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INERTIAL INSTRUMENTS: WHERE TO NOW?

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Abstract

Many types of inertial instruments have been invented in the past, are currently being invented, and will continue to be invented as the market for guidance, navigation, and control continues to expand. Some of the inertial instruments have found a niche in current applications, while some did not progress much beyond the laboratory/prototype stage. This will be true of future developments also. This paper begins by describing gyroscope and accelerometer technologies that dominate the current market (e.g., strategic, aviation, space, tactical) and explains, in terms of performance and technology, why they have been successful. It is clear from this section that electromechanical and ring laser technologies control the current market. However, since accuracy requirements can be attained by existing technologies, the competition to insert the new technologies into the current applications is driven by the desire for low life-cycle cost, small size, and low production cost. Thus, the success of future instruments will be driven by technologies that enable lower cost, highly reliable instruments. This paper then describes what technologies are currently displacing the existing instruments and what technologies are expected to dominate in the future. Also, the potential new applications and markets that will open up because of the batch processing and low cost of solid-state/microfabricated instruments are described. It becomes apparent that electromechanical instruments will be rapidly displaced over the next 20 years, surviving only where unique performance cannot be matched, and that because of the fierce competition in the solid-state arena, the key to success will depend on system architecture and market timeliness.

1. Introduction

Electromechanical inertial instruments have dominated guidance, navigation, and control applications since the dawn of inertial sensing. In recent years, new technologies have enabled other kinds of sensors that are challenging this dominance, and, in the case of the ring laser gyroscope, have already replaced electromechanical instruments in certain applications. New technologies continue to be developed to meet future market needs. However, since accuracy requirements can be attained by existing technology, and since the new and emerging technologies offer little in any performance improvement, the decision to insert or develop them will depend on low life-cycle cost, small size, and low production cost. While several of the new technologies are described herein, it is expected that only two or three will impact the market in a significant way.

This paper attempts to present the status of inertial sensor technology in today's applications, and to explain why certain sensors have found a niche. This is then followed by a prediction of where inertial instrument technology is leading, and in what applications the future sensor technologies will find a niche.

2. Current Inertial Sensor Technology Applications

Figures 1 and 2 depict a perspective of current gyroscope and accelerometer technologies, respectively, and their applications as related to ppm of scale factor (i.e., how well the gyroscope or accelerometer 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. Referring to Figures 1 and 2, it is immediately apparent that electromechanical instruments, in the form of spinning mass and force rebalance instruments, dominate today's applications. These are mature, proven technology concepts.

2.1 Gyroscopes

The spinning mass gyroscope first found a home around 1920 in the single-degree-of-freedom rate gyro used as a basic turn indicator for instrument flying. After continuous evolution and improvement it was later used to provide lead angle data for aircraft fire control sights, and later still for aircraft and missile flight control systems. The basic configuration of a rate gyro is a ball bearing rotor housed in a gimbal whose gyroscopic precession in response to an angular rate is restrained by a mechanical spring, making it relatively inexpensive, very rugged, and reliable. Rate gyros dominate the 10 deg/h and above applications such as flight control, stability augmentation, autopilots, etc.

With the need for better performance, such as aircraft navigation, it was natural to improve on the rate gyro. When it was identified that the rate gyro's performance was limited by its spring (i.e., the very mechanism that allows it to function also limits its capability), the performance requirements were mastered by the development of the single-degree-of-freedom, rate-integrating gyroscope. The integrating gyro is basically a rate gyro in which the primary restraining torque on the gyro gimbal is a damping reaction with a servo loop to maintain the gimbal at null. The perfection of the integrating gyro is largely due to Dr. Charles Stark Draper, who isolated the gyro gimbal by means of flotation fluid and low reaction torque electromagnetic suspensions, pickoffs, and torquers. The floated integrating gyro went from revolutionizing aircraft navigation in the 50s to enabling strategic missile guidance, autonomous submarine navigation, and space flight in the 60s, 70s and 80s.

The gas bearing was a significant part of the floated gyro evolution, leading to better stability, and a self-aligning capability for strategic missiles, a capability that no other instrument to date provides. Another benefit of the gas bearing is the reduction of the angle noise of the floated instruments, so that it is used in satellite navigation and control; its most recent application is in the Hubble telescope.

Floated integrating gyros have relatively high cost, are labor intensive, and have long warm-up (reaction) times. Clearly, if a suitable alternate technology could be found, it would take advantage of these perceived problems; and this is exactly what happened.

The free rotor gyroscope, which is basically a ball bearing rotated spinning mass that is unrestrained about the gyroscope precession axes, was another early development. The use of one or two gimbals allows these instruments to be used as directional gyros for directional references and cockpit

