angular rate. However, the IFOG can be operated as an integrating gyro by the addition of a feedback loop from the detector to a frequency shifter in the integrated optics circuit. The feedback loop shifts the frequency of the light entering the coil so that the detector reads at null. The IFOG is now operating closed-loop and the frequency shift measurement from the feedback loop is directly proportional to angle, provided feedback is at rates faster than the coil transit time.

The IFOG has some advantages over the RLG in that: the light source does not require high voltage; the broadband light source prevents backscatter so there is no lock-in at low input rates; it has the potential for lower cost and lighter weight. A unique feature of the IFOG is the ability to scale performance up and down. For example, doubling the coil length will decrease angle random walk by a factor of two. However, unlike the RLG, the open-loop IFOG is limited in dynamic range and only has moderate scale factor stability. Thus, for most applications, closed-loop operation is preferred.

The **Fiber Optic Gyro** is also a mature technology [Refs 4-6] with performance comparable to the RLG. The IFOG has not yet superseded the RLG in production due partly to the large existing RLG-based industrial infrastructure. However, IFOGs continue to penetrate the market, and have found applications in lower-performing areas, especially in tactical and commercial applications, such as Unmanned Underwater Vehicles

(UUVs) and Unmanned Air Vehicles (UAVs), torpedoes, camera and antenna stabilization, land navigation, AHRS, gyrocompasses, and oil drilling. There are numerous manufacturers of short-fiber-length FOGs such as KVH, Honeywell, Northrop Grumman (Litton), LITEF (Germany), Photonetics (France, Ref 7), JAE (Japan), etc. The Northrop Grumman LN200 series IMUs may be the most widely known; some of which have silicon accelerometers [Ref 8]. To date, Northrop Grumman has built more than 50,000 tactical-grade (1 deg/h bias error) fiber gyros. Traditional FOGs tend to have coils around 2 inches (25 mm) diameter at the lower performance range, and are expected to continue to operate in tactical grade applications.

It has become apparent that IFOGs can also achieve extremely high performance (<0.0003°/hr bias stability, <0.00008 deg/√hr ARW, and <0.5 ppm scale factor inaccuracy) (Ref. 9) at reasonable cost. This makes IFOGs suitable for precise aiming of telescopes, imaging systems, and antennas, or for strategic-grade navigation of submarines (Ref 10). Advances in Fiber Optic Gyros development continue to be aimed at cost and size reduction, while maintaining performance. Some of the potentially enabling technologies are presented below.

Miniature FOGs

The development of **Miniature FOG**s has taken advantage of recent ongoing technology developments in the communications field. One of them is photonic crystal fibers (PCF) which have the potential to be one of the enabling technologies for the next generation of IFOG instruments, called PC-IFOGs. There are several key advantages of PCFs for IFOG applications: (1) tight mode confinement results in bend losses much lower than conventional fiber the limit on IFOG coil diameter is primarily due to fiber winding losses and fiber size, (2) cladding diameters less than that for conventional fiber provide the potential for tighter fiber packing, resulting in smaller coils, (3) dispersion compensation can be incorporated into the PCF resulting in less spectral distortion, and (4) light guiding in an air-core photonic bandgap fiber offers the potential utilizing mid-infrared optical wavelengths. The lowest reported losses to date are 13 dB/km for air-core bandgap fiber at 1.5 μm (Corning) and 0.58 dB/km for silica index-guided holey fiber at 1.55 μm. Reference 11 presents data from an open loop PC-IFOG test bed at Draper Laboratory, with sense coil Length x Diameter product of 2.9 in-km. The sense coil was constructed with solid core PCF provided by OFS Laboratories. Earth's rotation was measured with an error less than 0.02 deg/h and ARW was 0.01 deg/ rt h. Figure 1 shows the major characteristics of the OFS fiber in which the diameter of the holes and the spatial period between the holes makes the fiber endlessly single mode, resulting in reduced relative intensity noise (RIN). Also shown is a schematic of the bench top test bed plus the Allan variance.

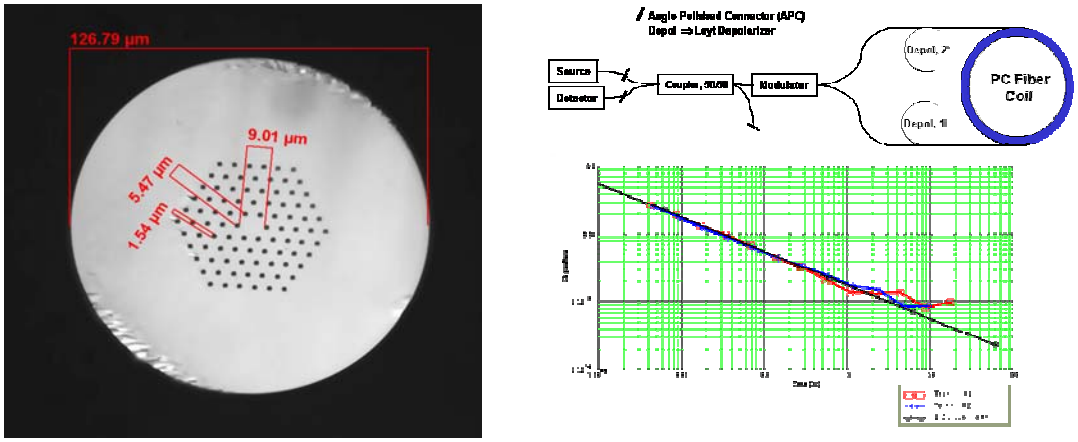


Figure 1. Photonic Crystal Fiber IFOG (PC-IFOG)

Another step in miniaturizing FOGs is the development of a monolithic optical chip which contains the source and detector as well as the modulator. However, overcoming problems of backscatter and residual intensity modulation must be resolved.

Another technology suitable for miniaturizing the FOG has been around since the early 1980s, but never perfected. This is the **Resonant FOG (RFOG)** which utilizes short lengths of fiber in which the cw and ccw light beams are kept in resonance. This requires a very narrow-band light source and low loss fibers. RFOGs offer the potential for equivalent IFOG performance, but with coil lengths up to 100 times shorter. Reference 12 presents a hollow core (photonic bandgap) fiber RFOG concept that may overcome the performance barriers of the past. Laboratory test data from a hollow core fiber ring resonator indicated very low losses and a stable resonance peak with low temperature sensitivity. Performance projections for an RFOG instrument using this fiber indicate 0.001 deg/rt h ARW is achievable with a 10 meter fiber in a 10mm diameter coil.

Integrated Optics Gyroscope (IOG)

The **Integrated Optics Gyro** (or optical gyro on a chip) has been a sought-after goal for several years. The IOG is an optical waveguide based Sagnac effect gyroscope in which two beams of light travel in opposite directions around a waveguide ring resonator in place of an optical fiber. The relative position of the resonances is a measure of rotation rate about an axis that is perpendicular to the plane of the ring resonator. The IO gyros are fabricated on wafers, combining the capabilities of integrated optic fabrication and MEMS fabrication. Figure 2 shows a schematic of an IOG with all of the components on-chip as well as a close-up of an optical waveguide.

