Small Inertial Navigation Sensors for GPS-Unavailable Environments

Neil M. Barbour, Donald E. Gustafson, Ralph E. Hopkins III
Charles Stark Draper Laboratory
555 Technology Square
Cambridge, MA 02139, USA
nbarbour@draper.com

Abstract

Navigation in applications where GPS is unavailable or intermittent, such as urban, indoor or subterranean environments, puts severe constraints on the inertial sensors. Also, the drive for low cost, small size and low power means that currently only tactical quality (gyroscopes and accelerometers performing at around 1 deg/h and 1 milli g bias stabilities, respectively) are suitable for use in these applications. Therefore, in order to achieve any reasonable navigation accuracy, it has been necessary to use additional sensors (e.g., velocity meters, magnetometers, lidar, beacons) and algorithms to augment the inertial system. This paper discusses some of the ongoing activities in the technology development of small inertial navigation sensors that could be used for improved performance missions in situations with little or no GPS signal. The activities discussed include higher performance optical gyros (miniature FOGs, integrated optics gyros, light force accelerometer), MEMS gyros and accelerometers, cold atom gyros and accelerometers, all-accelerometer navigation, and MEMS precision clocks. Simulations of position error over time are compared for certain GPS-unavailable missions based on hypothetical IMU performance expected from these inertial sensors, with and without a velocity meter. The benefit of higher performing inertial sensors is discussed based on these simulations. Projections for the future availability of the inertial technology are also presented.

Introduction

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. Table 1 presents a summary of several mission requirement goals for urban and subterranean/sub-ocean environments that have been specified in recent Broad Agency Announcements (BAAs).

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. 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. In fact a velocity meter and baroaltimeter are used in most of the numerical computations of position error found towards the end of this paper, for without them the mission accuracies would not be accomplished. This paper concentrates on current developments in inertial sensor technology, especially those related to improving performance while reducing size and power. Augmentation sensors are not discussed, but 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.

Table 1. Mission Requirement Goals

	Mission					
Goals	**Urban Personal Navigation System**	**Subterranean Personal Navigation System**		**Search & Rescue Robot**	**Autonomous Land Vehicle**	**Autonomous Undersea Vehicle**
Size (in^3)	10	12		4	25	25
Weight (lb)	0.5	3		1	2	2
Power (w)	5	5		1	20	20
GPS Availability	Intermittent	Denied		Denied	Intermittent	Denied
Mission Time (h)	No Limit	0.5	8	1	1	8
Position Knowledge (meters)	3	3	3	1	3	10
Velocity Meter	Yes	No	Yes	Yes	Yes	Yes
Max Speed (m/s)	1	1	1	1	10	10

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. These evolving inertial sensor technologies and their expected potential performance and applicability to GPS-unavailable navigation are discussed in the next sections.

Inertial 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 reduction 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 military 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. The remainder of this section discusses specific ongoing activities in all areas of inertial development that may find use in GPS-unavailable missions.

Optical Gyros

The **Ring Laser Gyro** is basically a mature technology, and most development efforts involve continued cost reduction. While performance may possibly be tweaked, no major gains are expected. 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.

The **Fiber Optic Gyro** is also a mature technology [Refs 1-3] 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), JAE (Japan), etc. The Northrop Grumman LN200 series IMUs may be the most widely known; some of which have silicon accelerometers [Ref 4]. 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. However, ongoing efforts on miniaturization that could potentially lead to performance around 0.001 deg/h, are discussed below.

The development of **Miniature FOGs** 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 5 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.

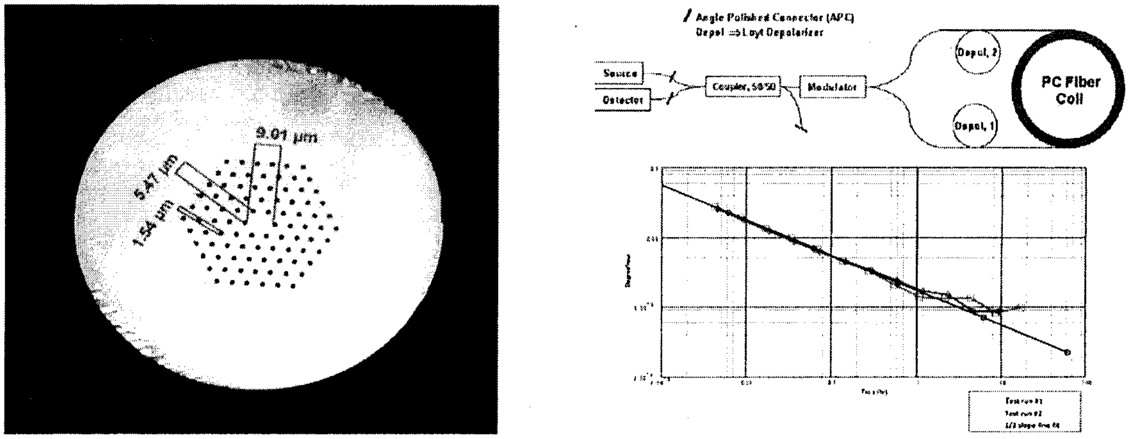


Figure 1. Photonic Crystal Fiber IFOG (PC-IFOG)

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 6 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.