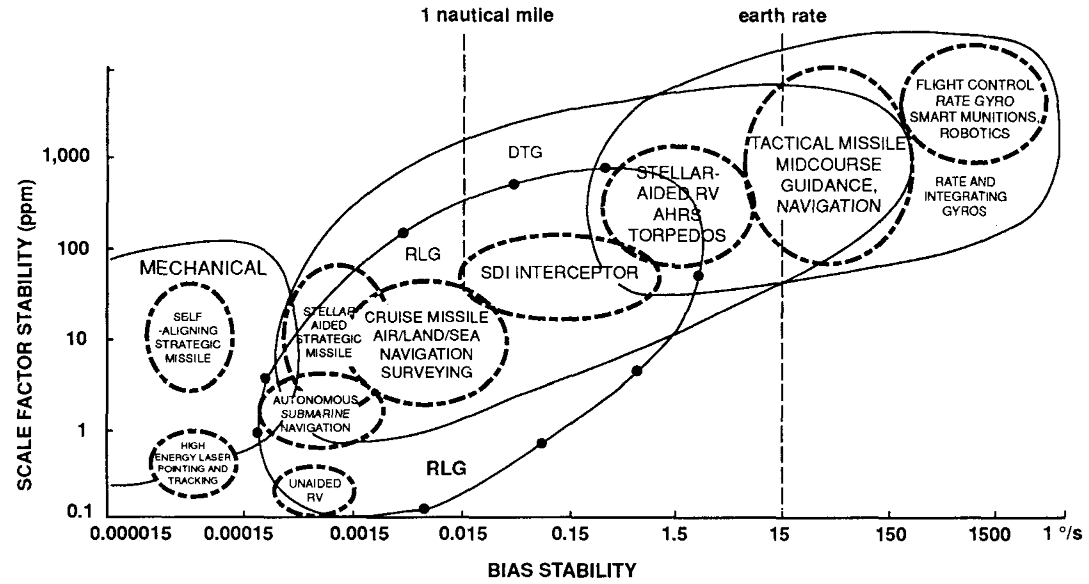


Figure 1. Current gyro technology applications.

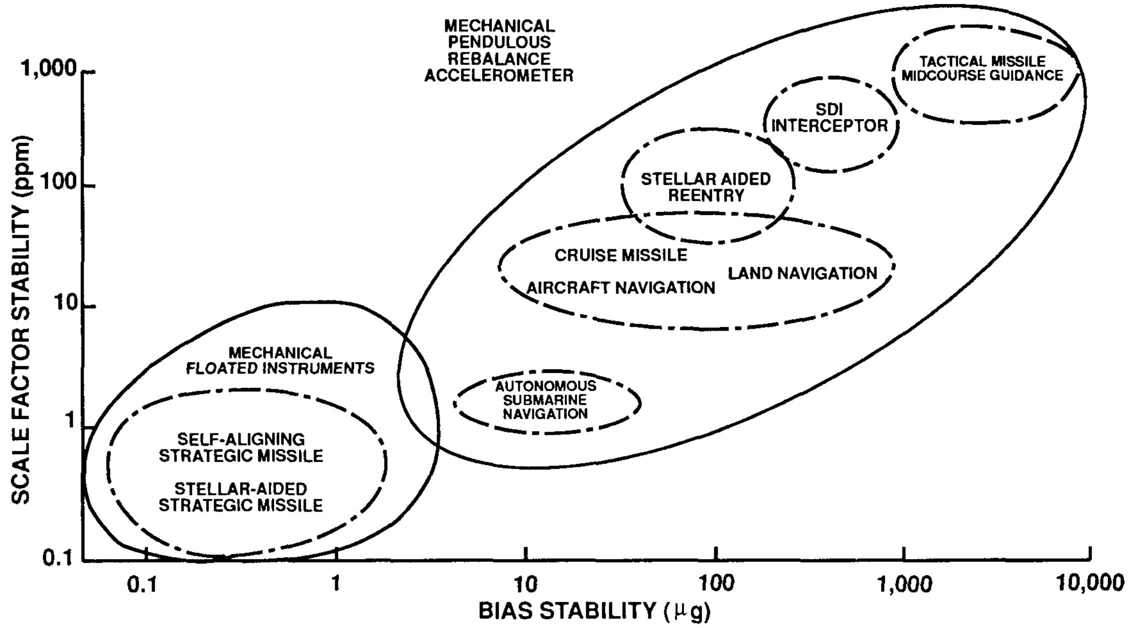


Figure 2 Current accelerometer technology applications.

displays such as the gyrocompass, artificial horizon, etc. These are very low-accuracy instruments, but have maintained their role in the market place.

Another early instrument that offered potential advantages over the floated gyro was the two-degree-of-freedom, gas-film supported, free rotor gyroscope, but it was not until the mid-50s that this instrument became viable when the rotor time constant problem was solved. Rockwell's gas film free rotor gyroscope has been used for aircraft navigation and Minuteman boost guidance. This type of instrument has fast reaction times and results in lower cost because of its two degrees of freedom, but it cannot match the best performing floated gyros.

The free rotor gyro can be regarded as a precursor to the two-degree-of-freedom electrostatic gyro (ESG). In the early 50s, ESG development was begun and was carried on through the 60s and 70s. The ESG only became viable when machining techniques became available to generate the very precise finishes and geometry required. The ESG was developed by Honeywell and Rockwell for inertial navigation and was used for aircraft and land navigation and surveying. Because of its exceptionally high stability, enabling long periods between calibration or update, ESGs have been used for attack submarine navigation (ESGN) and the Trident submarine on-board monitor (ESGM). The ESG has much lower drift than the best floated gyros and is small; however, its applications are limited to relatively benign environments since it has low g capability. ESGs are being replaced by lower cost technologies that are better suited for strapdown applications. For super accuracy, approximately three orders of magnitude better than floated instruments, as required for relativistic measurements, Stanford University's Gravity Probe B (to be launched in the mid 90s) ESG is operated in a cryogenic environment.

In the early 60s, the dynamically-tuned free rotor gyroscope (DTG) was invented. The DTG is a two-degree-of-freedom instrument whose rotor is suspended by a universal hinge of zero stiffness at the tuned speed and rotated by a ball bearing. Because of their relatively low cost, fast reaction time, small size and ruggedness, DTGs have taken the market from other mechanical instruments in most areas where performance is comparable. DTGs have been a phenomenal success in strapdown and gimbaled systems, and have found applications in aircraft and missile navigation, stellar-aided strategic missile boost and reentry, north seekers, and AHARS. DTGs have demonstrated exceptionally low angle noise and are used in satellite navigation and control, and are also being made very small for tactical missile seeker heads. There is a worldwide manufacturing capability for DTGs.