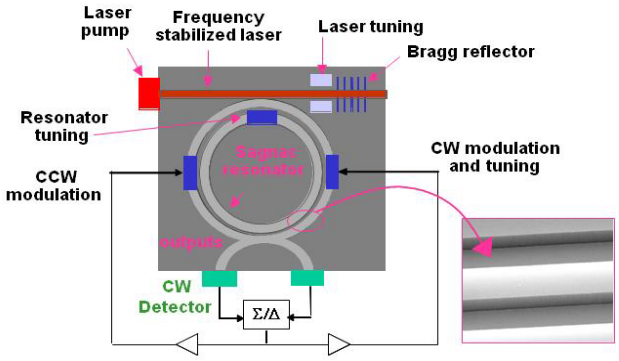


Figure 2. Integrated Optics Gyro (IOG)

One of the keys to achieving navigation grade performance (0.01 deg/h and 0.001 deg/rt h) is to be able to manufacture waveguides with losses less than 0.001 dB/cm. Current state of the art resonator waveguide losses are two orders of magnitude away [Refs 13 and 14]. Efforts are also ongoing to look at the advantages of slowing light to make an ultrasensitive optical gyroscope [Refs 15 and 16], but these are still at the basic research level. Integrated Optic technology also leads to improvements in IO chips for all Fiber Optic Gyroscopes. A large part of the cost of current FOGs involves purchasing and connecting a variety of fiber pigtailed components. A planar lightwave circuit (PLC) can replace 21 components, significantly reducing cost. IOGs are expected to be in the size range of 0.2 cubic inches (3.25 cc) with power around 0.25W. Currently, the IO gyro is targeted for 0.01 to 1 deg/hr applications met by ring laser gyros and IFOGs. However, at present, even tactical grade IOGs are still several years away.

Optical Accelerometers

Although optical readouts have very high sensitivity, optical accelerometers have not found a niche and none is available commercially. Several efforts continue on the development of fiber optic (FO)and fiber Bragg grating (FBG) accelerometers (Ref 17-20). At present, none can be considered an enabling technology for military applications. Measurement of acceleration has been demonstrated using optical microspheres, in which the change in the light coupled into an optically resonant microsphere, as the sphere moves toward a waveguide, is detected. Incorporating optical readouts into MEMS devices has also been tried with varying success. The advantages of an optical readout may only become apparent when resolving accelerations in the nano-g range for measuring seismic disturbances or gravity gradients. This means that the rest of the accelerometer‘s components must also be very low-noise. Optical accelerometers are expected to have similar applications to tunneling accelerometers.

The **light force accelerometer** is a novel device based upon the laser levitation of a dielectric particle proof mass. This basic idea was proposed over 30 years ago, but only recently has technology development driven by the telecommunications industry made possible a practical light force accelerometer (LFA). The LFA approach has several intrinsic advantages: it is a closed loop approach, linear over many decades of inertial input; the approach is capable of extreme low noise and high sensitivity. A simplified LFA implementation is depicted in Fig. 3. A particle is levitated against acceleration using a laser beam. A sensor (e.g., a split photodetector) is used to observe the particle position along the laser beam axis. As the acceleration along the laser beam axis changes, the LFA varies the laser power difference to maintain the particle’s axial position. The laser power is proportional to the acceleration applied to the particle. The architecture can be implemented using commercially available fiber pigtailed components, or custom fiber pigtailed components in conjunction with integrated optics Planar Lightwave Circuits (PLCs). A very compact instrument could be made using custom fiber optics and PLCs in conjunction with custom MEMS hardware for controlled, reproducible launching of particles. It has been estimated that with reasonable operating parameters, fundamental noise limits would permit an LFA subjected to a constant 1-g inertial input to achieve a 5 nano-g measurement error in only ten seconds of averaging. This is at the performance level required for GPS-denied navigation, but is still at the laboratory demonstration stage.

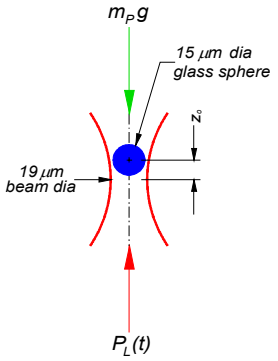


Figure 3a.
Light Force Accelerometer Concept

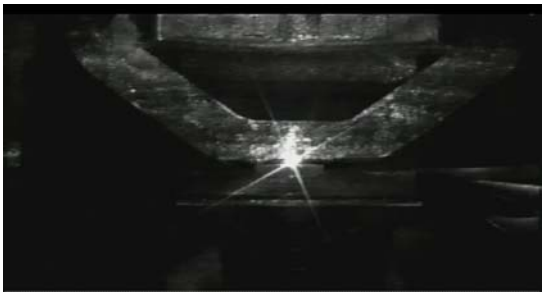


Figure 3b.
10-micron sphere levitated by a focused beam of ~75 mW

Hemispherical Resonant Gyro (HRG)

In the 1980s, Delco (now Northrop Grumman [Litton]) developed the **Hemispherical Resonator Gyro (HRG),** which is a high-performance vibratory gyro whose inertially sensitive element is a fused silica

hemispherical shell covered with a thin film of metallization. Electrostatic forcers surrounding the shell establish a standing resonant wave on the rim of the shell. As the gyro is rotated about its axis, the standing wave pattern does not rotate with the peripheral rotation of the shell but counter-rotates by a constant fraction (~0.3) of the input angle. Thus, the change in position of the standing wave, detected by capacitive pick-offs, is directly proportional to the angular movement of the resonator. In this mode of operation, termed whole angle mode, the HRG is an integrating sensor. The HRG can also be caged in a force rebalance mode to restrain the standing wave to a particular location, and acts as a rate sensor. The whole angle mode is useful when excellent scale factor stability and linearity are required over a wide dynamic range. The force rebalance mode offers excellent angle resolution for pointing operations.

The advantages of the HRG is that it is lightweight, very compact, operates in a vacuum, and has no moving parts, so that life expectance limited only by the electronics, which are provided redundantly for expected lifetimes of more than 15 years. It is a very high-Q device so that vibrations of the shell persist for several minutes after power interruptions. This tends to make it immune to radiation and electromagnetic disturbances, since the pick-off can find the pattern mode and position when power is restored. It has negligible sensitivity to acceleration. Since its debut in space in the mid-1990s, the HRG has been used on many spacecraft, including the Near Earth Asteroid Rendezvous (NEAR) spacecraft and the Cassini mission. Figure 4 shows a Space Inertial Reference Unit containing four HRGs whose hemispherical shells are 30 mm in diameter.

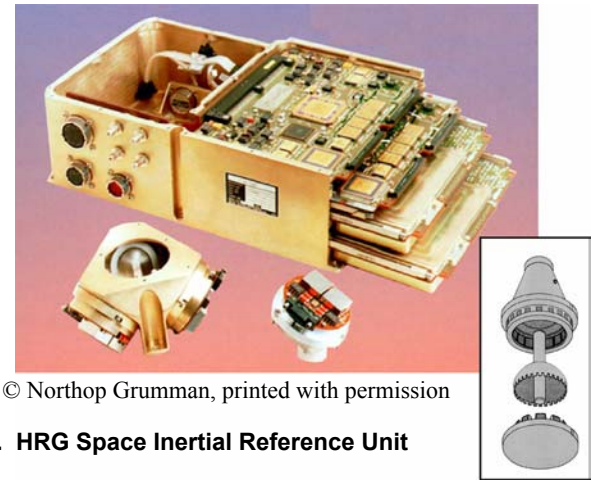


Figure 4. HRG Space Inertial Reference Unit

MEMS Inertial Sensors

MEMS inertial sensors are expected to enable so many emerging military and commercial applications that are becoming too numerous to list. MEMS is probably the most exciting new inertial sensor technology ever and development is a worldwide effort (Ref 21). Apart from size reduction, MEMS technology offers many benefits such as batch production and cost reduction, power (voltage) reduction, ruggedization, and design flexibility, within limits. However, the reduction in size of the sensing elements creates challenges for attaining good performance. In general, as size decreases, then sensitivity (scale factor) decreases, noise increases, and driving force decreases. Also, the change in Young's Modulus of silicon is ~100 ppm/°C, which leads to thermal sensitivity concerns. At present the performance of MEMS IMUs continues to be limited by gyro performance [Ref 22], which is now at around 10 - 30 deg/h, rather than by accelerometer performance, which has demonstrated tens of micro g or better. One of the most recently developed MEMS IMUs is by Northrop Grumman/Litef with performance announced at better than 5 deg/h and 3 milli g.

