Inertial Sensor Technology Trends

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***Abstract*—This paper presents an overview of how inertial sensor technology is applied in current applications and how it is expected to be applied in near- and far-term applications. The ongoing trends in inertial sensor technology development are discussed, namely interferometric fiber-optic gyros, micromechanical gyros and accelerometers, and micro-optical sensors. Micromechanical sensors and improved fiber-optic gyros are expected to replace many of the current systems using ring laser gyroscopes or mechanical sensors. The successful introduction of the new technologies is primarily driven by cost and cost projections for systems using these new technologies are presented. Externally aiding the inertial navigation system (INS) with the global positioning system (GPS) has opened up the ability to navigate a wide variety of new large-volume applications, such as guided artillery shells. These new applications are driving the need for extremely low-cost, batch-producible sensors.**

***Index Terms*—Accelerometer, gyroscope, inertial, MEMS.**

I. Introduction

ELECTROMECHANICAL inertial sensors have generally dominated guidance, navigation, and control applications since the dawn of inertial sensing in the early 1920s [1]–[4]. In recent years, however, new technologies have enabled other kinds of sensors that are challenging and have successfully challenged this dominance [4]–[6]. For example, the ring laser gyroscope, which was invented in the 1960s, replaced electromechanical instruments in many applications by the late 1980s and early 1990s. Early on, the driving force for introducing these new technologies was to improve performance and reliability. Over the last 30 years or so, the primary driving force has been to achieve equivalent performance at lower cost. Today, new sensor technologies continue to be developed to meet future market needs for applications previously not considered feasible for guidance and navigation. These new and emerging technologies offer little, if any, performance improvement, but are geared toward low life-cycle cost, small size, low production cost, and large-volume manufacturing. Excellent descriptions of the fundamentals of inertial sensor technology are given in [7].

Another factor that has had a significant influence on inertial sensor development is external aiding. External aiding [whether Doppler, star tracker, seeker, or global positioning system (GPS), for example] is usually required to meet mission accuracy because aiding overcomes inertial sensor drift. Another way of looking at this is that externally aiding the inertial system allows less accurate and therefore less costly inertial sensors to be used. Recently, GPS has become the inertial navigation system (INS) aid of choice because of its relatively low cost and ubiquity [8]. In fact, for a minimum maneuvering vehicle with continuous access to the GPS signal, the navigation function could be accomplished by GPS alone. In reality, the problems of unintentional interference (e.g., blockage by buildings or trees) and ionospheric delays and the need for high-bandwidth/high-speed angular rate and acceleration information, particularly when GPS is deliberately jammed, means that an INS is always required and its relevance enhanced. The need to maintain reasonable cost levels when integrating an INS with GPS is thus driving the need to develop much lower-cost inertial sensors, while concurrently improving their accuracy and low noise levels to accomplish mission performance in the absence of GPS [9]. For future military and civilian applications, it is expected that the use of INS/GPS systems will proliferate and ultimately result in a worldwide navigation accuracy on the order of 1 meter, which will need to be maintained under all conditions.

This paper presents the status of inertial sensor technology in today's applications, followed by a discussion of inertial sensor technology trends and cost and concluded by predictions of the near- and far-term sensor technology applications. It is an update of projections of inertial sensor trends described in [10].

II. Current Sensor Technology Applications

Figs. 1 and 2 depict a perspective of current gyroscope and accelerometer technologies and their applications as related to parts per million (ppm) of scale-factor stability (i.e., how well the sensor reproduces the sensed rate or acceleration) and μg or deg/h of inherent bias stability (i.e., the error independent of inertial rate or acceleration). While these performance factors are not the only ones that influence sensor selection, they are useful for comparison purposes. Sensors appearing in the lower-left are generally of high performance, high cost and limited quantity. Those appearing in the top right are of low performance, lower cost, and high quantity.