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.

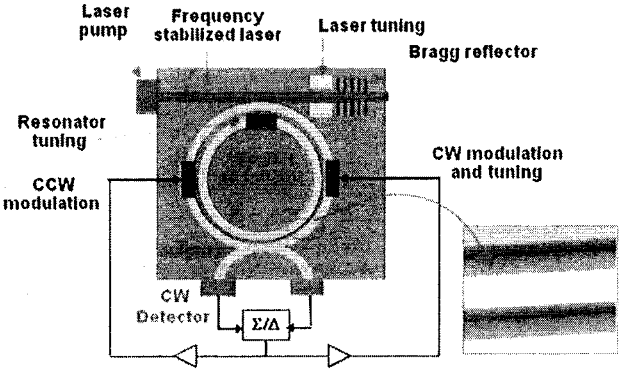


Figure 2. Integrated Optic Gyro (IOG)

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 7 and 8]. Efforts are also ongoing to look at the advantages of slowing light to make an ultrasensitive optical gyroscope [Refs 9 and 10], 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

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.

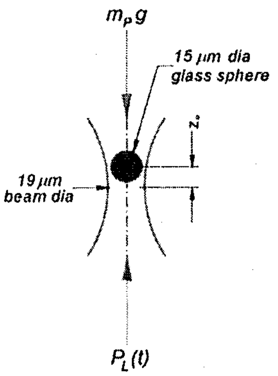


Figure 3a. Light Force Accelerometer Concept

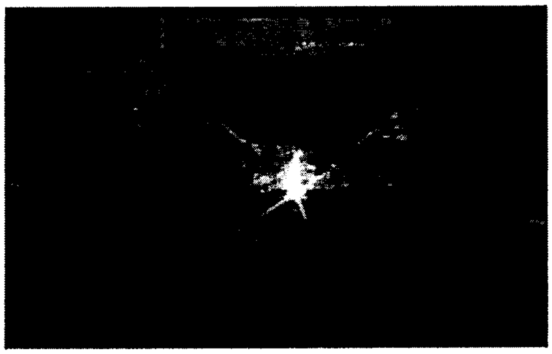


Figure 3b. 10-micron sphere levitated by a focused beam of ~75 mW

MEMS

MEMS inertial sensor development continues to be a world-wide effort. At present the performance of MEMS IMUs continues to be limited by gyro performance [Ref 11], which is now at around 1 deg/h, rather than by accelerometer performance, which has demonstrated tens of micro g or better. Therefore, MEMS rate sensors and all-MEMS IMUs are restricted to commercial systems or tactical grade INS/GPS systems, and 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 12 and 13]. Reference 13 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 14] 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.

Reference 15 indicates that the way to get higher performance (e.g., navigation grade) devices is to perfect the rate integrating MEMS gyro; basically a free oscillating two-dimensional resonator. Data from a preliminary design is presented. In general though, it appears that production quantities of MEMS gyros with performance beyond tactical grade is still several years away.

The most accurate **MEMS 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 16]. 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 4a 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 4b shows the small size (approximately 1 cu inch) for a prototype instrument. Another resonant accelerometer is described in Reference 17, however, this is in early development and data are very limited.

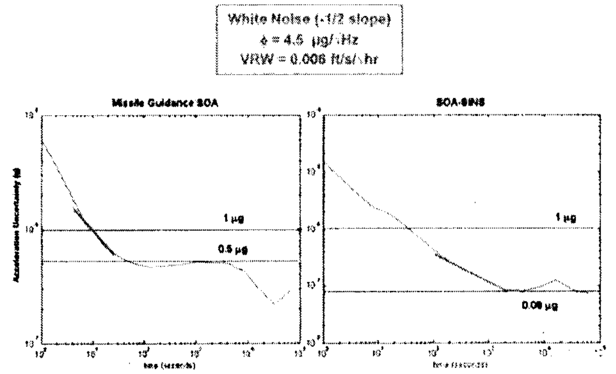


Figure 4a. Missile Guidance & SINS SOA Allan Variance

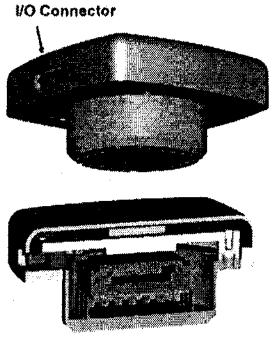


Figure 4b. SOA EMD Instrument Working Concept

Quartz IMUs continue to show improved performance in several areas. Systron Donner's MMQ50 series combines a quartz rate sensor with a silicon MEMS accelerometer [Ref 18]. The quartz rate sensor is based on technology developed for the automobile industry to which over 25 million have been shipped to date. Systron Donner continues to develop more accurate and robust sensors for future products. Also, ONERA (Fr) [Ref 19] continues development of the VIA (Vibrating Inertial Accelerometer) and the VIG (Vibrating Integrating Gyro). The VIA's accuracy is currently around 300 micro g, A further reduction in size, with targeted accuracy of 100 micro g, is underway by configuring the accelerometer on one single chip rather than two.