At the same time that the DTG was being invented, the principle of detecting rotation by the Sagnac effect was first demonstrated (1963) in a ring laser gyroscope (RLG). The RLG operates by setting up clockwise and counterclockwise resonant light beams reflected around a closed cavity by mirrors and detecting phase shifts between these beams due to a rotation. The laser is inside the cavity, which contains the lasing medium; hence, the RLG is termed an active device. Development of RLG technology into a usable instrument required significant time and investment to overcome lock-in problems and to perfect the mirrors, and it was not until the early 80s that an aircraft navigation-grade RLG became available. Thereafter, RLGs advanced rapidly into the world's civil aircraft (757, 767, Airbus) and military helicopters, displacing DTGs and integrating mechanical gyros. The RLG has stellar-aided strategic missile boost grade performance, while the smallest versions are suitable for tactical missile applications. RLG technology is still advancing, but is at the practical limit for today's technology. There are many RLG manufacturers worldwide.

The perseverance applied to RLG technology stemmed primarily from the desire for strapdown operation, which became more and more practical as digital computing in strapdown algorithms grew in the 70s and beyond. Mechanical instruments can operate in the strapdown mode, but the RLG is an excellent strapdown device because of good scale-factor (SF) linearity and SF stability in the tens of parts per billion compared with tens of parts per million for mechanical sensors, and almost negligible g sensitivity. The RLG has other attractive features such as digital output, very fast reaction times, excellent dormancy characteristics, lower cost, and the absence of moving parts. The need to dither to avoid lock-in problems did introduce a mechanical component to the RLG, but this can be avoided without mechanical means as in Litton's ZLG (zero-lock gyro).

2.2 Accelerometers

Referring to Figure 2, it is apparent that technologically mature electromechanical accelerometers dominate today's market. The majority of these are the restrained mass or force rebalance types, in which a proof mass is supported in a plane perpendicular to the input (sense) axis by a flexure, torsion bar, or pivot and jewel. The motion of this proof mass under changes of acceleration is detected by a pickoff. A rebalance force may be generated through a servo feedback loop to restore the proof mass to its null position. Closed-loop, force rebalance operation provides significant performance advantages such as linearity, wide dynamic range, reduced cross-axis sensitivity, and good scale-factor stability. Open-loop operation is currently used primarily for environmental measurements, switching, and vibration sensing, where high performance is not an issue. This will change with certain types of new open-loop resonator accelerometers.

The force rebalance type of accelerometer has been successful not only because it is relatively small, simple, very rugged, and reliable, but also because it can be designed to meet different performance and application requirements by careful selection of the flexure and mass configuration, electromagnetic pickoffs and forcers, servo electronics, fluid and damping, and materials. There are many manufacturers of force rebalance accelerometers such as Bell's Model XI, Litton's A-4, Kearfott's Mod VII, Sundstrand's Q-flex, and Systron Donner's 4841. Force rebalance accelerometers can operate in strapdown or gimbaled modes. The output needs to be digitized.

The most accurate of the force rebalance accelerometers is the Draper-designed and Honeywell-built Pulsed Integrating Pendulous Accelerometer (PIPA), which is a floated, single-degree-of-freedom, essentially zero restraint device, which is digitally torque pulsed to maintain the float (or pendulum) at null. The PIPA is used in submarine-launched strategic missiles. PIPA accuracy is limited by nonlinear errors proportional to the float velocity during pulse torquing.

The highest performance accelerometer available is the Pendulous Integrating Gyro Accelerometer (PIGA), which is used for strategic missile guidance. The PIG part of the PIGA is identical to the floated single-degree-of-freedom, integrating gyro with the addition of a pendulous mass located on the spin axis. The PIG is mounted on a self-contained, servo-driven member (SDM) that rotates the PIG to produce a gyroscopic torque to balance the pendulous torque. The SDM is equipped with a resolver or encoder to measure SDM rotation angle, which is proportional to the time integral of the input acceleration. The PIGA is a very stable, linear device, with very high resolution over a wide dynamic range, and is the only accelerometer to date capable of meeting strategic missile thrust axis requirements. Its major advantage over force rebalance accelerometers is the lower requirement on measuring SDM rotation angle and velocity versus torque pulse quantization, plus the error cancellation effect from the SDM rotation. PIGAs are relatively complex and perceived to have high life-cycle costs due to the three rotating mechanisms (gas bearing, SDM ball bearing, and slip ring). The Draper-designed PIGA is manufactured by Honeywell and Litton (U.S.A.); Sagem (France) and Russia also manufacture PIGAs.

Another type of accelerometer is the resonator or open-loop type such as the vibrating string accelerometer, which was used in early ICBM guidance and for local lunar gravity surveying on the lunar rover. This device had low shock tolerance.

Angular accelerometers were initially used in the 50s for dynamic compensation of ac servomechanisms. The basic configuration is a fluid-filled ring with a vane extending into it. Under rotational motion of the ring, the vane is restrained by a torquer, whose current indicates the angular displacement. Devices, such as those built by Systron Donner, are used in applications requiring high bandwidths (2000 Hz), small magnitude stabilization, or jitter compensation. However, angular displacement sensors are not as accurate as floated gyros or DTGs below about 20 Hz, but the high cost of those gyros restricts their use.

2.3 Multisensors

For the purpose of reducing cost and size, multisensors that perform the combined function of measuring angular rate and linear acceleration were developed. The multisensor is ideal for applications where redundant acceleration information is required.