With reference to Fig. 1, it can be seen that electromechanical gyros are sharing the applications with optical gyros, such as the ring laser gyro (RLG) and the tactical interferometric fiber-optic gyro (IFOG) [7] and quartz resonant gyros [7] (one well-known use of the quartz resonant gyro is for Cadillac anti-skid control). The dynamically-tuned gyro (DTG) [7] is an electromechanical gyro that was invented in the 1960s to address perceived cost problems of the existing mechanical gyros by offering two axes of rate information in one sensor. However, even this gyro has fallen prey to the RLG in many situations. The RLG is an excellent sensor and its rise can be attributed to the fact that it is ideal for strapdown applications [11], which became feasible in the 1970s when high-speed computing became available. Strapdown navigation is the system mechanization of choice for tac-

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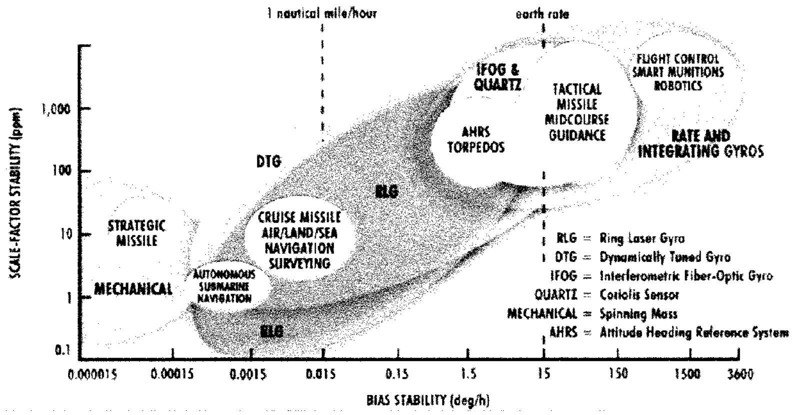

Fig. 1. Current gyro technology applications.

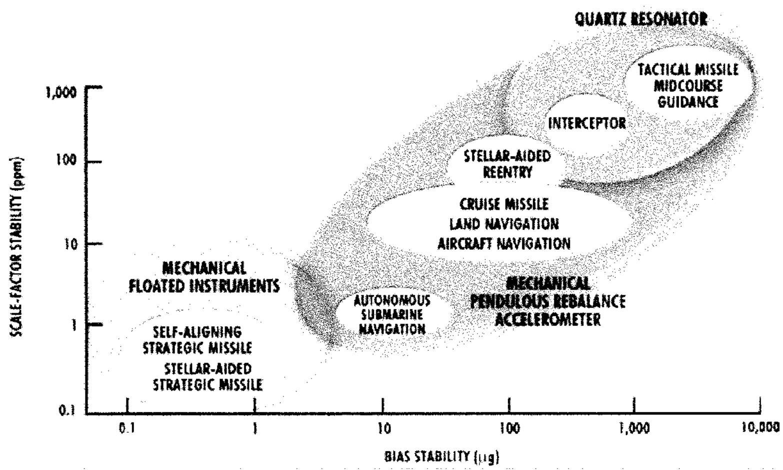

Fig. 2. Current accelerometer technology applications.

tical and navigation grade since it does not require gimbals, which are relatively expensive.

Another type of gyro, the hemispherical resonant gyro (HRG) [7], is a high-performance vibrating shell gyro which has found a niche in spacecraft inertial reference units (IRUs) [5].

Current accelerometers (Fig. 2) are still dominated by electromechanical sensors [7], not only because they are generally cost-reasonable over the performance required, but also because no challenging alternative technology has succeeded previously, except for quartz resonators, which are used in the lower-grade tactical and commercial applications.

In the early 1990s, microelectromechanical system (MEMS) silicon sensors were identified as a definite growth area, but at that time, we were unsure of the performance attainable [6]. Even today, MEMS inertial sensors have not yet seriously broached the market, although they are on the verge of so doing, especially in consumer applications.

III. Inertial Sensor Technology Trends

Technology developments for new inertial sensors are ongoing for a wide variety of new military and commercial applications. Cost reduction activities are underway worldwide to develop new inertial sensors for tactical-grade and navigation-grade missions. These new technologies are fiber-optic gyro improvements and silicon MEMS gyros and accelerometers.

A. Fiber-Optic Gyros (FOGs)

Like the RLG, the FOG was also invented in the 1960s, but developed more slowly than the RLG. Its developments have really tracked the communications industry light source and optical fiber developments. Its principle of operation, like the RLG, depends on measuring the Sagnac effect [7].