Gimbaled MEMS systems is another technique used to enhance the performance of MEMS IMUs. The incorporation of miniature gimbals has also been shown to produce performance improvements by an order of magnitude [Ref 20] by allowing periodic calibration and alignment.

Another technique to achieve performance, especially over high dynamic range, is to use **controlled arrays** of MEMS sensors. This was used in the development of guided artillery shells [Ref 21]. More recently, Reference 22 presents the results of a three year US Army component development program that investigated multiplexed COTS and custom accelerometer arrays. Two orders-of-magnitude increase in dynamic range was demonstrated. Also, in the same reference, the integration on the same chip of an angular rate sensor with an accelerometer array and temperature sensors was shown to improve gyro compensation for vibration and thermal effects. Co-location of several devices on the same chip will significantly reduce size, but probably only with marginal performance gains.

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). A typical atom de Broglie wavelength is 30,000 times smaller than an optical wavelength, and because atoms have mass and internal structure, atom interferometers are extremely sensitive. In theory, this means that atom interferometers could make the most accurate gyroscopes, accelerometers, gravity gradiometers, and precision clocks, by orders of magnitude [Ref 23]. 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 5 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.

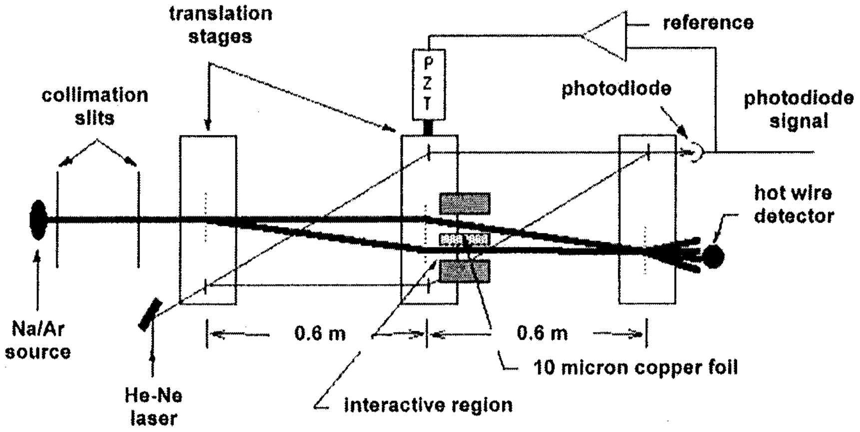


Figure 5. Atom Interferometer Schematic
(Courtesy A. Cronin, University of Arizona, and David Pritchard, MIT)

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 24]). 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 is the IMU developed by L-3 Communications called the μSCIRAS (Micro-machined Silicon Coriolis Inertial Rate and Acceleration Sensor). A similar technique 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 25-28] for the direct approach. Theoretical data from Reference 29 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 24, 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.

Timing Clock

In all applications a small, low power, highly **accurate clock** is required for processing purposes. Reference 30 describes a miniature atomic clock (MAC) under development as an intermediate milestone towards a full chip scale atomic clock (CSAC). The MAC is a complete packaged atomic clock with overall size 10 cm cubed and power consumption <200 mW. The CSAC design goals are total volume <1 cm cubed and power <30 mW [Ref 31]. CSAC is a collaborative effort between Symmetricom, Draper Laboratory, and Sandia. CSAC will limit errors from long term clock drift, and is 1-2 years from production.

Inertial Technology Status Summary

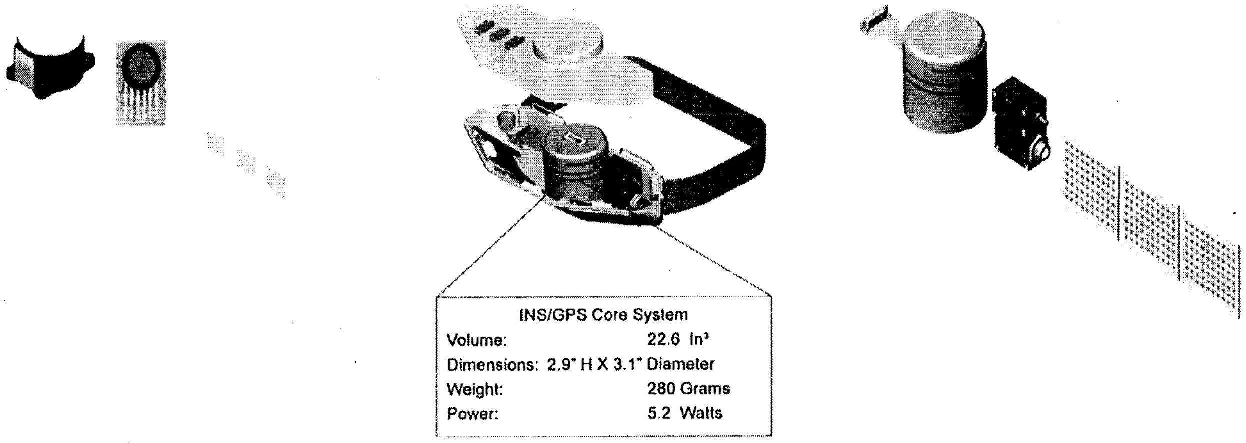
From the discussions above it is clear that inertial technology development continues to be very active, and that the opportunity to reduce size while maintaining or even improving performance exists. In an attempt to relate these developments to GPS-unavailable missions, the gyro and accelerometer technologies have been paired to optimize performance and size of hypothetical IMUs that might be used to meet these missions. This is presented in Table 2. The next section then uses some of these IMU performance projections as a basis to perform a comparative analysis to see what benefits are to be gained from the technologies under development.