In the 70s, Draper developed a navigation-grade floated multisensor by adding a pendulous mass along the output axis of a floated single-degree-of-freedom gyro. This allowed two axes of acceleration sensing and one axis for rate sensing. The Litton multisensor incorporated two tuned rotors mounted on opposite ends of a ball bearing spin shaft; one of the rotors acts as a DTG, while the other acts as a two-degree-of-freedom accelerometer due to an added mass imbalance.

The ability to reduce size and cost significantly is achieved by sensing the Coriolis acceleration force on a rotating body in the presence of an angular rate. Rockwell Collins and GEC Marconi have developed multisensors consisting of two pairs of piezoelectric ceramic sensing elements, with each pair attached orthogonally on a rotating drive structure, which provide rate and acceleration inputs on two orthogonal axes. They are being used in tactical missiles. Sundstrand has developed a multisensor using two accelerometers to produce an angular velocity for Coriolis force sensing. This configuration provides one acceleration and one gyro axis. Several other companies in the U.S. and Japan are developing multisensors.

3. Where To Now?

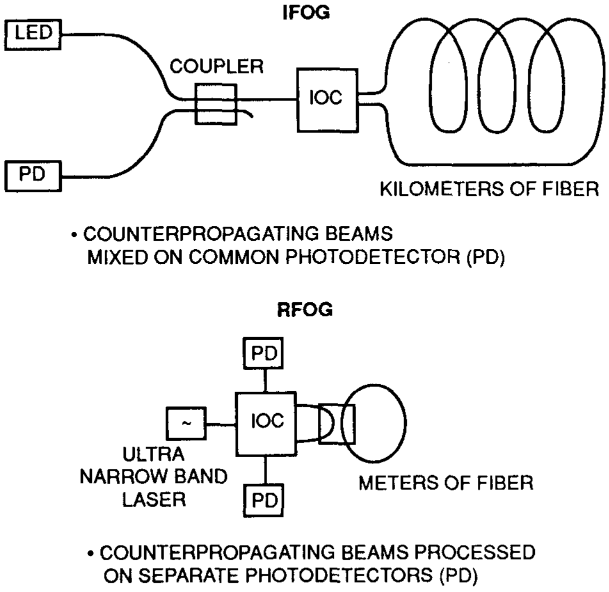
3.1 Inertial Instrument Technologies for the Future

Major changes are currently underway in those technologies associated with inertial sensors such as gyroscopes and accelerometers. These changes are likely to result in the proliferation of inertial sensors into a wide variety of new military and commercial applications. This is expected to occur, and is in many respects already underway, because inertial sensors are beginning to adopt many of the fabrication techniques that have been developed by the solid-state electronics industry over the last decade. Inertial sensors are being fabricated in silicon, quartz, and with electro-optic materials, such as lithium niobate, by employing the low-labor-intensive batch processing techniques that were developed earlier for solid-state electronics. It is predicted that the utilization of these techniques will result in very low associated cost, high reliability, small size, and light weight for inertial sensors and for the higher level systems into which they are integrated. Some inertial sensors have already been fabricated with dimensions so small that they are barely visible to the naked eye. *It is not expected that there will be* any performance improvement with these new sensors and, in fact, the performance is often considerably less than conventional inertial instruments provide. Nevertheless, the largest majority of applications exist at these lower performance levels, especially in the commercial area.

Fiber-Optic Gyros (RFOG, IFOG, and CFOG)

Sagnac effect rotation rate sensors result from the counter propagation of beams of light in a waveguide with optical reciprocity between its clockwise and counterclockwise propagation paths. Rotation normal to the waveguide plane upsets this symmetry, which is then photoelectronically detected and processed to provide an output of rate. The FOG is implemented using an integrated optics chip constructed in lithium niobate, and fiber-optic sensing coil, diode light source, and photodetectors. This configuration is expected to be supplemented eventually by quantum well technology, such as gallium arsenide, which will then allow integration of most of the above components into a single substrate, increasing reliability, and reducing costs even further. FOG sensors have no gas or mirrors and do not exhibit lock-in at low rate.

There are two fundamentally different implementations of a FOG sensor; one is a resonant optical structure or RFOG, and the other is an interferometric optical structure or IFOG. Since the IFOG sensor has been in active development longer than the RFOG, it is closer to a flight-testable prototype. Figure 3 indicates the fundamental differences between the RFOG and IFOG.



- COUNTERPROPAGATING BEAMS MIXED ON COMMON PHOTODETECTOR (PD)

- COUNTERPROPAGATING BEAMS PROCESSED ON SEPARATE PHOTODETECTORS (PD)

Fig. 3. FOG differences.

The RFOG utilizes a short closed loop of fiber as an extremely high finesse resonant optical waveguide. Ideally, with no rotation, each of the two counterpropagating light beams remain in the fiber at resonance, and no light leaves the loop. Rotation shifts the beams from their resonance frequency, and light then leaves the loop. An optical coupler together with an integrated optics chip, directs this escaping light for each beam direction onto separate photodetectors. With these beams Doppler shifted off resonance in opposite frequency directions, their corresponding photodetector differentials provide a measure of the rotation rate. Because of the resonant optical structure, the RFOG must be driven by a very narrow line laser diode. The RFOG is expected to have size and radiation hardness advantages over the IFOG due to less fiber and cost advantages over the RLG; performance better than 1 deg/h is expected.