Currently it appears that a MEMS system with performance of around 1 deg/hr and hundreds of μg may be available by 2009. This will be a serious threat to tactical RLG and IFOG systems. Therefore, MEMS rate sensors and all-MEMS IMUs will still be restricted to commercial systems or tactical grade INS/GPS systems, and will require the integration of augmentation sensors in GPS-denied environments.

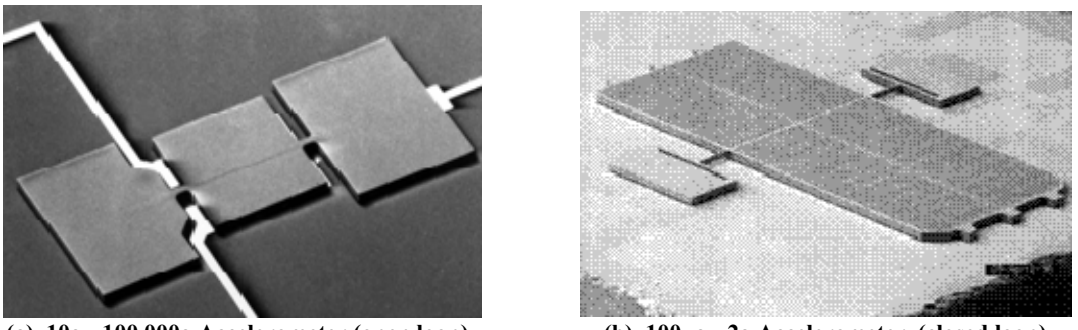
Interest in obtaining higher performing MEMS gyros is strong, and there are ongoing initiatives to move beyond the traditional Coriolis Vibratory MEMS gyro [Refs 23 and 24]. Reference 24 describes a magnetically suspended MEMS spinning wheel gyro offering navigation grade performance. However, this is in the very early stages of development. Another initiative is the DARPA BAA in 2004 for navigation grade MEMS gyros. Also, the European Space Agency (ESA) has funded several market analyses and feasibility studies [Ref 25] based on European developments of MEMS gyros by companies such as BAE SYSTEMS (UK), Bosch (Ger), EADS CRC (Ger), Litef (Ger), Sagem (Fr), SensoNor (Norway), and Thales (Fr). Desired goal is around 0.1 deg/h bias stability. In general though, it appears that production quantities of MEMS gyros with performance better than tactical grade is still several years away.

MEMS Accelerometers

MEMS accelerometers detect acceleration in two primary ways: (i) the displacement of a hinged or flexure-supported proof mass under acceleration results in a change in a capacitive or piezoelectric readout; (ii) the change in frequency of a vibrating element is caused by a change in the element's tension induced by a change of loading from a proof mass. The former includes the class usually known as pendulous or lateral displacement accelerometers and the latter are usually known as resonant accelerometers, or VBAs (Vibrating Beam Accelerometers). The pendulous types can meet a wide performance range from 1 mg for tactical systems down to aircraft navigation quality (25 μg). VBAs, or resonant accelerometers, have the potential for higher performance down to 1 μg. Numerous types of MEMS accelerometers are being developed throughout the world at universities, government organizations, and in industry.

MEMS Pendulous Mass (Z-axis) Accelerometers

Figure 5 shows typical out-of-plane (z-axis) MEMS accelerometers, in which a hinged pendulous proof mass, suspended by torsional spring flexures over a glass substrate, rotates under acceleration perpendicular to the plane of the device. Motion is detected via change in the capacitance gap using electrodes on an insulator substrate. Under a 1g acceleration, the change in angle of the proof mass is typically around 70 microradians; i.e., a $3x10^{-8}$ meter change in sense gap, which results in a 12 femtofarad (10^{-15}) peak change in capacitance. For a dynamic range of 15 g to 100 μg, it is necessary to resolve motion of $3x10^{-12}$ meters, or about 22.5 electrons charge change on the proof mass per carrier cycle.



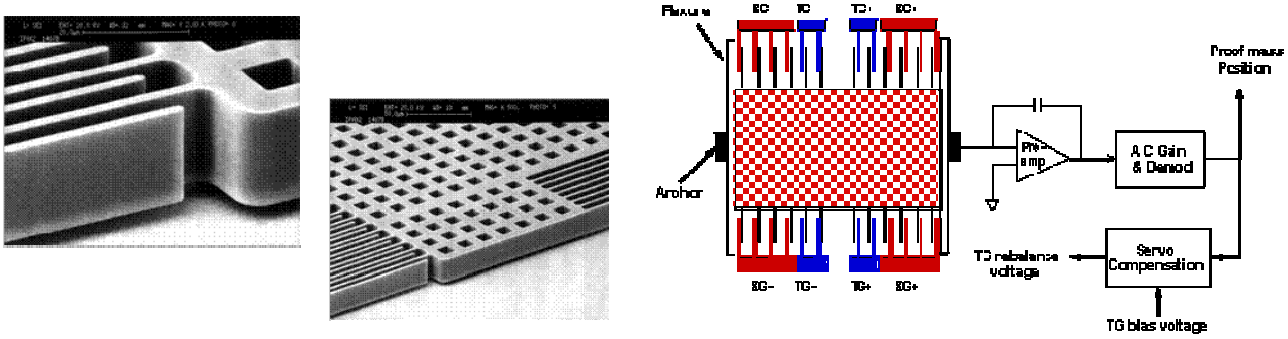
(a) 10g - 100,000g Accelerometer (open loop) **(b) 100μg - 2g Accelerometer (closed loop)**

Figure 5. MEMS Pendulous Accelerometers

A well-known example of this type of accelerometer is Northrop Grumman's SiAc™, of which over 20,000 have been produced. Two versions have been developed (tactical grade and inertial grade) and have wide usage, such as AMRAAM, GMLRS, and Commanche helicopter. Other examples are Draper/Honeywell, Applied MEMS Inc. Si-Flex™, Silicon Designs, and numerous others.

MEMS Lateral Mass-Displacement Accelerometers

Figure 6 shows an in-plane (lateral) accelerometer in which proof mass displacement is measured by the change in capacitance across the comb fingers. This accelerometer is much more sensitive to accelerations in the left-to-right (rather than top-to-bottom) direction. The combination of z-axis and lateral accelerometers results in optimized system volume, since three axes of acceleration measurement can be achieved from three planar chips.



(a) In-Plane Accelerometer **(b) In-Plane Accelerometer Schematic**

Figure 6. MEMS Lateral Accelerometer

The most well-known of the in-plane accelerometers are probably the Analog Devices ADXL150 and ADXL250. The latter measures lateral accelerations in two axes with a noise floor of 1mg/√Hz.

MEMS Resonant Accelerometers

'Resonant accelerometers' covers the general category of vibrating beam accelerometers (VBA), and can be z-axis or lateral. In resonant accelerometers, acceleration is sensed as a change in the resonant frequency of beam oscillators under the inertial loading of a proof mass, rather than measuring the mass displacement.