Sagnac effect rotation rate sensors result from the counterpropagation of light beams in a waveguide that exhibits optical reciprocity between its clockwise and counterclockwise paths. Rotation normal to the waveguide plane upsets this symmetry, which is then photoelectronically detected to provide an indication of rotation rate. The FOG is implemented using a fiber-optic sensing coil (meters to a kilometer long), an integrated optics chip constructed in lithium niobate, a broadband light source, and a photodetector (see Fig. 3). Eventually, this configuration may be supplanted by quantum well technology, which will allow integration of most of the electro-optic components into a single substrate attached to the fiber-optic sensing coil, thereby reducing cost and size.

It is quite possible that FOG performance improvements will allow applications in strategic applications where the perfor-

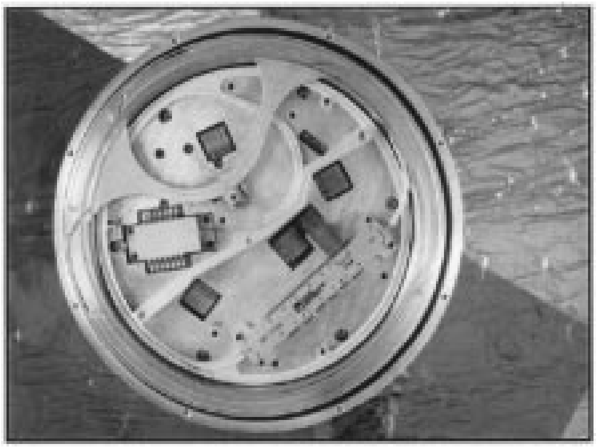

Fig. 3. Fiber optic gyro (courtesy of Draper Laboratory).

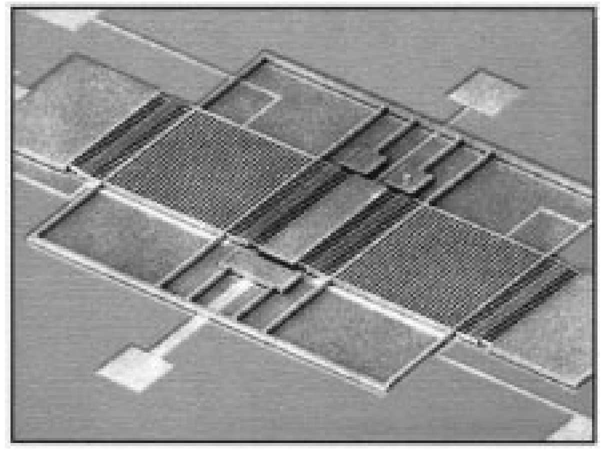

Fig. 4. Micromechanical tuning fork gyro (courtesy of Draper Laboratory).

mance requirements exceed 0.001 deg/h. In addition, FOG sensors have no gas or mirrors, do not require precision machining or alignment and do not exhibit lock-in at low rate, which are inherent in RLGs and tend to keep RLG costs high. Therefore, in similar production quantities, FOG sensors should be an economical replacement for the RLG, especially in the lower-performance tactical and commercial applications.

B. Micromechanical Gyros

Micromechanical gyros (or MEMS gyros) are usually designed as an electronically driven resonator, often fabricated out of a single piece of quartz or silicon. Such gyros operate in accordance with the dynamic theory that when an angular rate is applied to a translating body, a Coriolis force is generated. When this angular rate is applied to the axis of a resonating tuning fork, its tines experience a Coriolis force, which then produces torsional forces about the sensor's axis. These forces, which are proportional to the applied angular rate, cause displacements that can be measured capacitively in a silicon instrument or piezoelectrically in a quartz instrument. The output is then demodulated, amplified and digitized to form the device output. Silicon micromechanical instruments can be made by bulk micromachining (etching) single-crystal silicon or by surface-micromachining layers of polysilicon. Many manufacturers are developing gyros and accelerometers using this technology [12]. Their extremely small size, combined with the strength of silicon, makes them ideal for very high acceleration applications. Between 3,000 and 10 000 devices can be produced on a single 5-in silicon wafer.