In contrast to the RFOG, the IFOG uses a longer, multiple-turn, fiber coil with a nonresonant, very broad optical structure. As a result, a broadband diode is used as the light source. A single IFOG photodetector measures the interference between the two counterpropagating light beams, each of which are driven from a common source. With identical optical path lengths (i.e., no rotation), this photodetector provides a measure of the correlation of the light source after passage through the fiber coil. With rotation, the counter-rotating path propagation times change differentially, resulting in an optical phase shift between these two beams, which is then read at the photodetector.

The performance of IFOGs has not been quite as good as the RLGs to date for comparable size and weight, but that may be only the result of the relative immaturity of the technology. However, it has a potential for extremely long MTBF (>150,000 h), since it is truly a solid-state device (versus having a gas-filled cavity as in a RLG). The device may be open or closed loop (for higher performance versions). "Reentry-only" grade gyros (~1 deg/h) are approximately 3 inches in diameter; stellar-aided-boost quality gyros are about 7 inches in diameter. Only the 3-inch class models are out of the laboratory stage of development at present.

By cryogenically cooling a fiber-optic gyro, certain types of losses are practically eliminated, thereby enabling higher performance in a very small instrument. Laser diode and detector performance are also enhanced. A liability, of course, is the necessity of providing a cryogenic coolant source for operation. It may be possible to incorporate a set of gyros on a cooled focal plane (e.g., for an IR sensor) to provide a synergistic thermal design for such a sensor package. Because these would be very small instruments, the CFOG performance may be too crude for most currently envisioned integrated guidance missions.

Also under development is an integrated optics gyroscope in which the fiber is replaced with a waveguide on the integrated optics; performance better than 1 deg/h is anticipated.

Josephson Junction Gyro (JJG)

Some theoretical work has been done at NADC and Temple University on applying some properties of "high-temperature" superconducting materials to inertial sensing. This particular gyro concept utilizes the phase coherence of the superconducting electrons and a Josephson Junction to measure rotation around a sensitive axis. This is achieved by producing a persistent current in a ring of superconducting material. Again, the Sagnac effect is used as in RLGs, i.e., the electrons (rather than light) experience a phase shift if a rotation is applied to the ring. As with the RLG, the sensitivity of the instrument is a function of the area enclosed by the ring and the phase sensitivity of the electrons (versus light). Because electrons have a much higher phase sensitivity (~100) than photons, the JJG is theoretically capable of being two orders of magnitude smaller (in volume) than an equivalent RLG. Again, this instrument is only in the theoretical stage of development.

Hemispherical Resonating Gyro (HRG)

Under development by Delco for many years, the HRG resembles a quartz "wine glass" shape. By exciting the wine glass into resonance, a standing wave pattern is produced on the instrument. Pickoffs sense the position of this wave pattern, which rotates around the device if an inertial angular rate is applied about the instrument's sensitive axis. The size of the instrument increases if high performance is desired. Small, thimble size, instruments perform in the 1-deg/h range. Considerably larger instruments would be required to support a stellar-aided boost mission. The instrument is still in the development stage and has been funded (on and off) by both the Navy and Air Force. Currently, new electronics are being redesigned and tested to improve instrument performance. The HRG has been incorporated into Delco's Carousel INS for Lufthansa.

Tuning Fork Gyros

This type of gyro is designed as an electronically-driven tuning fork, often fabricated out of a single piece of quartz or silicon. Such gyros operate in accordance with the dynamic theory that when an angle rate is applied to a translating body, a Coriolis force is generated. When this angle rate is applied to the axis of an oscillating tuning fork, its tines receive a Coriolis force, which then produces torsional forces about the sensors axis. These forces are proportional to the applied angle rate, which then can be measured capacitively (silicon) or piezoelectrically (quartz); the output needs to be demodulated for digital processing. Systron Donner's QRS (Quartz Rate Sensor) has been incorporated into tactical missile guidance. Others, including Draper, are developing tuning fork gyros; Murata (Japan) uses an equilateral triangle free-free-bar as a sensitive element.

Silicon Micromechanical Instruments

Silicon micromechanical instruments can be made by bulk micromachining (chemical etching) single crystal silicon or by surface micromachining layers of polysilicon. Many manufacturers are developing gyros and accelerometers using this technology. Their extremely small size combined with the strength of silicon makes them ideal for very high g applications.

Several manufacturer's accelerometers incorporate piezoresistive bridges such as those used in early micromechanical pressure gauges. More accurate accelerometers are the force rebalance type that use closed-loop capacitive sensing and electrostatic forcing. Draper's micromechanical accelerometer (Figure 4) is a typical example, where the accelerometer is a monolithic silicon structure (i.e., no assembly of component parts) consisting of a torsional pendulum with capacitive readout and electrostatic torquer. This device is about 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 angular position. The torque required to maintain this balance is proportional to the input acceleration; performance around 250 μg and 250 ppm SF have been achieved.