Z-axis resonant accelerometers have been achieved by micromachining a piezoelectric resonator in an area of high stress on one or more beams or flexures. As the flexure bends under proof mass motion, the resonant frequency changes accordingly. Examples of this type are: Systron Donner's VQA; Kearfott's Silicon Micromachined Vibrating Beam Accelerometer (MVBA); Honeywell's SiMMA; and ONERA's Quartz Vibrating Inertial Accelerometer (VIA). ONERA's VIA design is of particular interest because it has an interesting mechanical isolating system which insulates the vibrating beam from the mounting base and protects the active part from thermal stresses due to the thermal expansion differences between quartz and the case material (Ref. 26). In-run bias stability of ~100 µg has been reported.

The most accurate **MEMS resonant accelerometer** is Draper Laboratory's Silicon Oscillating Accelerometer (SOA), which has demonstrated performance of 1 micro g and 1 ppm under independent laboratory testing [Ref 27]. The SOA is a resonant accelerometer as opposed to a pendulous one. Two versions of the SOA are

under development: one for missile guidance and one for submarine navigation (SINS). The SINS version has much lower noise and reduced operational dynamic range. Figure 7a shows the Allan variance plots (standard deviation of indicated acceleration against data averaging time) for both versions of the SOA. The missile guidance SOA shows 0.5 micro g resolution over 100s averaging time and the navigation SOA shows 80 nano g resolution over 1000s averaging. The velocity random walk for both versions is calculated (using the minus ½ slope) to be 0.006 ft/s/rt h. Figure 7b shows the small size (approximately 1 cu inch) for a prototype instrument. Another resonant accelerometer is described in Reference 28, however, this is in early development and data are very limited.

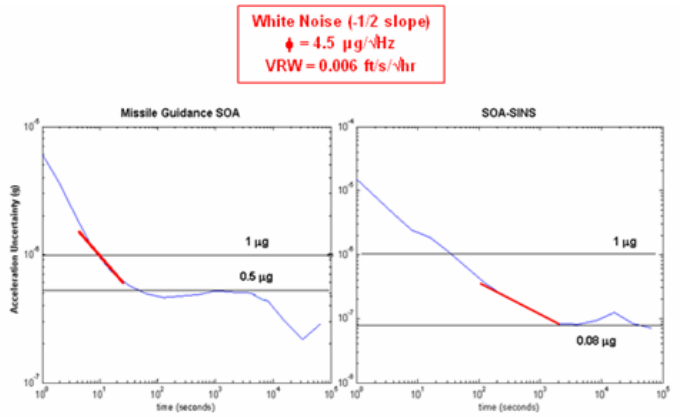


Figure 7a. Missile Guidance & SINS SOA Allan Variance

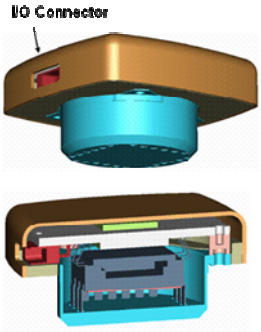
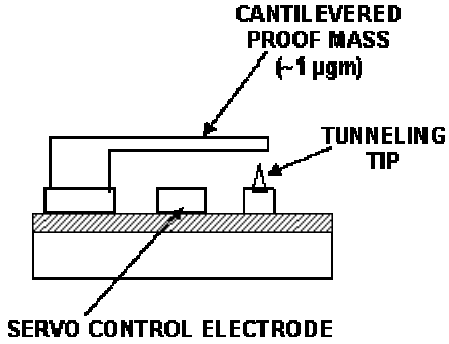


Figure 7b. SOA EMD Instrument Working Concept

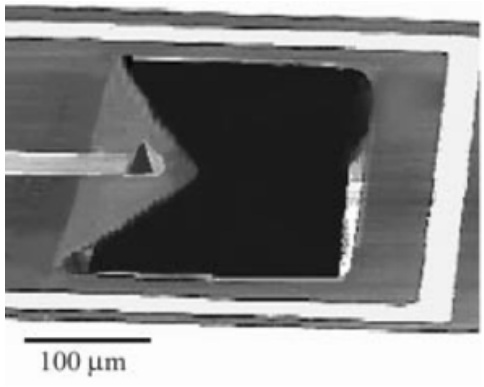
The SOA MEMS fabrication process is silicon-on-glass; the silicon is crystalline quality and perfectly elastic leading to very high precision frequency control and stability. The SOA is packaged in a high reliability ceramic vacuum package to achieve high oscillator Q, and quality factors above 100,000 are typical. SOA sensor actuation and readout requires less than 1W of power. For a 100 Hz/g scale factor and a nominal oscillator frequency of 20 kHz, a frequency stability of 5 ppb is needed for 1 µg bias stability.

MEMS Tunneling Accelerometers

A technology under development (by Hughes Research Laboratory, Stanford University, and others) that offers a very high sensitivity readout and therefore better resolution, smaller size, and higher BW than capacitive accelerometers, is the tunneling accelerometer. Figure 8(a) shows a schematic of a tunneling accelerometer. The control electrode electrostatically deflects the cantilever into the tunneling position (<1 µm and ~20V). A servo mechanism holds constant the gap between the tunneling tip (Figure 8[b]) and the cantilever, and hence holds constant the tunneling current (~1 nA). The output signal is the change in voltage at the electrode under acceleration. These devices are designed to resolve accelerations in the nano-g range, and require low-resonant frequency proof masses and sub-angstrom resolution readouts. Recent microfabricated tunneling accelerometers have resolved 20ng/√Hz over 5 Hz to 1.5 kHz (Ref. 29) with a closed-loop dynamic range of over 90dB. However, maximum acceleration measurement capability is very low (~1 mg) without further loop modification.



(a) Output is voltage required to keep cantilevered beam in fixed tunneling position during acceleration



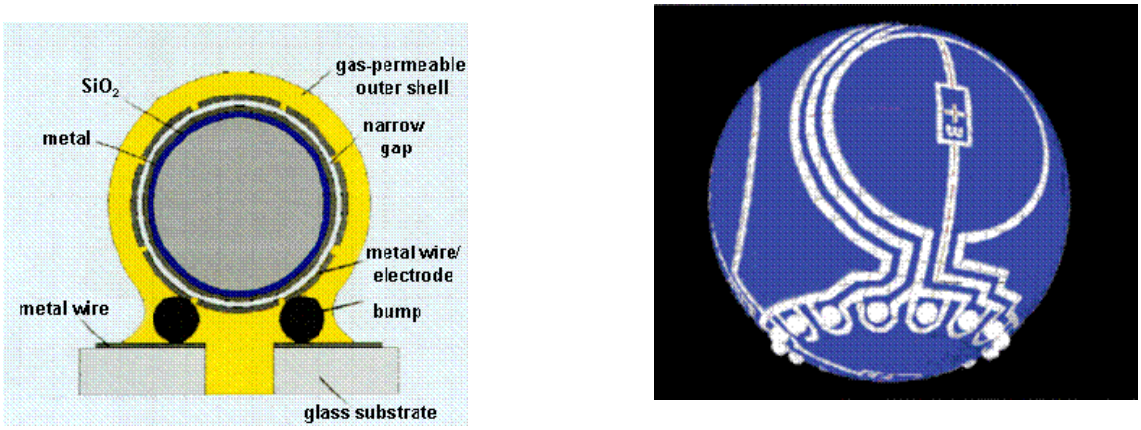
(b) A scanning electron microscopic (SEM) view of triangular nitride cantilever and tunneling tip
(See Ref. 29 © IEEE 2001)

Figure 8. MEMS Tunneling Accelerometer

Electrostatically Levitated MEMS Accelerometers

Electrostatically levitating a proof mass eliminates the need to overcome the elastic restraint of mechanical supports. Theoretically, this would result in much higher sensitivity, less dependence on certain fabrication tolerances, and more flexibility in adjusting the device characteristics to BW and sensitivity without the need to redesign flexures. A further advantage is the potential for multi-axis sensing from one device. The major obstacle to development is the complexity of the control loop.