Fig. 4 shows one of a range of silicon tuning fork gyroscopes with folded-beam suspension in which the flexured masses are electrostatically driven into resonance with a comb-like structure. Rotation is sensed capacitively along the axis normal to the plane of vibration. The first gyroscope (1 deg/s, uncompensated) was developed for the commercial automobile market as a yaw rate sensor for skid control. Gyros with lower drift rates (10 to 100 deg/h with algorithmic thermal compensation) have been developed for competent munitions, such as guided artillery shells [13]. Drift data close to 1 deg/h (temperature-controlled) have been demonstrated. Future improvements are expected to bring the performance of these devices to better than 0.1 deg/h drift stability. Another major thrust is the packaging of the electronics and sensors to provide three axes of sensitivity on one chip in a volume as small as 0.2 cu. in. [13].

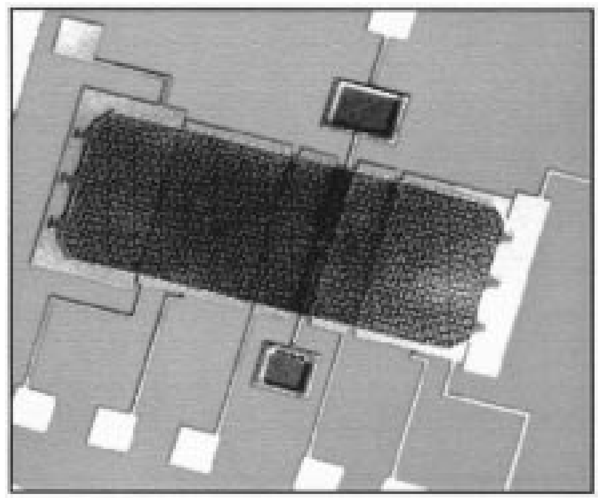

Fig. 5. Micromechanical pendulous rebalance accelerometer (courtesy of Draper Laboratory).

C. Micromechanical Accelerometers

Micromechanical accelerometers are either the pendulous/displacement mass type that use closed-loop capacitive sensing and electrostatic forcing, or the resonator type [12]. The force rebalance micro-mechanical accelerometer of Fig. 5 is a typical example, in which the accelerometer is a monolithic silicon structure (i.e., no assembly of component parts) consisting of a torsional pendulum with capacitive readout and an electrostatic torquer. This device is approximately 300×600 μm in size. The pendulum is supported by a pair of flexure pivots and the readout and torquing electrodes are built into the device beneath the tilt plate. The output of the angle sensor is integrated and then used to drive the torquer to maintain the tilt plate in a fixed nulled position. The torque required to maintain this balance is proportional to the input acceleration. Performance (compensated) around 100-μg bias error and 100 ppm of scale-factor error has been achieved and further improvements are expected.

Fig. 6. Quartz resonant accelerometer (courtesy of Draper Laboratory).

These silicon accelerometers are being developed for a wide range of applications commercially (such as automotive air bags and ride control), as well as the competent munition and autonomous vehicle markets. Their ability to withstand extremely high g forces can be used to measure shell velocity inside an artillery gun [14].

Resonant accelerometers (sometimes referred to as vibrating beam accelerometers) have a proof mass that loads two vibrating flexures on opposite sides of the proof mass (Fig. 6). When the accelerometer proof mass is loaded, one tine is put into tension and the other into compression. These tines are continually excited at frequencies of tens to hundreds of kilohertz range when unloaded. As a result, when "g" loaded, one tine's frequency increases while the other tine's frequency decreases. This difference in frequency is a measure of the device's acceleration. This form of accelerometer is an open-loop device in that the proof mass is not rebalanced to its center position when force is applied. For accuracy, it relies on the scale-factor stability inherent in the material properties. Fabrication techniques result in low-cost, highly reliable accelerometers with a measurement accuracy of better than 100-μg bias error. Quartz resonant accelerometers have proliferated widely into tactical and commercial (e.g., factory automation) applications [15]. Silicon micromechanical resonator accelerometers are also being developed [16].

D. Optical MEMS Sensors

Optical MEMS [also known as micro-optics, or micro-optical-electromechanical systems (MOEMS)] sensors have been under development for about 20 years. To date, none has been successful because the fundamental concept of sensing using the Sagnac principle depends on the length of the circulating light path times the diameter. Thus, small devices have difficulty achieving reasonable performance. Work is underway to develop low-loss waveguides and extremely narrow-band light sources. It appears that very high Q sensors need to be developed, such as resonant micro-optical cavities, or an RLG on a chip, to make these devices feasible. These sensors are far term, but do offer advantages over MEMS sensors since they will be true solid-state devices.

