Emerging Technologies in Microguidance and Control

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Abstract

The Charles Stark Draper Laboratory has invented and developed inertial guidance systems for earth and space applications for over 50 years. Employing recent advances in microfabrication, Draper has developed inertial instruments of very small size and low cost. Microfabrication employs the batch processing techniques of solid-state electronics, such as photolithography, diffusion, and etching to carve mechanical parts. Within a few years, microfabricated gyroscopes should perform in the 10 to 100 deg/h range. Microfabricated accelerometers have demonstrated performance in the 50 to 500 microgravity range. These instruments will result in not only the redesign of conventional military products, but also new applications that could not exist without small, inexpensive sensors and computing.

Draper's microfabricated accelerometers and gyroscopes will be described and test results summarized. Associated electronics and control issues will also be addressed. Gimballed, vibrating gyroscopes and force rebalance accelerometers constructed from bulk silicon, polysilicon surface-machined tuning fork gyroscopes, and quartz resonant accelerometers and gyroscopes will be examined. Draper is pursuing several types of devices for the following reasons: (1) to address wide ranges of performance; (2) to realize construction in a flat pack; and (3) to lessen the risks associated with emerging technologies.

Introduction

The Charles Stark Draper Laboratory has invented and developed inertial guidance systems for earth and space applications for over 50 years. Recent advances in microfabrication have resulted in inertial instruments of very small size and low cost. Microfabrication employs the batch processing techniques of solid-state electronics, such as photolithography, diffusion, and etching to carve mechanical parts. These instruments and digital computing will result in not only the redesign of conventional military products, but also new applications which could not exist without small, inexpensive sensors, inertial measurement units (IMU), and computing.

Draper's microfabricated accelerometers and gyroscopes will be described and test results summarized. Associated electronics and control issues will also be addressed briefly. Gimballed, vibrating gyroscopes and force rebalance accelerometers constructed from bulk silicon, polysilicon surface-machined tuning fork gyroscopes, and quartz resonant accelerometers and gyroscopes will be examined. Draper is pursuing several types of devices for the following reasons: (1) to address wide ranges of performance; (2) to realize construction in a flat pack; and (3) to lessen the risks associated with emerging technologies.

Silicon Instruments

Gimballed Gyroscope

The silicon gimballed gyro was the first micromachined instrument which Draper has designed and built. A photograph of a gimballed gyro is shown in Figure 1. The gyro's operation is shown schematically in Figure 2. The gyro does not rotate continuously. The outer gimbal is driven at the resonance of the inner, sense gimbal resulting in a sinusoidal velocity of the effective masses along the X axis (defined by the inner flexures). Coriolis acceleration induced by a rate applied about the perpendicular Z axis causes a torque about the inner flexures, the sense axis.

Open loop, the amplitude of the inner gimbal position signal at drive frequency is proportional to the substrate angular rate about the vertical axis. The inner gimbal is operated closed loop with quadrature and in-phase loops with demodulation of gyro position output and remodulation of torques. Other possible loops include a frequency control loop, motor amplitude control, and two low frequency tilt control loops.

For optimal performance, on-chip preamplifiers are constructed using passive and active elements compatible with the gyro machining. To minimize the size and power of associated electronics, which can dwarf the actual instrument requirements, it is desirable to select configurations that simplify the electronic requirements and minimize the number of control loops.

The torsional flexures define a well modeled spring inertia system. As shown in Figure 1, units have been constructed and tested with bridge and buried electrodes. The active area of current units is 350 x 580 μm^2.

In 12 hour drift runs with temperature control, drift stability of 300 °/h has been measured. Performance objectives for gyros are 10 (navigation) to 500 °/h (missile control).

Micromachining

The silicon gimballed gyro and accelerometer are etched from single crystal silicon using EDP anisotropic etching and a highly doped boron etch stop. The process is outlined in Figure 3. If a rectangular window is aligned with the <100> axes of the silicon crystal, the EDP etches undoped or lightly doped silicon so that <111> planes remain; that is, inside the window, a pit with sloped walls is dug and inside corners are sharply defined. The highly doped boron material resists the etch and is not removed.

Boron electrodes are first diffused into the silicon substrate (Figure 3). Photolithography defines the shapes of the electrodes. An epitaxial layer is then grown. Boron diffusion defines the gimbals and flexures. A silicon oxide window defines the outer geometry of the pit. Metal is deposited for electrical connections or for bridge electrodes. The EDP etches the silicon material inside the oxide window and beneath the gimbals to free up the gyro.