Figure 9 (Ref. 30) shows a cross-section of a 1-mm dia., 1.2 milligram proof mass supported electrostatically. Position of the ball is sensed capacitively and closed-loop electrostatic forces maintain its position. During the MEMS fabrication process, the gap between the ball and outer shell is formed by a sacrificial layer of polysilicon, subsequently etched through the outer shell. This device is under development by Ball Semiconductor, Tokinec, Inc., Japan, and Tokohu University, Japan. For high-performance microgravity measurements in space, a noise floor of better than 40 µg/√Hz is expected. A levitated disk concept is under development at the University of Southampton, UK (Ref. 31), as well as at other organizations. A spinning levitated MEMS mass technology, if perfected, could result in an extremely accurate gyroscope.



(a) Cross-sectional View of Accelerometer (1-mm dia. proof mass)

(b) Electrode Pattern

Figure 9. Electrostatically Levitated MEMS Sphere (See Ref. 30 © IEEE 2002)

MEMS Gyroscopes

For inertial MEMS systems, attaining suitable gyro performance is more difficult to achieve than accelerometer performance. The Coriolis force is the basis for all vibratory gyroscopes. Basically, if a mass is vibrated sinusoidally in a plane, and that plane is rotated at some angular rate Ω , then the Coriolis force causes the mass to vibrate sinusoidally perpendicular to the frame with amplitude proportional to Ω. Measurement of the Coriolis-induced motion provides knowledge of Ω. This measurement is the underlying principle of all quartz and silicon micromachined gyros. There are numerous MEMS gyros under development at present (Ref. 32); however, fundamentally MEMS gyros fall into four major areas: vibrating beams, vibrating plates, ring resonators, and dithered accelerometers.

MEMS Vibrating Beam (Tuning Fork) Gyros

In 1990, Systron-Donner started initial production for the USAF Maverick missile, with 18,000 quartz rate gyros produced in 2 years. In the mid-1990s, the technology was applied to low-cost, high-volume production of yaw rate sensors, the first application being for Cadillac in 1997. Figure 10 shows Systron Donner's well-known H-shaped quartz gyro. By 2008, over 40,000 rate gyros per day are being produced, and are being used for platform stabilization. High g versions have been developed for smart munitions. A six-degree-of-freedom IMU, containing 3 gyros and 3 vibrating accelerometers, called the Digital Quartz IMU (DQI), was developed in 1992 and beyond. The DQI has been inserted in Rockwell's C-MIGITS (Ref. 33), to which Systron Donner has obtained the rights.

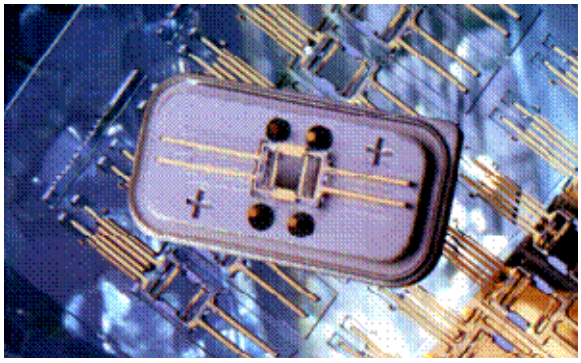
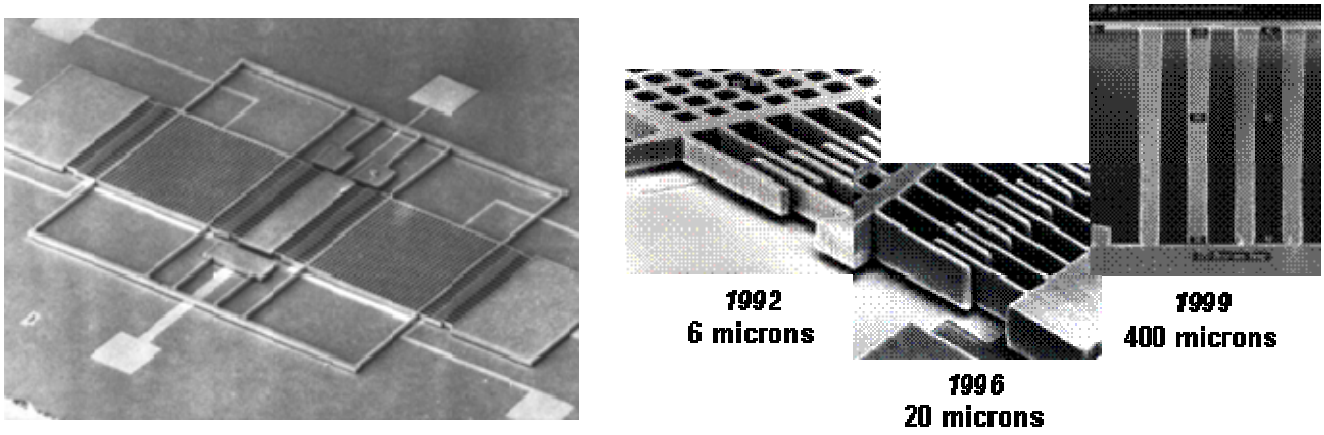


Figure 10. Systron Donner Quartz Rate Sensor (QRS)
(© BEI Systron Donner Inertial Division, printed with permission)

Sagem's Quapason gyro has four quartz tines extending upward from a common base. The advantage is the ability to reduce unwanted cross-coupling from drive to sense (Ref. 34).

Vibrating Plate MEMS Gyros

The gyroscope in Figure 11(a) consists of two silicon proof mass plates suspended over a glass substrate by folded beams and vibrating in-plane 180° out of phase. This design is also referred to as a double-ended tuning fork gyro. Dimensions are on the order of 300 microns by 400 microns. The out-of-plane motion induced by the Coriolis force is detected by changes in capacitance between the proof mass and the substrates. For a typical MEMS gyro, a 1-radian-per-second (in-plane) input rate results in a force of ~9×10^{-8} N on the proof mass, ~1×10^{-9} m of peak motion perpendicular to the sense electrodes, ~3 atofarads (10^{-18}) peak change in capacitance. Measuring 1 deg/h requires resolving motions of ~5×10^{-15} m and about 0.25 electrons per cycle of motor motion. The Draper/Honeywell TFG series are a proven design for high-g applications and have undergone many iterations incorporating performance-enhancing features and fabrication improvements. Performance data indicate that the TFG currently performs at levels in the 3 to 50 deg/h range (3σ, compensated), over temperature ranges of -40°C to 85°C for many months, and over shock inputs of up to 12,000 g. These have been evaluated in both the Extended Range Guided Munition and the CMATD Guided Artillery Shell, and are currently under development for the U. S. Army's 2 cu. in. (33 cc) Common Guidance IMU (Ref. 35).