IV. Cost Projections

Since the end of the Cold War, the actual number of military inertial systems that will be procured in the future has been uncertain. However, the general trend is clearly moving away from large strategic systems toward smaller tactical systems and toward military applications of commercial products. These new applications are likely to be in extremely large numbers (e.g., guided artillery shells) and require low-cost inertial sensors.

Fig. 7 shows INS/GPS system cost as a function of technology and performance. The systems are classified as: laser gyro or IFOG systems containing various types of accelerometer technologies, quartz systems with both quartz gyros and quartz accelerometers, and MEMS/ MOEMS systems, which are all silicon. The solid line indicates the range of approximate costs available today. Clearly, the quantity of systems produced affects the cost; large production quantities would be at the lower end of the cost range. The IFOG systems have the potential for lower cost than laser gyro systems because the IFOG should be well below the cost of an RLG. However, this has not happened to date, primarily because the RLG is in relatively large-volume production in well-facilitated factories and the IFOG is not yet manufactured in similar production quantities. Clearly, the MEMS/MOEMS INS/GPS systems offer the lowest cost. The ultimate low cost only becomes feasible in quantities of millions. This can be achieved only with multi-axis instrument clusters and on-chip or adjacent-chip electronics and batch packaging [17]

V. Near-Term Sensor Technology Applications

Solid-state inertial sensors like those described previously have potentially significant cost, size, and weight advantages, which has resulted in a proliferation of the applications for which such devices can be used in systems. While there are many conventional military applications, there are also many newer applications that will emerge with the low cost and very small size inherent in such sensors, particularly at the lower performance end of the spectrum [13], [17]. A vision of the inertial instrument field for relevant military applications for the near-term is shown in Figs. 8 and 9 for the gyro and accelerometer, respectively.

The MEMS and improved fiber-optic technologies are expected to replace many of the systems using RLGs and mechanical instruments. In the near term, fiber-optic gyro-based INS systems will be used for navigation missions. However, one particular area where the RLG is expected to retain its superiority over the IFOG is in applications requiring extremely high scale-factor stability. The change to all-MEMS technology hinges primarily on MEMS gyro development. The performance of MEMS instruments has reached tactical grade and they are currently being developed for many applications [17]. Design improvements have been identified to meet the performance requirements for precision guidance that will allow a minimum degradation of precision for a significant time after a GPS jamming. It is anticipated that by the year 2005, it will be possible to have a MEMS INS of 2 cu. in. [13] with navigation-grade performance over several minutes. The cost is likely to be $1 K,

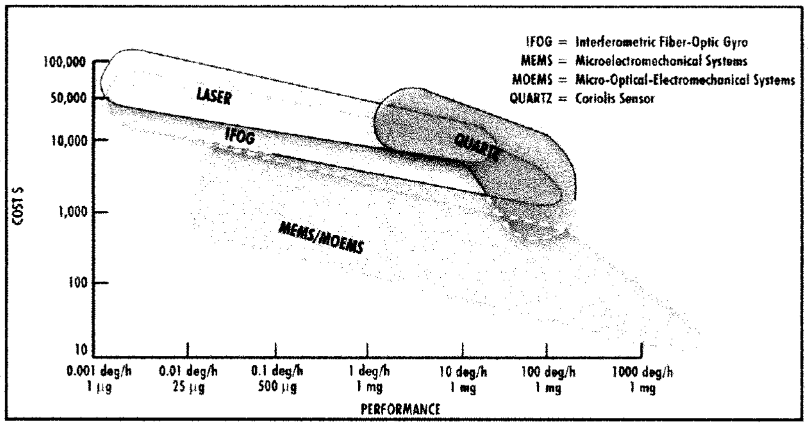

Fig. 7. INS/GPS cost as a function of instrument technology.