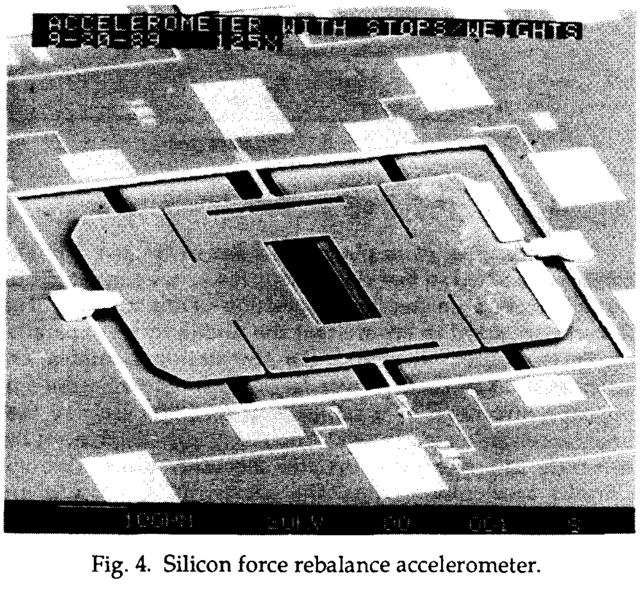
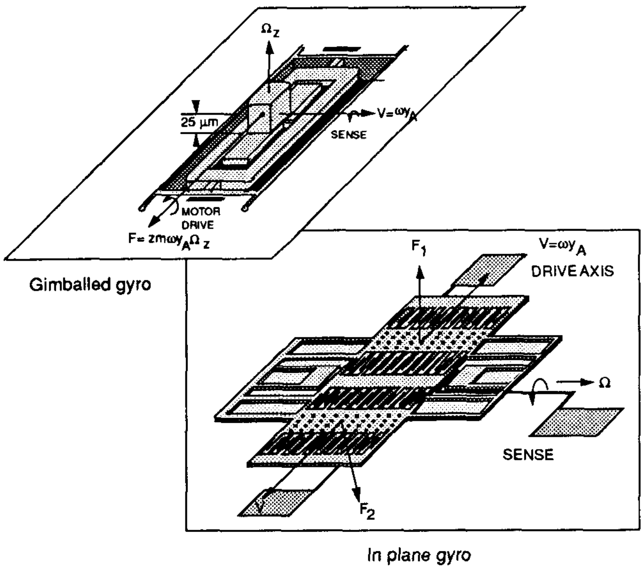


Fig. 4. Silicon force rebalance accelerometer.

Micromechanical accelerometers can also be fabricated using wafer bonding sandwich construction techniques, as in Litton's silicon accelerometer developed for AHRS and tactical missile guidance. Kearfott and Sundstrand are developing micromechanical VBAs. Analog Devices has an interdigitated polysilicon capacitive accelerometer fabricated with an on-chip BiMOS process to include a precision voltage reference, local oscillators, amplifiers, demodulators, force rebalance loop and self-test functions. Complete integration of sensor and electronics will become common in all future micromechanical instruments.

Micromechanical gyroscopes are primarily Coriolis force sensors. Draper is developing two such devices. The first is a double gimbal structure (Figure 5) with a vertical gold mass mounted on the inner gimbal. The inner gimbal can be thought of as the gyro and the outer gimbal as the motor. Each gimbal is attached to the other through a set of orthogonal flexure pivots. These pivots are relatively weak in torsion, but strong in all other directions. When the outer gimbal vibrates through a small angle, the inner gimbal becomes sensitive to angular rates about the axis normal to the plane of gimbals. In the presence of an angular rate about the axis normal to the plane of the gimbals, the inner gimbal responds by vibrating at the outer gimbal vibration frequency at an amplitude proportional to the input angular rate. This gyro is the companion to the Draper accelerometer, and could ultimately be processed on the same chip. Performance of 300 deg/h has been achieved.



Gimballed gyro

In plane gyro

Fig. 5. Operation of gimbaled and tuning fork gyro.

The second is an in-plane gyro design (Figure 5). The combs are excited so that electrostatic forces are generated that do not depend on the lateral position of the masses. The flexures are sized to ensure that the tuning fork antiparallel mode is excited and that the translational modes are attenuated. The comb drives large-amplitude vibrations in opposite directions by a self-excited oscillator loop so that linear acceleration is rejected. Angular rate in the plane of the substrate lifts one mass up and the other down through Coriolis acceleration, thus, the sense and input axis are identical. Capacitors below the proof mass are used for sensing.

Development of micromechanical gyros having spinning wheels or configured as an HRG have been reported. Northrop is using a dual micromechanical accelerometer configuration as a gyro.

Resonating Beam Accelerometers

The resonating beam accelerometer (also referred to as the vibrating beam accelerometer (VBA)) is similar in principle to the vibrating string accelerometer concept that was developed many years ago. This form of accelerometer is essentially an open loop device, that is, the proof of mass is not rebalanced to its center position during the application of specific force. For accuracy, it relies on the scale-factor stability inherent in the material properties of the proof mass supports.

A schematic of the resonating accelerometer concept is shown in Figure 6. These accelerometers can be constructed using several different fabrication techniques. One method is to etch the entire device (proof mass, resonating tine, and support structure) from a single piece of quartz. Using such techniques can result in low-cost, highly reliable accelerometers with performance capabilities of better than 100 µg. Constructing this accelerometer from a single piece of quartz results in high thermal stability, along with dynamic ranges approaching those obtainable in the timekeeping industry. The principle of operation is similar to that of a violin. When the violin string is tightened, its frequency of operation goes up. Similarly when the accelerometer proof mass is loaded, one tine is put into tension and the other into compression. These tines are continually electrostatically excited at frequencies in the hundreds of kilohertz range when unloaded. As a result, when "g" loaded, one tine frequency increases while the other tine frequency decreases. This difference in frequency is a measure of the device's acceleration.

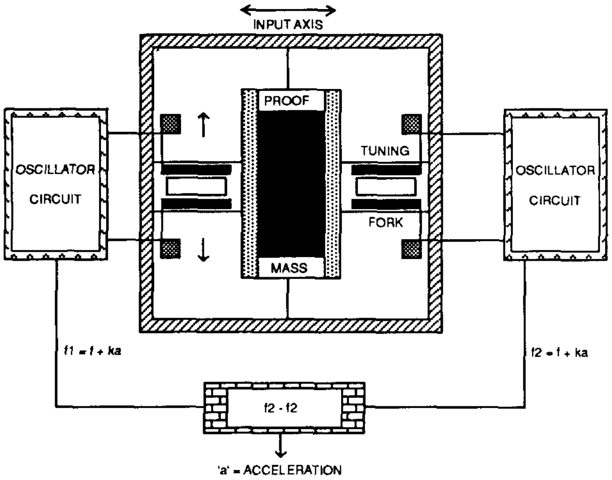


Fig. 6. QRA schematic.