(a) Top view of MEMS vibrating plate gyroscope (TFG-2)

(b) Gyro comb fingers, highlighting aspect ratios and etch improvements over time

Figure 11. Vibrating Plate MEMS Gyro

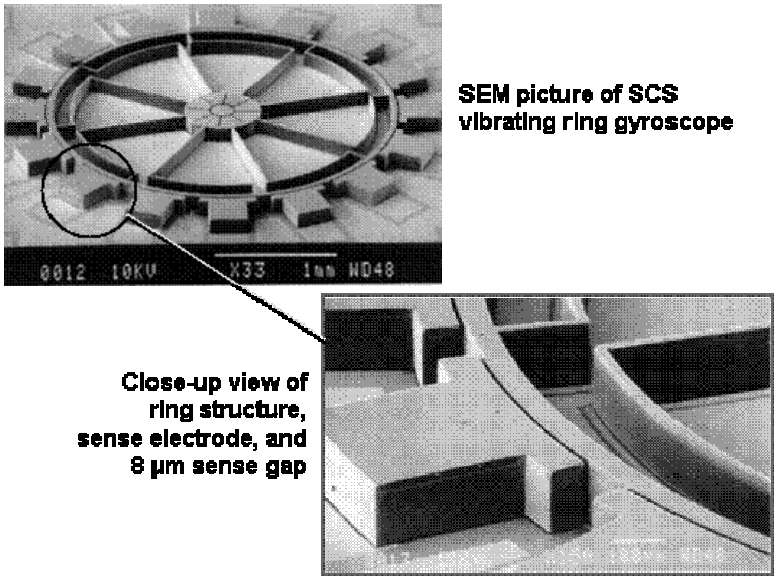
There are many kinds of vibrating plate gyros driven by the comb drive invented by the University of California, Berkeley. Many of the configurations have been designed to minimize coupling between sense and drive. Some are in-plane and some are z-axis gyros; some are oscillating circular disks. Studies indicate that the optimal gyro performance is achieved at a thickness of between 50 and 100 µm. Continued evolution of advanced processes to build thicker, more 3-dimensional parts that are less susceptible to fabrication tolerances is critical to the performance and cost targets. Initially this was hindered by the inability to perform deep high aspect ratio etching. However key improvements in fabrication equipment and process development have resulted in major advances, as depicted in Figure 11(b). Imperfections in the MEMS fabrication process can easily introduce unwanted performance errors. Optical techniques are being developed to characterize as-built geometry, alignments and symmetry, as well as behavior under temperature and electrostatic drive excitation (Refs 36 and 37).

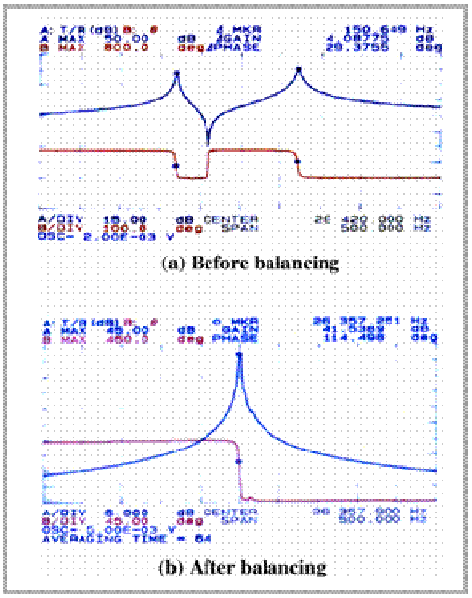
Other types of vibrating plate MEMS gyros are under development. JPL's MEMS gyro (Ref. 38), in which a two degree-of-freedom resonating 4-leaf clover shape, suspended by four springs and containing a vertical post providing the main inertial mass, is driven in a rocking motion about an axis in the plane of the cloverleaf. Analog Devices now has a commercially available ADXRS gyro whose sense and drive axes are both parallel to the substrate which allows operation in one atmosphere of gas, but at limited performance.

Resonant Ring MEMS Gyros

Resonant ring MEMS gyroscopes have an advantage in that the ring structure maintains the drive and sense vibrational energy all in one plane. However, there is also a disadvantage in that the ring has a low vibrating mass and hence lower SF. Figure 12(a) shows a single crystal silicon vibrating ring gyro from U. Michigan (Ref. 39). The ring vibrates at 20 kHz and is 2.7 mm diameter, 50 µm wide, and 150 µm high. The ring is electrostatically vibrated by the forcer electrodes into an in-plane, elliptically shaped, primary flexural mode. A rate about the z-axis (normal to the plane of the ring) excites the Coriolis force which causes energy to be transferred from the primary to the secondary flexural mode, 45° apart. The amplitude of the secondary mode is detected capacitively. Any frequency mismatches arising during fabrication can be electronically compensated by the balancing electrodes. Figure 12(b) shows the drive and sense flexural modes before and

after electronic balancing. This device has a SF of 132 mV/deg/s, resolution of 7.2 deg/h, and output noise of 10.4 deg/hr/√Hz.





(a) SEM Picture (b) Effect of Balancing

Figure 12. U. Michigan Vibrating Ring Gyroscope (See Ref. 39 © IEEE 2002)

BAE SYSTEMS has a SiVSG (Silicon Vibrating Structure Gyro) which consists of a ring resonator supported by compliant spokes. Coriolis-induced motion of the ring is detected by change in the magnetic field supplied by a central magnet. BAE SYSTEMS, UK, and Sumitomo, Japan, are producing silicon gyro products. In May 1999, pilot production was 3,000 gyros/month. BAE SYSTEMS' inductive vibrating ring gyro (Ref. 40) was successfully used in an attitude reference system to control a production-standard, medium-range TRI-Nation Guided Anti-Tank (MR-TRIGAT) missile in flight in June 2000. It has also been evaluated in other military systems as well as part of the stabilization of the Segway™ Human Transporter. An all-silicon capacitive vibrating ring gyro is under development.

Multi-Axes Gyro and Accelerometer Chips

Further size reductions are underway through the combination of two in-plane (x- and y-axis) and one out-of-plane (z-axis) sensors on one chip. Draper Laboratory has demonstrated working devices of two TFGs and one OPG on one chip, and two IPAXs and one out-of-plane pendulum accelerometer on another single chip (Figure 13). These will result in IMUs around 0.2 cu. in (3.3 cc), but further development is required to develop high-performance chips. This is likely to be the ultimate in small IMUs enabling such things as personal navigation and guided bullets . It is likely that commercial investment will push this size-reduction technology, since there is a much stronger sized-based commercial need, rather than performance-based military need at this time.