Table 2. Inertial Technology Performance Goals

	A	*B*	*C*	*D*	*E*	*F1*	*F2*
	Current Tactical-Grade IMUs	**Future MEMS**	**IOG & SOA**	**MFOG & SOA**	**Cold Atom Gyro & Accel**	**All Accelerometer Navigation**	
						SOA	***Cold Atom***
Gyro							
Bias Stability (°/h)	1	0.1	0.01	0.001	0.0001	NA	NA
SF Stability (ppm)	300	100	25	1	5	NA	NA
ARW (°/√h)	0.1	0.01	0.001	0.0001	4 x 10^{-6}	NA	NA
Accel							
Bias Stability (μg)	1,000	100	1	1	0.1	1	0.1
SF Stability (ppm)	300	100	1	1	0.1	1	0.1
VRW (ft/s / √h)	0.2	0.05	0.001	0.001	10^{-5}	0.001	10^{-5}
IMU							
Volume (cu. in)	4 - 35	2	4	8	4	4	4
Weight (lb)	2	0.2	0.3	2	0.3	0.3	0.3
Power (w)	12	5	5	5	5	5	5

GPS-Unavailable Mission Analyses

In the simulation analyses below, four representative IMUs spanning the low, high, and very high performance ranges, were selected from Table 2. The four IMUs selected were: column A, current tactical grade IMU; column B, a hypothetical IMU representative of future MEMS capabilities; column D, hypothetical IMU containing miniature FOGs and SOAs; column E, hypothetical IMU containing cold atom gyros and accelerometers. The rms position, velocity, and attitude errors were initialized to zero. The assumed trajectory was a random walk generated using an rms heading rate parameter of 0.005 rad/s/rt-s. Thus these simulations do not reflect a particular mission, but are for comparison purposes only. Maximum speed is 1 meter/s and mission time is 8 hours. GPS is assumed denied throughout. The inertial-alone solution is compared to the solution when a velocity meter and a baroaltimeter are available. The velocity meter is assumed to give valid velocity readings for only some percentage of the time. It is assumed that bad readings are detected perfectly and not used. The velocity meter controls the low-frequency drift of the inertial solution, and is assumed to have an rms error (white noise) of 3 cm/s/rt-s. The baroaltimeter stabilizes the inertial navigation in the vertical direction and is assumed available throughout with an rms error (white noise) of 2 meters and altitude readings at one second intervals. The availability of a magnetometer has not been assumed. Figure 6 shows an example of a prototype personal navigation system with a velocity meter, INS, and baroaltimeter that has been used to verify components and algorithms.



INS/GPS Core System
Volume: 22.6 In³
Dimensions: 2.9" H X 3.1" Diameter
Weight: 280 Grams
Power: 5.2 Watts

Figure 6. Prototype Personal Navigation System

Inertial-Only Solution

For an inertial-alone solution, none of the technologies under development can meet all the mission requirements of Table 1. This is shown in the simulation results in Figure 7. After only 30 minutes the position error would be 24,000 meters, 24 meters, and 2.4 meters with a tactical grade IMU, an MFOG/SOA IMU, and a cold atom IMU respectively. After 8 hours the respective errors would be 120,000 meters, 120 meters, and

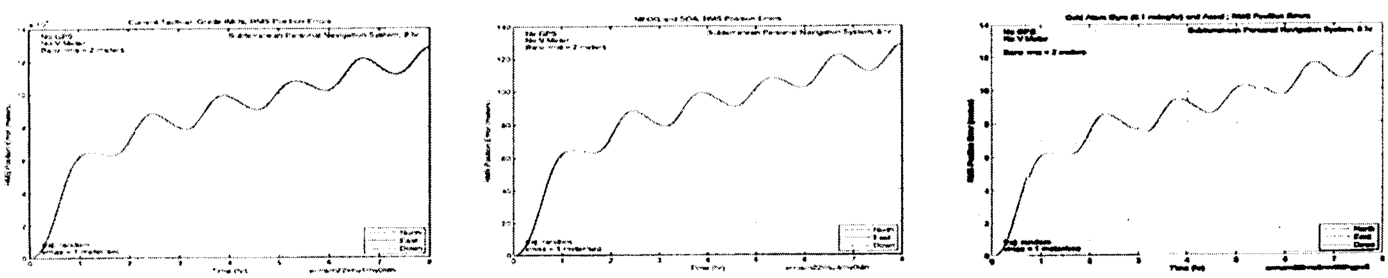


Figure 7a. Current Tactical-Grade IMU

Figure 7b. MFOG/SOA IMU

Figure 7c. Cold Atom IMU

Figure 7. Inertial-only Solution - No Velocity Meter

12 meters. Only the cold atom quality IMU meets the position knowledge requirements of 3 to 10 meters in Table 1 for a substantial amount of time. In all cases, the down error was maintained at a value comfortably below the accuracy requirement via use of the baroaltimeter.