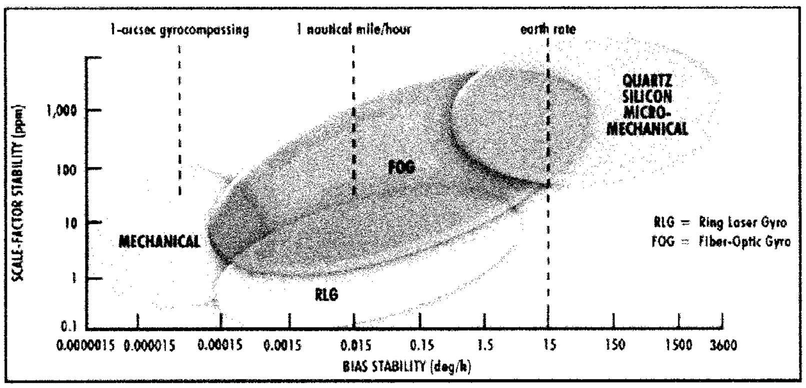

Fig. 8. Near-term gyro technology applications.

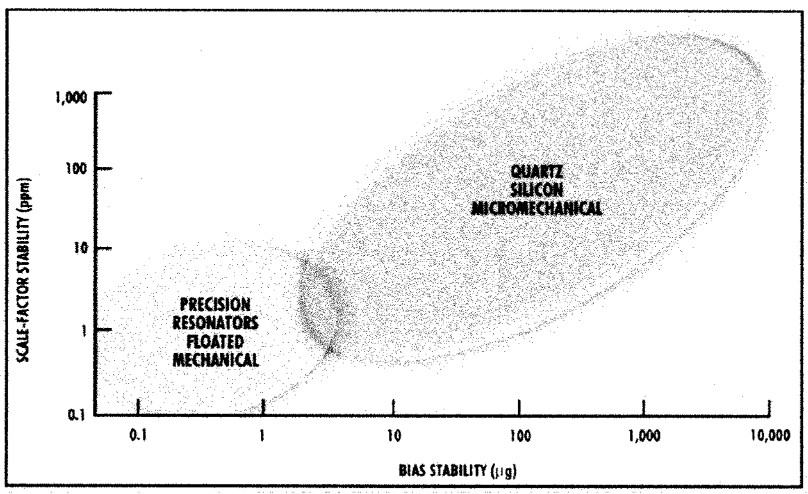

Fig. 9. Near-term accelerometer technology applications.

compared with an IFOG system of $15 to 20 K. This low cost can only be attained by leveraging off the consumer industry, which will provide the infrastructure for supplying the MEMS sensors in extremely large quantities (millions). The use of these techniques is resulting in low-cost, high-reliability, small-size and lightweight inertial sensors, and the systems into which they are integrated.

The future of strategic guidance systems for inter-continental ballistic missiles (ICBMs) and submarine-launched ballistic missiles (SLBMs) is highly dependent on what weapon system and what strategic missions are required. At this time, there is much uncertainty as to whether a strategic system will be used as a deterrent or as a precision surgical strike. Today's strategic nuclear deterrent missiles are expected to be operational until 2020 and beyond. Current guidance systems use mechanical gyros and accelerometers [pendulous integrating gyro accelerometers (PIGAs)] on a space-stabilized platform for boost guidance [5]. PIGA accuracy is unsurpassed to date.

TABLE I
NEAR-TERM INS/GPS ERROR BUDGETS (1 SIGMA) AND COSTS

	Flight Controls, Smart Munitions	Tactical Missiles	Tactical Missiles	Cruise Missiles, Aircraft INS
Type of Accelerometer Technology	Silicon Micromechanical	Quartz Resonant or Silicon Micromechanical	Quartz Resonant or Silicon Micromechanical	Quartz Resonant or Silicon Micromechanical
Accelerometer Bias Stability (μg) 1σ	1000	200	100	50
Type of Gyro Technology	Silicon Micromechanical	Silicon Micromechanical or Fiber-Optic Gyro	Fiber-Optic Gyro	Fiber-Optic Gyro
Gyro Bias Stability (deg/h) 1σ	10	1	0.1	0.01
Future INS Production Cost	$500	$1,000	$10,000	$20,000

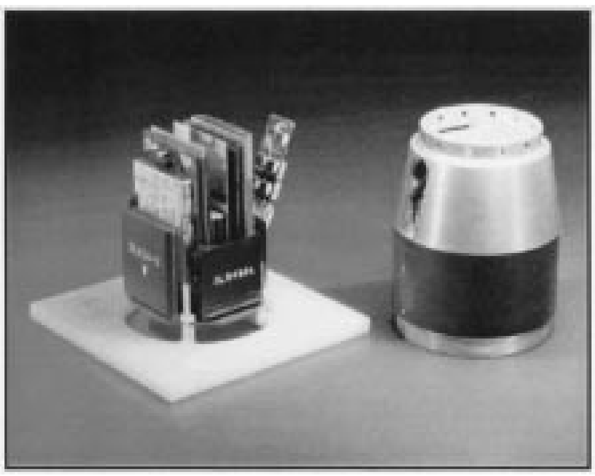

Fig. 10. 8 in^3 tactical INS/GPS system (courtesy of Draper Laboratory).