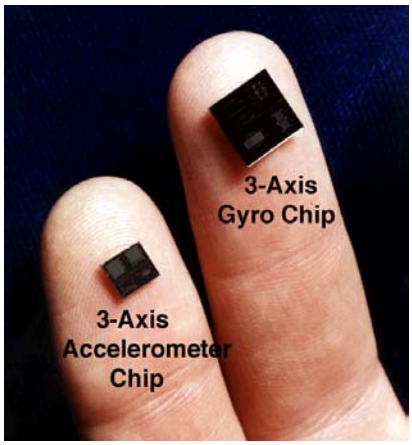


Figure 13. Photo of 3-Axis MEMS Chips

Atom Interferometer Sensors

A potentially promising technology, which is in its early development stages, is inertial sensing based upon atom interferometry (sometimes known as cold atom sensors), which exploits the wave nature of atoms. Since atoms have internal mass and structure, matter wave interferometry is analogous to light wave interferometry. In order to interfer a matter wave, an atom stream must be generated and then split, guided, and recombined. Laser cooling provides the required velocity (wavelength) control for the atom source. The cooling slows down the atoms so that (in comparison to the speed of a light wave) they will have more time (referred to as hang time) to experience the effects of angular rate or acceleration, and so have greater separation upon recombination. In theory, this means that atom interferometers could make the most accurate gyroscopes, accelerometers, gravity gradiometers, and precision clocks, by orders of magnitude [Refs 41 and 42]. Much of the development to date has been at universities (Yale, Stanford, MIT, U. Arizona) and at AOSense Inc. Efforts are underway to reduce the size of the elements required for atom interferometry, as they are currently rather large. Atom interferometer inertial sensors to date have used incoherent atoms propagating in free space, and laser pulse based free space interferometers appear to offer the best potential for practical applications in the short to intermediate term. In the future, it may be possible to use coherent Bose-Einstein condensates for atom guided interferometer structure, although problems of excitation of internal degrees of freedom of the condensates, need for high vacuum, and the complex processes involved need to be overcome. Figure 14 shows a schematic of an atom interferometer. If this technology can be developed, then it could result in a 5 meter/hour navigation system without GPS, in which the accelerometers are also measuring gravity gradients. The potential may ultimately exist for an all-accelerometer (including gradiometry) inertial navigation system. Miniaturization is a most challenging aspect.

There is significant interest in accurate gravity gradient measurements (Refs 43 and 44) for detecting underground facilities as well as to improve navigation accuracy, which is ultimately limited by imperfect knowledge of the gravity vector. A superconducting gravity gradiometer (comprising nine superconducting accelerometers, six linear and three angular) has been developed at University of Maryland (Ref. 44) and has shown performance of 2×10^{-11} s^{-2} $Hz^{-½}$.

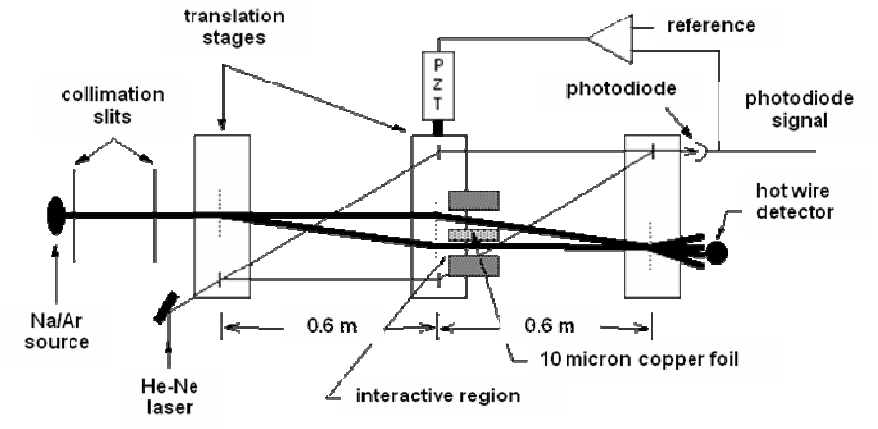


Figure 14. Atom Interferometer Schematic
(Courtesy A. Cronin, University of Arizona, and David Pritchard, MIT)

All-Accelerometer Navigation

The difficulty in producing high performing small gyros has created further interest in all-accelerometer systems (also known as gyro-free). Two approaches are typically used. In the first the Coriolis effect is exploited and typically, three opposing pairs of monolithic MEMS accelerometers are dithered on a vibrating structure (or rotated). This approach allows the detection of angular rate. In the second approach, the accelerometers are placed in fixed locations and used to measure angular acceleration (also known as the 'direct' approach [Ref 45]). In both approaches, the accelerometers also measure linear acceleration to provide the full navigation solution. However, in the direct approach, the need to make one more integration step makes it more vulnerable to bias variations and noise, so the output errors grow by an order of magnitude faster over time than a conventional IMU. To date, only systems of the first kind have been reduced to practice. One example (Ref 46) is the IMU developed by L-3 Communications called the μSCIRAS (Micro-machined Silicon Coriolis Inertial Rate and Acceleration Sensor). A similar technique (Ref 47) is used in Kearfott's Micromachined Vibrating Beam Multisensor (MVBM). However, these devices only provide tactical grade performance, and are most useful in GPS aided applications.

Techniques concerning the number of accelerometers and their specific placements continue to be studied [Refs 48-52] for the direct approach. Theoretical data from Reference 52 indicate that an angular rate measurement of 2 deg/s can be accomplished with 9 single axis accelerometers with 10 micro g resolution located on one planar 4 inch disk. However, as noted in Reference 45, the concept of a navigation grade all-accelerometer IMU requires accelerometers with accuracies on the order of nano-g's or better, and with large separation distances. Therefore the use of all-accelerometer navigation for GPS-unavailable environments will not be viable until the far future, if ever.

AUGMENTATION SENSORS

Many of the mission requirement goals in current and future GPS-unavailable applications are extremely demanding. Typical missions are personal navigation in urban (indoor and outdoor) environments, search and rescue robots in difficult access (e.g., rubble) environments, autonomous land vehicle in urban or rural environments, and autonomous underwater vehicles in littoral or deep ocean environments. Typical position

knowledge desired is 1 to 3 meters over periods of minutes to hours, while experiencing operational temperatures from -25 to +130 degrees F and rate and acceleration measurement ranges up to 360 deg/s and 5g.

In the absence of GPS the navigation system relies on dead reckoning navigation, so that accuracy tends to degrade in direct proportion to time and distance traveled. Currently available IMUs have very rapid position error growth. For example, position uncertainty with a tactical grade IMU (1 deg/h, 1 milli g), or even an navigation grade IMU (0.01 deg/h, 25 micro g), would be tens to hundreds of meters after just a very few minutes. Also, current navigation grade IMUs are too heavy and use too much power for many of the GPS-unavailable missions. Looking at it another way, consider a personal navigation application where horizontal position needs to be known to 1 meter after 1 hour in the absence of GPS. This means that the gyro and accelerometer bias performance needs to be ~5 micro deg/hr and ~15 nano g, respectively. No suitable (e.g., cost, size, power) inertial technology exists today, or is under development with expectations of getting close to this performance. Therefore, the use of active and passive augmentation sensors (aiding devices) are required to provide velocity and/or attitude updates to bound the error due to the drift in the inertial system. Examples of augmentation sensors are velocity sensors, odometers, baroaltimeters, magnetometers, ranging devices, proximity sensors, and GPS pseudolites. Velocity sensors and odometry, such as doppler radar or wheel counts, control the low-frequency drift of the inertial solution. Baroaltimeters stabilize the inertial navigation in the vertical direction, and today's devices provide 15cm resolution. Magnetometers provide a heading reference and inclination and can help bound the roll gyro errors in determining down in a spinning munition. There can also be improvements from using special procedures such as ZUPTs (Zero Velocity Updates), mapping information, or path crossings. Augmentation sensors open the door to the use of much lower performing inertial sensors, so that current technology can be used. It is interesting to note that the automotive industry is one of the major drivers for these technologies, while personal communications is driving miniature packaging technology and low-power electronics for all sensors.

Clearly, what would be ideal is a technology that has MEMS-like size, weight, and power attributes but with performance several orders of magnitude better. Whether or not this can be done will not be known for several years. However, inertial technology development activities, geared towards smaller size and higher performance at low to reasonable cost, are still moving forward on several fronts. These activities include higher performance MEMS gyros and accelerometers, MEMS precision clocks, miniature FOGs, integrated optics gyros; cold atom gyros and accelerometers, and all-accelerometer navigation.