Inertial plus Velocity Meter

Figures 8 through 11 show simulation results when a velocity meter is included. The tradeoff parameter is the probability of a good velocity measurement at each time step (one second increments) for each axis (denoted pv(on) in the plots). Simulated probabilities are for pv(on) equal to 0.03, 0.10, and 0.50. The probabilities are independent over axes, so that one, two or three axes could have bad measurements at the same time step. Figure 8 shows error spiking (sometimes to very high values) for the current tactical-grade IMU at low probability levels; this is attributable to significant periods of measurement outage. Note that the position error is reduced after the spikes; this is due to the correlations built up between position and velocity during the period of the spike, which is used to reduce position errors when good measurements are subsequently obtained from the velocity meter. The Future MEMS IMU (Figure 9), while showing little improvement in average position error over the current MEMS IMU, significantly bounds the instantaneous error spikes. There is essentially no error spiking with the MFOG/SOA IMU (Figure 10) or the Cold Atom IMU (Figure 11) even at very low probability levels.

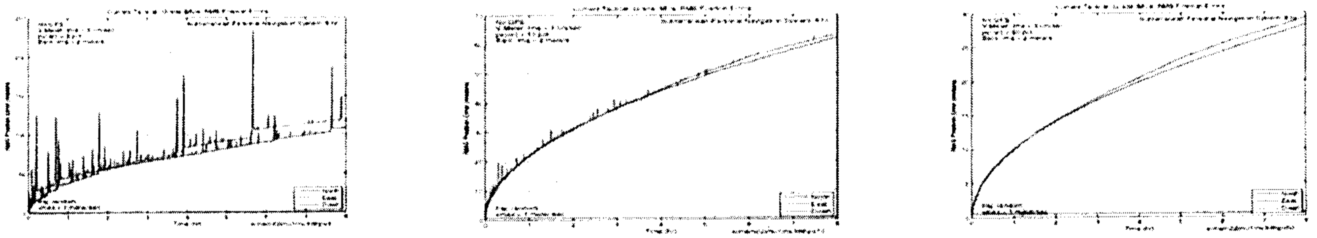


Figure 8a. Pv(on) = 0.03

Figure 8b. Pv(on) = 0.10

Figure 8c. Pv(on) = 0.50

Figure 8. Current Tactical-Grade IMU

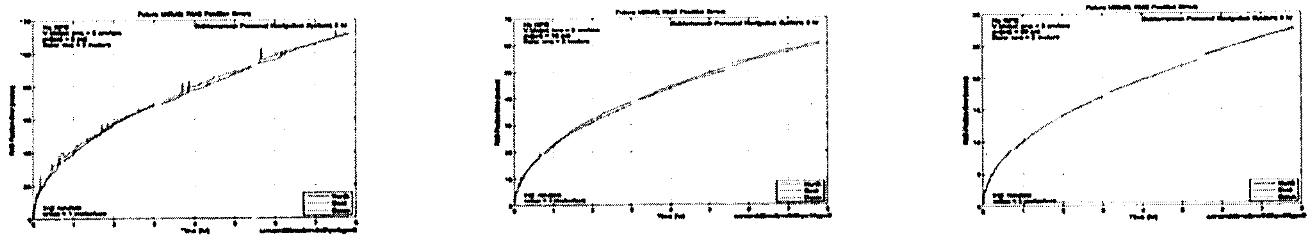


Figure 9a. Pv(on) = 0.03

Figure 9b. Pv(on) = 0.10

Figure 9c. Pv(on) = 0.50

Figure 9. Future MEMS IMU

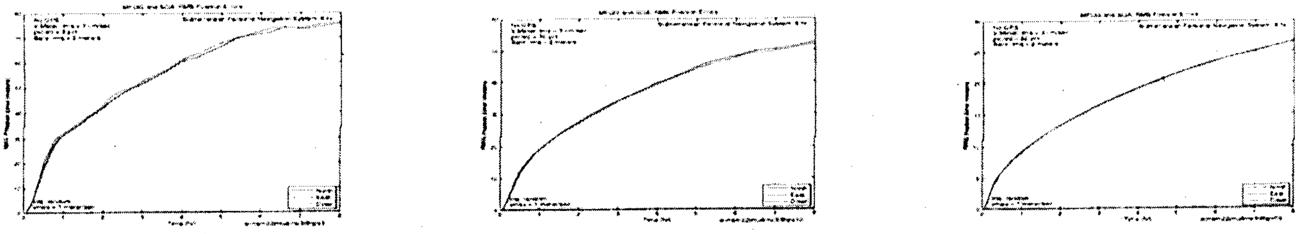


Figure 10a. Pv(on) = 0.03

Figure 10b. Pv(on) = 0.10

Figure 10c. Pv(on) = 0.50

Figure 10. MFOG/SOA IMU

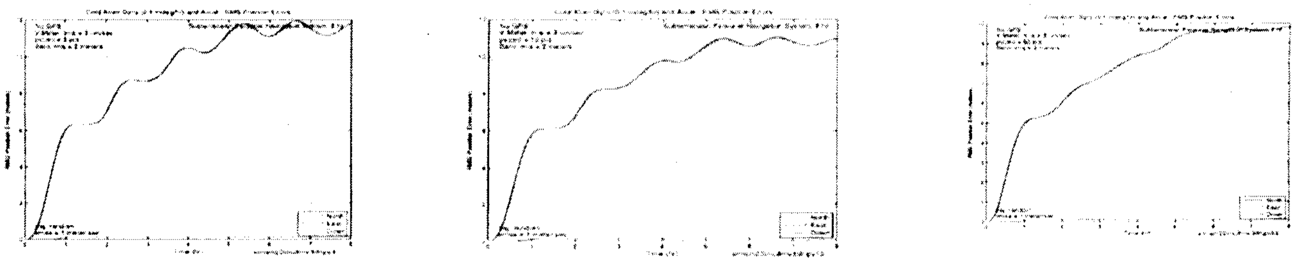


Figure 11a. Pv(on) = 0.03 **Figure 11b. Pv(on) = 0.10** **Figure 11c. Pv(on) = 0.50**

Figure 11. Cold Atom IMU

When a velocity meter is used, it dominates in the ability to maintain high accuracy; there is only a slight reduction in rms position error after 8 hours using an MFOG/SOA IMU compared to a current tactical-grade IMU (~26 meters vs. ~28 meters along North and East for the case Pv(on) = 0.50). Even with a velocity meter none of the inertial technologies meets the 1 to 3 meters position knowledge requirements in Table 1 for more than a few minutes. All the technologies can meet