Although a next-generation system has not yet been identified, inertial sensor development in anticipation of a next-generation system is likely to concentrate on IFOGs and possibly HRGs and resonant accelerometers (quartz or silicon MEMS). IFOGs are also being considered as a lower-cost alternative for ballistic-missile-carrying submarine (SSBN) navigation [18]. A nearer-term, next-generation system will probably be a space-stabilized platform (gimballed) or thrust-following platform (semi-gimballed) for boost guidance. Smaller systems may be required inside the reentry bodies for reentry guidance. The IFOG appears to be the size driver because of the optical fiber coil. A physics technology breakthrough, allowing smaller IFOGs or MEMS/MOEMS gyros with strategic performance, will be required to miniaturize any future strategic systems.

The tactical (lower) performance end of the application spectrum will be dominated by micromechanical inertial sensors. The military market will push the development of these sensors for applications such as “competent” and “smart” munitions, aircraft and missile autopilots, short-time-of-flight tactical missile guidance, fire control systems, radar antenna motion compensation, “smart skins” using embedded inertial sensors, multiple intelligent small projectiles such as flechettes, or even “bullets,” and wafer-scale INS/GPS systems. The world’s smallest system, using micromechanical instruments and a GPS receiver, currently has a total volume of only 8 in^3 (Fig. 10) [13]. This volume compares with current RLG systems of about 600 cu. in. and FOG systems with a volume of about 100 cu. in. If micromechanical instrument performance improvements continue, they will come to dominate the entire inertial instrument application spectrum.

The potential commercial market for micromechanical inertial sensors is orders of magnitude larger than any contemplated military market. The application of micromechanical gyro technology to the automobile industry is one case where, for example, a true skid control requires a measure of yaw rate in order to operate successfully [19]. Products designed for this industry must be inexpensive and reliable, both characteristics of solid-state technology. Many other micromechanical inertial sensor applications exist for automobiles, such as airbags, braking, leveling, and GPS-augmented navigation systems. Additional commercial applications can be found in products such as camcorders, factory automation, general aviation and medical electronics. The performance of the micromechanical instruments will likely continue to improve as more commercial applications are found for this technology.

Table I gives some projections of cost for quantity production of near-term inertial systems, including a military, all-in-view GPS receiver. The systems are made up of near-term-technology gyros and accelerometers that have performance that match the mission requirements.

VI. FAR-TERM SENSOR TECHNOLOGY APPLICATIONS

Figs. 11 and 12 show how the gyro and accelerometer technology may be applied to new applications in the far term, somewhere around 2020. The figures show that the MEMS and MOEMS technology will dominate the entire low- and medium-performance range. The rationale behind this projection is based on two premises. The first is that gains in performance in the MEMS devices will continue with similar progression to the dramatic three to four orders-of-magnitude improvement that has already been accomplished in the last decade. That further improvements are likely is not unreasonable since the designers are beginning to understand the effects of geometry, size, electronics, and packaging on performance and reliability. Second, efforts are already underway to put all six sensors on one (or two) chips, which is the only way to reach the desired cost goal of less than $1000 per navigation-grade

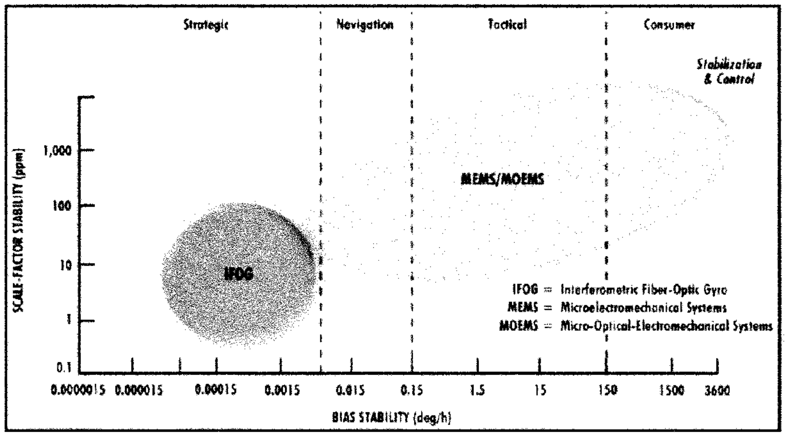

Fig. 11. Far-term gyro technology applications.