THE FUTURE

Inertial sensor maturity is depicted in Figure 15. Most of the technologies are in the lower-right hand corner, which represents a high maturity level. No new sensor technology appears to be on the near horizon, so what is next for the sensor designer? The desire for much lower cost and smaller size exists at all performance levels. Therefore, development over the next few years will continue to emphasize performance improvement and efficient packaging of MEMS sensors. Commercial applications require extremely low cost so the payback will come from selling very large quantities (billions). Military applications desire low cost but the quantities are not so large (thousands to millions). The payback will be from providing the entire GN&C system, not just the sensors. We may expect to see the development of various MEMS-based arrays to augment and support the inertial solution (Refs 53 and 54). This will be a worldwide effort with potential markets in the billions.

Figure 16 shows inertial technology maturity and an estimated timeline when the developing inertial technologies could meet their projected performance goals as well as their estimated cost in production. Much

of the monetary investment is still going into MEMS-type development activities, because of the enormous potential for MEMS to be used in numerous applications.

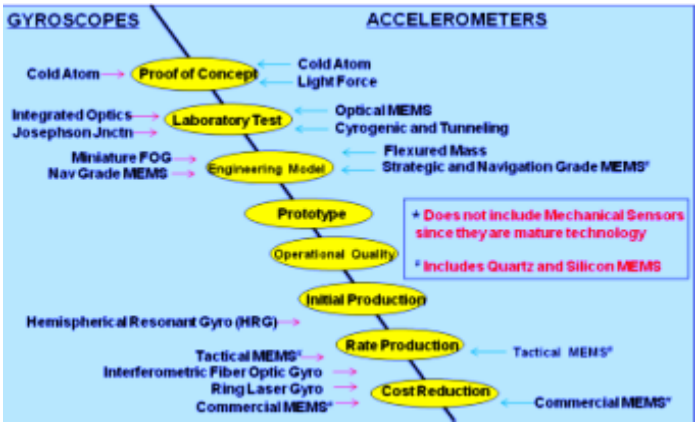


Figure 15. Inertial Technology Maturity

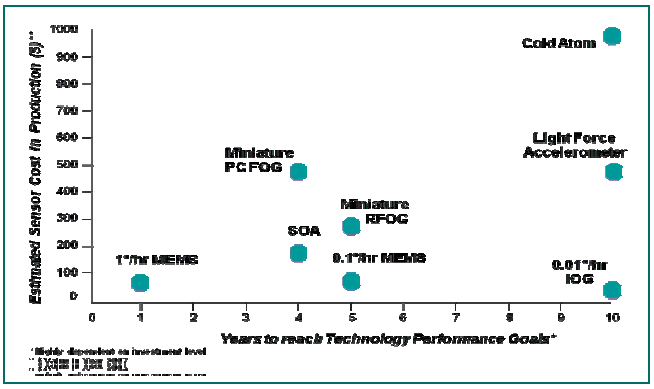


Figure 16. Inertial Technology Development Timeline

The potential market for navigation systems in GPS-unavailable environments is quite substantial as shown in Table 1. The cost and size goals are ultimate goals for the entire system including inertial and augmentation sensors and will be very difficult to achieve. Actual cost will be dependent on number of units sold, so the cost goals shown will only be attained in large quantities. However, it appears that this is a sufficiently lucrative market to provide payback for the expense of developing higher performance inertial sensors.

Table 1. Potential Market for Low-Cost Navigation Systems in GPS-Unavailable Environments

Mission	Number of IMUs	Ultimate Cost Goal	Ultimate Size Goal
Personal/Soldier Navigation	100s of thousands	<1k	<2 cu. in.
Distributed Networks	100s of thousands	<1k	<2 cu. in.
Unmanned Land Vehicles	thousands to tens of thousands	<5k	<10 cu. in.
Unmanned Air Vehicles	thousands	<10k	<10 cu. in.
Unmanned Marine Vehicles	thousands	<10k	<10 cu. in.

Fiber-optic gyros will continue pushing into areas traditionally held by RLGs. However, the continued development of a 2 cu. in (33 cc) MEMS IMU with 1 deg/h performance may result in an IMU available for use in up to 80 percent of the tactical military applications after 2009. This will have a significant impact on the tactical RLG and tactical FOG market. The relatively large production number of these MEMS IMUs will result in some of the promised cost benefits from MEMS being realized. RLG and FOG systems will maintain a niche in areas where they have better performance than MEMS. FOGs may hold their ground if higher bend-radius fiber, such as photonic crystal fiber, results in smaller FOGs. The integrated optics gyro (IOG) is a true solid-state, optics-on-a-chip sensor, manufactured with MEMS-like batch processing, with the potential (theoretically) to provide navigation-grade performance or higher. This has the potential to be a winning technology.

MEMS still needs performance improvement in turn-on repeatability and initial transient response for certain applications, such as short time-of-flight and rapid reaction weapons (e.g., guided bullets). In 1998 (Ref. 21), it was pointed out that MEMS performance enhancement (noise) had improved by a factor of 10, every two years since 1991. While this has slowed recently, MEMS inertial sensors still have the potential for one to two orders-of-magnitude performance improvement over the next decade by improved precision micro-fabrication, reduced sensitivity to packaging, and improved electronics.

Figure 17 shows possible future application areas for inertial sensor technology. Areas where FOGs are likely to remain unchallenged is in the field of precision pointing and tracking, and precision navigation (e.g., submarine). However, cold atom sensors are being developed as a very high performance, long-term competitor, but it is too early to predict with confidence. In the very long term, we may possibly develop NEMS (Nano-Electro-Mechanical Systems), or Optical NEMS, or even biological NEMS. In a few years, we may all have our own personal navigators in our mobile telephones. In fact, navigation and position knowledge will soon become a commercial commodity item; everyone will expect to have it at all times. However, military navigation needs will continue to require higher-performance navigation sensors than commercially available, and it will be a difficult and expensive challenge to meet all requirements.

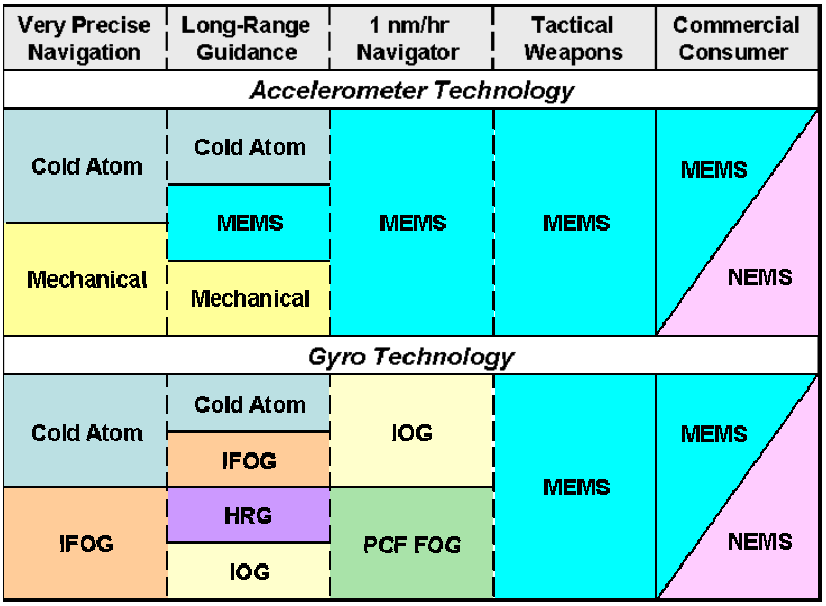


Figure 17. Future Applications for Inertial Sensor Technology

NB/lah

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