the 10 meter requirement for at least one hour with pv(on) at 50 percent. Therefore, the major driver for improving the performance of the IMU would be to eliminate or reduce the intermittent position error spikes, when the velocity meter has low probability of providing accurate measurements. For a very high performance IMU such as the cold atom, comparing Figures 11c and 7c shows that the velocity meter smooths the inertial solution, but has little effect on average position error (~10 meters vs. ~12 meters inertial-alone).

Inertial plus Intermittent GPS

Figure 12 shows the simulation results for three IMUs with no velocity meter, but with intermittent GPS availability, as in an autonomous land vehicle mission. GPS is assumed to be available such that one three-axis measurement of position and velocity is obtained every 120 s. The GPS signal allows the navigation solution to be bounded. The benefits of high performing IMUs for meeting the mission requirements in Table 1 are clearly evident in this situation.

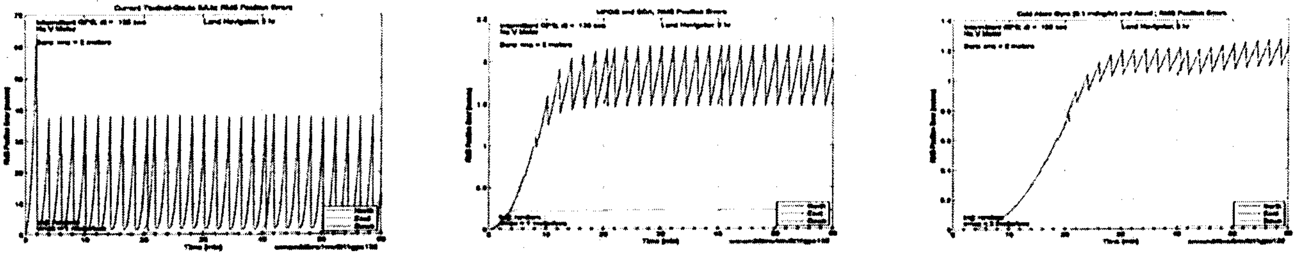


Figure 12a. Tactical-Grade IMU **Figure 12b. MFOG/SOA IMU** **Figure 12c. Cold Atom IMU**

Figure 12. Autonomous Land Vehicle, Intermittent GPS - 1 Hour

All-Accelerometer Inertial

A brief analysis of an all-accelerometer IMU performance has been extrapolated from a COTS IMU for low cost missiles. With accelerometer errors of 400 milli g, 1000 ppm and 2.5 milli g/root-Hz, the attitude rate errors were ~1 deg/sec at a continuous input angle rate of 0.5 Hz/axis. Extrapolating to the cold atom IMU, we expect error reduction of between 10^{-10} due to bias and 10^{-6} due to noise. If we take an average value of 10^{-8}, then we get a rate error of 10^{-8} deg/sec, or 3.6×10^{-5} deg/hr, at 0.5 Hz input rate. A continuous rate of 0.5 Hz would be much too high for GPS denied missions. If we reduce the continuous input rate to 9 deg/sec (0.025 Hz) and assume centripetal force as the primary signal, then the equivalent rate error would be 5.76×10^{-2} deg/hr, which lies between the values for the Future MEMS IMU and the IOG/SOA IMU in Table 2. Therefore, there would be no benefit from using this IMU as it requires highly accurate accelerometers to obtain navigation performance equivalent to that from traditional IMUs with much lower performance sensors.