Kearfott and Sundstrand have developed laboratory prototypes aimed at strategic missile guidance, the driving force being that they are solid-state devices and therefore hold potential for good MTBF. Sundstrand, Systron Donner, Draper Lab, and others have produced navigation- and tactical-grade quartz VBAs.

Microwave Resonant Accelerometer (MRA)

This is also a solid-state device with a strategic missile performance goal. It is also an alternative to the high-performance VBA, and is approximately the same size as a mechanical instrument of comparable performance. It operates by maintaining the electromagnetic field in two opposing cavities (separated by a proof mass) in resonance by injecting microwaves into the cavities. The size (or volume) of each cavity dictates the resonant frequency. Under acceleration, the centered proof mass deflects, thereby changing the size of both cavities thus producing an up and down shift in the resonant frequencies. This frequency difference is detected and related to the input specific force. The potential problems of radiation sensitivity and inversion transients are being addressed early in the instrument's development program. A schematic of MRA operation is shown in Figure 7.

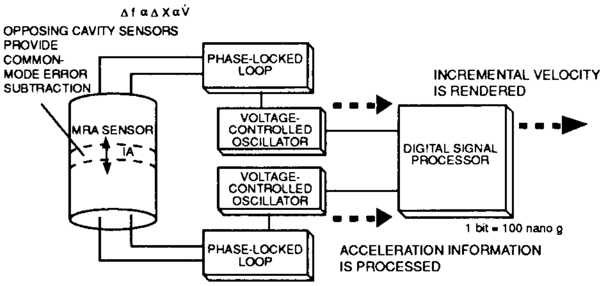


Fig. 7. Microwave resonator accelerometer block diagram.

Others

Other devices that are still very immature are being studied, such as the Surface Acoustical Wave (SAW) device, Laser accelerometer, Tunneling accelerometer, and Nuclear Magnetic Resonance (NMR) gyros. One other interesting candidate that may have a potential for high performance is based on using optical fibers in a mercury-filled, small (1 in^3) three-axis instrument to interferometrically measure acceleration-induced pressure gradients in the fluid. This "FLUACC" concept is being studied at Draper.

3.2 Future Technology Applications

The utilization of solid-state inertial sensors like those described above have potentially significant cost, size, and weight advantages over conventional instruments, which will result in a rethinking of the options for which such devices can be used in systems. While there are many such applications of the conventional military type, 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.

Predictions for the future path of technology, however inappropriate they may appear to be, can and have been made. In nearly every case, when these newer solid-state inertial technologies have been evaluated against today's technology, given compatible technical requirements, this new class of solid state inertial sensors becomes the winner. The basis for this technological selection is almost always lower cost. A vision of how the inertial instrument field might be expected to change over the next 20 years is shown in Figures 8 and 9 for the gyro and accelerometer, respectively. It is apparent that electromechanical instruments will become rapidly displaced.

At the high-performance end however, fielded strategic missile applications will still be dominated by mechanical floated gyros for self-alignment, PIGAs, and force rebalance accelerometers for cross-axis measurements. No new design efforts on these instruments are expected, and future activity will be devoted to supporting longevity. New initiatives will involve solid-state strapdown, stellar or satellite-aided missions for which the development of solid-state thrust-axis accelerometers (MRA and VBA) will be paramount, with IFOGs or RLGS for the gyro. It is quite likely that resonant accelerometers will take over the cross-axis and reentry measurement functions. A solid-state thrust-axis accelerometer, such as the MRA or VBA, could meet the small size required for advanced gradiometry borehole applications. For the esoteric relativistic measurements in space, only the cryogenic ESG will satisfy the requirements; super low noise (~1 nrad) floated gyros may be required for stabilization in some satellite applications.

The middle-performance ground is expected to become dominated by optical gyros, primarily fiber optic, which will process their rate-induced Sagnac frequency shifts in lithium niobate or gallium arsenide. The ring laser gyro is an excellent instrument, but its intrinsic manufacturing is heavily dominated by precision machining processes and alignment requirements, which force its costs to remain relatively high. However, one particular area where the ring laser gyro is expected to retain its superiority is in the area of scale factor. The laser gyro has its optical path in a gas, whereas the fiber-optic gyro has its path in glass, making the FOG fundamentally much more susceptible to environmental effects. For comparable performance applications, the selection between the FOG and the RLG will very likely depend on the supplier of the system as well as the specific mission requirements. The use of GPS will greatly ease the requirements on inertial navigation systems. IFOGs are slated for the Boeing 777 INS.

The military and commercial space community tend to be very conservative, so that the shift to new technology will take much longer and require significant evaluation. Thus, DTGs and floated gyros will continue to dominate the satellite market for the next 10 to 20 years. However, because of their low power and low cost, IFOGs and resonant accelerometers will eventually capture this market. Mechanical control moment gyros and ball bearing spin momentum and reaction wheels will continue to be used for attitude control.

Land navigation will be dominated by low-cost, rapid-reaction, thermally-modelable gyros, such as the RLG and FOG, and resonant accelerometers.