In-Plane Tuning Fork Gyroscope

Within the past year, in-plane gyro designs have been developed. The gyro's operation is shown schematically in Figure 2 and photograph, in Figure 4. The combs are excited so that electrostatic forces are generated which do not depend on the lateral position of the masses. The flexures are sized to insure 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 (Figure 2).

Capacitors below the proof masses are used for gyro sense and, perhaps, force although open loop operation may be feasible. The fabrication may be done by bulk micromachining, as described above, or by polysilicon surface micromachining, a process developed at the University of California, Berkeley, (Ref. 3) and the University of Wisconsin. The fabrication allows for gaps of a few microns.

Thus far, a pathfinder was constructed of nickel to demonstrate that the antiparallel mode could be excited and that the tuning fork configuration did indeed sense rate. Possible benefits of the tuning fork approach include: (1) simpler fabrication and better performance than gimballed; (2) compatibility with CMOS, which enables easy integration with on-chip electronics; (3) with the gimballed gyro, a complete inertial measurement unit (IMU) on a chip; and (4) static balance and stiffer springs that reduce sticking.

Force Rebalance Accelerometer

The Draper micromechanical accelerometer, which is shown in Figure 5, is constructed similarly to and is compatible with the gimballed gyro. The 300 x 600 μm^2 silicon proof is supported by torsional flexures. The location of gold mass determines whether the pendulum will sense accelerations parallel or perpendicular to the substrate; thus, one basic design enables the IMU on a chip. The angular rotation of the gimbal is sensed electrostatically by capacitors buried below the gimbal (Figure 5). Closed loop electronics generate a rebalance voltage proportional to acceleration that is applied electrostatically.

Mechanical stops are seen in Figure 3. Because of the small dimensions, molecular forces can become important. Mechanical stops reduce the surface area and lever arms and offer alternate materials so that sticking is avoided.

The measured performance of the photographed unit is 250 μg (overnight drift stability and residual of 1 g tumbles). As for the gyros, better performance requires larger gimbals.

Quartz Instruments

Resonant Accelerometer

The Draper quartz resonant accelerometer (QRA) is displayed in Figure 6. The accelerometer is constructed by simply stacking quartz pieces. Others have used sensitivity of resonant frequency to force to realize accelerometers. Draper's unique contribution is low cost fabrication where the frame, two pairs of tuning forks, and the proof mass base are photolithographically etched. Masses are attached to the proof mass base. Bonded to the active layer, frames restrain the proof mass against accelerations normal to the plane. Quartz tuning forks and proof are 1.5 cm long. The tuning forks are collinear, connected to opposite ends of the proof mass base. Active elements and frames are purchased from Statek, Orange, CA, manufacturer of tuning forks for timekeeping applications.

The QRA sensitive axis is parallel to the tuning forks. Tension in the tines increases lateral stiffness; hence, the resonant frequency is increased. Compression decreases the natural frequency. Each tuning fork is constructed into an oscillator circuit, seen in Figure 6, which interfaces easily with digital electronics.

Measured performance, overnight drift stability and residual of 1 g tumbles, is 50 to 100 μg in units sized for 130 g (crossing of the individual tuning fork resonant frequencies) with break acceleration of 800 g. Uncompensated thermal sensitivity after common mode rejection by the opposing tuning forks is less than 100 μg/°C.

Larger in size than the silicon accelerometers, the QRA was developed earlier because its stiff suspension enables solid-state processing developed for time-keeping while avoiding sticking issues.

Tuning Fork Gyroscope

With parts manufactured by Statek, a quartz resonant gyroscope (QRG) is being assembled. The QRG is a single ended tuning fork, 5 mm long, with drive and sense electrodes on each tine. Operation is similar to the silicon tuning fork gyro; however, the electrostatic drive and sense are replaced by piezoelectric effects.

Summary

Draper has been developing silicon and quartz gyros and accelerometers for several years. The Draper gyros were the first, and, perhaps, the only, silicon gyros to have been demonstrated and tested.