The Future of Inertial in GPS-Unavailable Missions

In this paper we have discussed some of the ongoing inertial sensor technology development geared towards higher performing, small size IMUs. Some of these are evolutionary and some quite revolutionary. Comparitive simulations were performed, using these higher performing sensors in hypothetical IMUs, to examine the benefits to position error knowledge. The inclusion of a velocity meter to augment the inertial solution, did not realize the 1 – 3 meter position error goals of Table 1 except for short periods of time, although benefits were gained by with better IMU performance. In practice several different augmentation schemes would be incorporated into the inertial solution. It is only when inertial performance equivalent to that expected from cold atom technology is available that the some of the reliance on other aiding schemes can be relaxed in GPS-denied situations. However, no matter what augmentation is used, improved performance inertial sensors will improve the overall position solution.

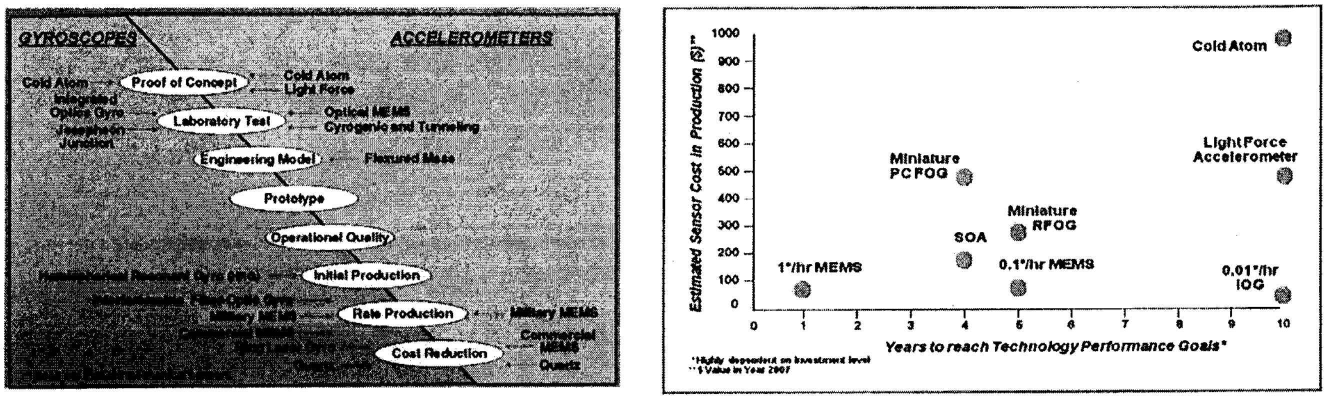


Figure 13a. Inertial Technology Maturity **Figure 13b. Inertial Technology Development Timeline**

Figure 13. Inertial Technology Development

Figure 13 shows inertial technology maturity and an estimated timeline when the 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.

Table 3. 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.

The potential market for navigation systems in GPS-unavailable environments is quite substantial as shown in Table 3. 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.

NB/lah

Acknowledgements

Peter Sherman from Draper Laboratory for advice on personal navigation systems. Jess Tawney from Draper Laboratory for information on Photonic Crystal Fibers (PCFs) and the PC-IFOG. Rick Stoner from Draper Laboratory for information on the LFA and Atom Interferometers. David Butts from MIT for the picture of the LFA in Figure 3b.

References

[1] Pavlath G., *Fiber Optic Gyros: The Vision Realized*, 18th International Conference on Optical Fiber Sensors, Cancun, Mexico, October 2006.

[2] Divakaruni S. and Sanders S., *Fiber Optic Gyros – A Compelling Choice for High Accuracy Applications*, 18th International Conference on Optical Fiber Sensors, Cancun, Mexico, October 2006.

[3] KVH Industries Inc., *An Update on KVH Fiber Optic Gyros and Their Benefits Relative to Other Gyro Technologies*, March 2007.

[4] Volk C., Lincoln J., and Tazartes D., *Northrop Grumman's Family of Fiber-optic Based Inertial Navigation Systems*, IEEE PLANS 2006, San Diego, CA, April 2006.

[5] Tawney J. et al, *Photonic Crystal Fiber IFOGs*, Optical Society of America, 18th International Conference on Optical Fiber Sensors, Cancun, Mexico, October 2006.

[6] Sanders G., Strandjord L., and Qiu T., *Hollow Core Fiber Optic Ring Resonator for Rotation Sensing*, 18th International Conference on Optical Fiber Sensors, Cancun, Mexico, October 2006.