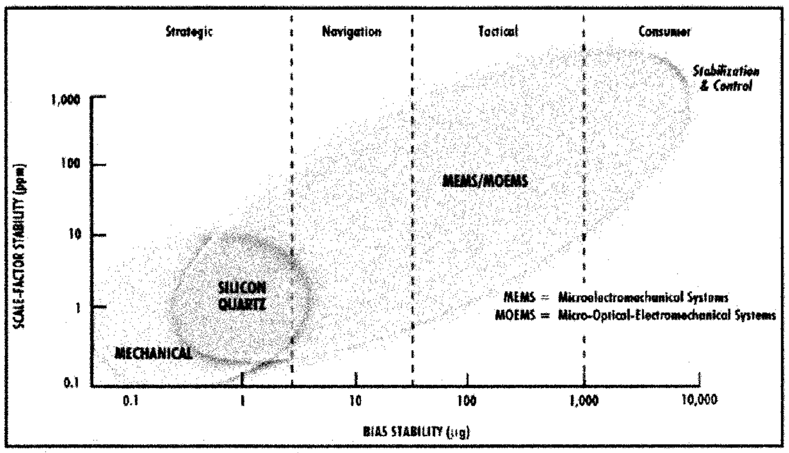

Fig. 12. Far-term accelerometer technology applications.

INS/GPS system. In addition, since many of the MEMS devices are vibrating structures with a capacitive readout, this may restrict the performance gains at the higher end (navigation grade). It is in this area that the MOEMS technology is most likely to be required to provide a true solid-state micromechanical gyro with optical readout. These MOEMS devices would have essentially no "g" sensitivity. At this time, the technology to make a very small, accurate MOEMS gyro does not exist, but advances such as resonant microspheres are already under development in the communications industry.

For the strategic application, the IFOG could become the dominant gyro. Work is underway now to develop radiation-hard IFOGs as well as super-high-performance IFOGs to replace electrostatically-suspended gyros (ESGs). For the strategic accelerometer, MEMS devices are likely to attain the performance. Work is now underway at several companies to develop silicon resonators. Quartz resonators are also in the running.

It is likely that the far-term accelerometer technology projections will be realized many years sooner than the gyro.

VII. Conclusion

The technology of inertial sensors has undergone continuous change. Fig. 13 depicts the maturity of emerging sensor technology. 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 horizon, so what is next for the sensor designer?

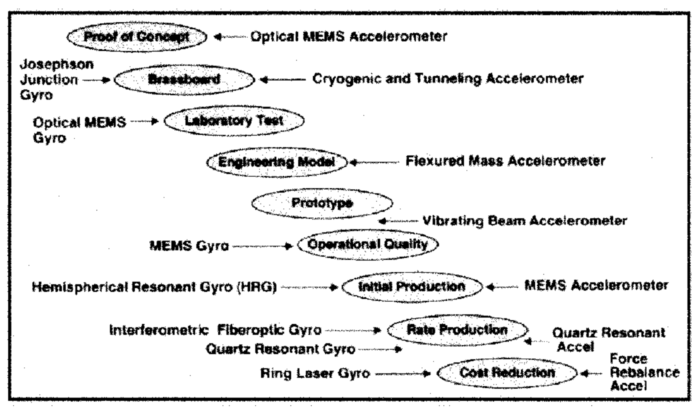

Fig. 13. Inertial sensor maturity.

The desire for very low cost and small size still exists at all performance levels. Therefore, the next few years will continue to emphasize performance improvement and efficient packaging of MEMS sensors. This will be a worldwide effort with potential markets in the billions. We may expect to see the development of optical MEMS devices. In the very long term, we may possibly develop nanoelectromechanical systems (NEMS) or Optical NEMS.

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