The need for a counterforce (such as Naval Theater Missile Defense) to the proliferation of tactical ballistic missiles, will involve gun-launched missile systems, and self-guiding Kinetic Energy Weapons (KEW). These applications require very rapid reaction and possibly very high-g capability instruments.

The low-performance end of the application spectrum will be dominated by micromechanical inertial sensors. These could be, for example, gyros and accelerometers or IMUs photolithographically constructed in silicon or quartz and subsequently etched in very large numbers as a single batch. It is expected that 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 utilizing embedded inertial sensors, multiple intelligent small projectiles such as flechettes or even "bullets," and wafer-scale GPS/inertial integrated systems.

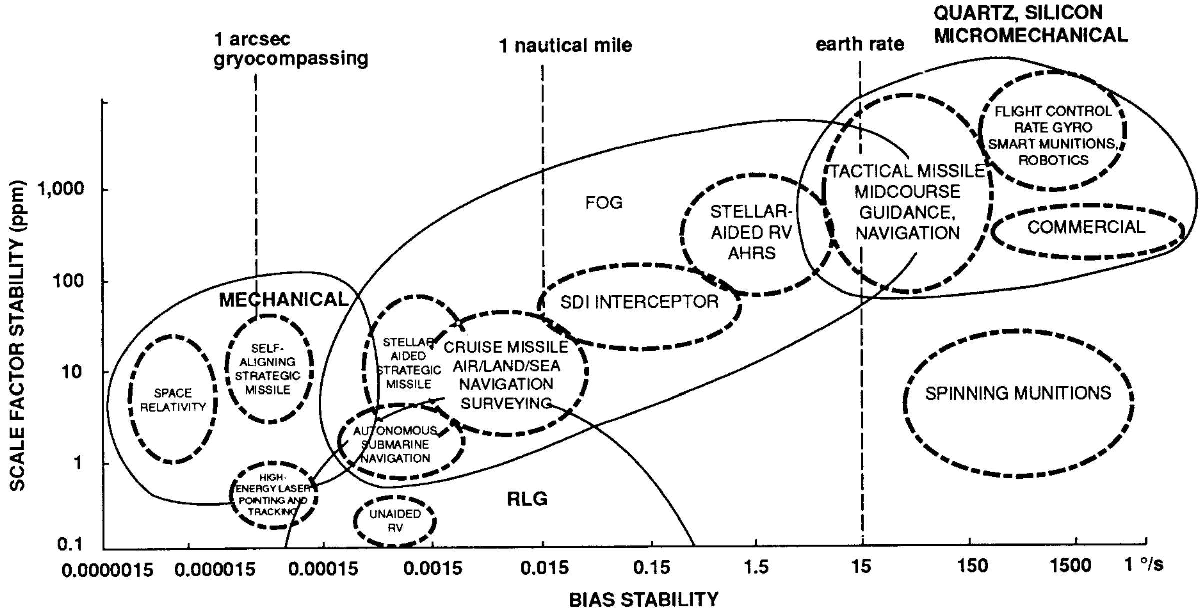


Figure 8. Future gyro technology applications.

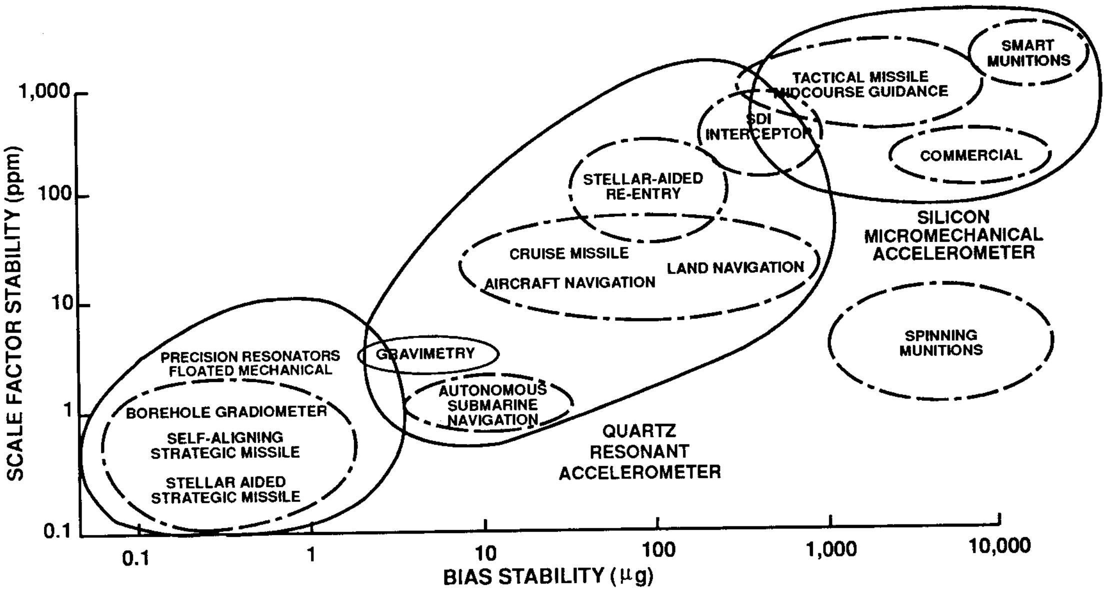


Figure 9. Future accelerometer technology applications.

These instruments will continue to evolve into the middle-performance ground. The 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. For example, a true skid detector requires a measure of inertial rate in order to operate successfully. 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 augmentation to GPS navigation systems. Additional commercial applications can be found in products such as camcorders, factory automation, general aviation, medical electronics, and perhaps one of the largest areas of all, children's toys and games. If the cost can be brought down low enough, one could expect to see an IMU in every home.

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