[7] Suzuki K. et al, *Monolithically Integrated Resonator Micro-optic Gyro on Silica Planar Lightwave Circuit*, Journal of Lightwave Technology, Vol 18, No 1, January 2000.

[8] Li G. et al, *Design, Fabrication, and Characterization of an Integrated Optic Passive Resonator for Optical Gyroscopes*, ION Annual Meeting, Dayton, OH, June 2004.

[9] Scheuer J. and Yariv A., *Sagnac Effect in Coupled resonator Slow-Light Waveguide Structures*, Physical Review Letters, Vol 96, 053901, February 2006.

[10] Steinberg B. et al, *Slow-Light Waveguides with Mode Degeneracy: Rotation Induced Super Structures and Optical Gyroscopes*, 18th International Conference on Optical Fiber Sensors, Cancun, Mexico, October 2006.

[11] Weinberg M. and Kourepenis A., *Error Sources in In-Plane Silicon Tuning Fork Gyroscopes*, JMEMS, Vol 15, No. 3, 2006.

[12] Mezentsev A. et al, *Subminiature Dynamically Tuned Gyroscope - Design and Development*, 11th St. Petersburg International Conference on Integrated Navigation Systems, St. Petersburg, Russia, May 2004.

[13] Dauwalter C. and Ha J., *Magnetically Suspended MEMS Spinning Wheel Gyro*, IEEE A&E Systems Magazine, Vol 20, No 2, Feb 2005.

[14] Dussy S. et al, *MEMS Gyro for Space Applications – Overview of European Activities*, AIAA GN&C Conference and Exhibit, San Francisco, CA, August 2005.

[15] Shkel A., *Type I and Type II Micromachined Vibratory Gyroscopes*, Position, Location, And Navigation Symposium, IEEE/ION, Coronado, CA, April 2006.

[16] Hopkins R. et al, *The Silicon Oscillating Accelerometer: A High-Performance MEMS Accelerometer for Precision Navigation and Strategic Guidance Applications*, ION 61st Annual Meeting, Cambridge, MA, June 2005.

[17] Su, S., Yang H., Agogino A., *A Resonant Accelerometer with Two-Stage Microleverage Mechanisms Fabricated by SOI-MEMS Technology*, IEEE Sensors Journal, Vol 15, No 6, December 2005.

[18] Jaffe, R., Ashton, T. Madni, A., *Advances in Ruggedized Quartz MEMS Inertial Measurement Units*, Position, Location, And Navigation Symposium, IEEE/ION, Coronado, CA, April 2006.

[19] Le Traon O. et al, *A New Quartz Monolithic Differential Vibrating Beam Accelerometer*, Position, Location, And Navigation Symposium, IEEE/ION, Coronado, CA, April 2006.

[20] Ash M. and Martorana R., U.S. Patent 6,778,908 - August 2004; U.S. Patent 6,895,678 - May 2005

[21] Gustafson D., R. Hopkins; N. Barbour and J. Dowdle, *A Micromechanical INS/GPS System for Guided Projectiles*, ION 51st Annual Meeting, Colorado Springs, CO, June 5-7, 1995.

[22] Hudson T., et al, *Multi-Sensor Inertial Array Technologies for Advanced Microsystems*, Position, Location, And Navigation Symposium, IEEE/ION, Coronado, CA, April 2006.

[23] Kasevich M. and Salomon C. - Editors, *Special Issue: "Quantum Mechanics for Space Application: From Quantum Optics to Atom Optics and General Relativity"*, Applied Physics B, Vol 84, August 2006.

[24] Zorn A., *GPS-Aided All-Accelerometer Inertial Navigation*, ION GPS-2002, Portland, OR, September 2002.

[25] Hanson R. and Pachter, M., *Optimal Gyro-Free IMU Geometry*, AIAA GN&C Conference and Exhibit, San Francisco, CA, August 2005.

[26] Tan C-W and Park, S., *Design of Accelerometer Based Inertial Navigation Systems*, IEEE Transactions on Instrumentation and Measurement, Vol 54, No 6, Dec 2005.

[27] Pamadi K., Ohlmeyer, E., Pepitane, T., *Assessment of a GPS Guided Spinning Projectile Using an Accelerometer-Only IMU*, AIAA GN&C Conference and Exhibit, Providence, RI, August 2004.

[28] Wang J-H. and Gao, Y., *GPS-Based Land Vehicle Navigation System Assisted by a Low-Cost Gyro-Free INS Using Neural Network*, Journal of Navigation, Vol 57, No 3, Sept 2004.

[29] Chen T-L and Park, S., *MEMS SoC: Observer Based Coplanar GyroFree Inertial Measurement Unit*, Journal of Micromechanics and Micro Engineering, Vol 15, No 9, Sept 2005.

[30] Lutwak R. et al, *The MAC - A Miniature Atomic Clock*, Joint IEEE International Frequency Control Symposium and Precise Time and Time Interval (PTTI) Systems and Applications Meeting, Vancouver, BC, Canada, August 2005.

[31] Mescher M. et al, *An Ultra-Low-Power Physics Package for a Chip Scale Atomic Clock*, Transducers 05, Seoul, Korea, June 2005.