The silicon micromechanical instruments are being constructed for very small inertial measurement units designed to fit into a flat pack (Figure 7). The illustration contains three gyros and accelerometers, vacuum packaging for the gyros, and custom digital electronics. Performance objectives for the silicon gyros are 10 (navigation) to 500 °/h (missile control). A relatively low marginal per silicon gyro projected cost of $500 is based on production orders of 10,000. For commercial applications with market potentials of 20 million gyros, the projected per unit costs would be less than $10 (Ref. 1).

The quartz instruments are larger than the silicon but have simpler electronics and are designed for systems with better performance.

The solid-state inertial sensors have cost, size, and weight advantages over conventional instruments and will result in both redesign of existing systems and conception of new applications. The commercial market is orders of magnitude larger than any contemplated military market. Possible applications for small inertial systems include:

automobiles (the instruments could be used for position location, anti-skid braking systems, air bag deployment, automatic leveling); miniature satellites and spacecraft (where launch weight is a major cost factor); artillery rounds for increased accuracy; camcorders; general aviation ; medical electronics; and the largest area-children's toys.

Acknowledgements

Many individuals contributed to the design and construction of the instruments described above. Draper principals include Paul Greiff, Burton Boxenhorn, John Elwell, Dr. Jonathan Bernstein, Lance Niles, James Campbell, Brenda Coletti, Michelle Lind, Dr. Anthony Petrovich, James Sitomer, Anthony Kourepenis, A. Thomas King, Edward Cusson, Kirk Smith, Ralph Haley, and Eric Hildebrant.

References

1. J. Elwell, "Progress on Micromechanical Inertial Instruments", Proceedings AIAA Guidance and Control Conference, August 13, 1991.

2. A. Kourepenis, A. Petrovich, M. Weinberg, "Low Cost Quartz Resonant Accelerometer for Aircraft Inertial Navigation", Proceedings of IEEE 6th International Conference on Solid-State Sensors and Actuators, June 24-28, 1991.

3. W.C. Tang, Electrostatic Comb Drive for Resonant Sensor and Actuator Applications, Ph.D. Dissertation, University of California, Berkeley, 1990.

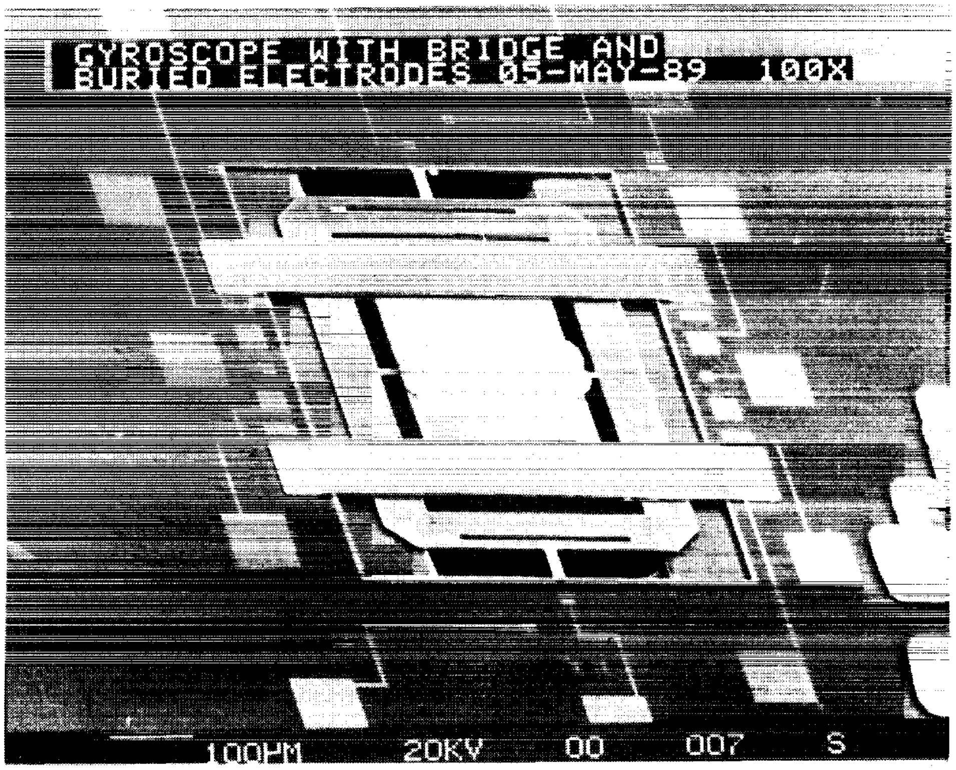
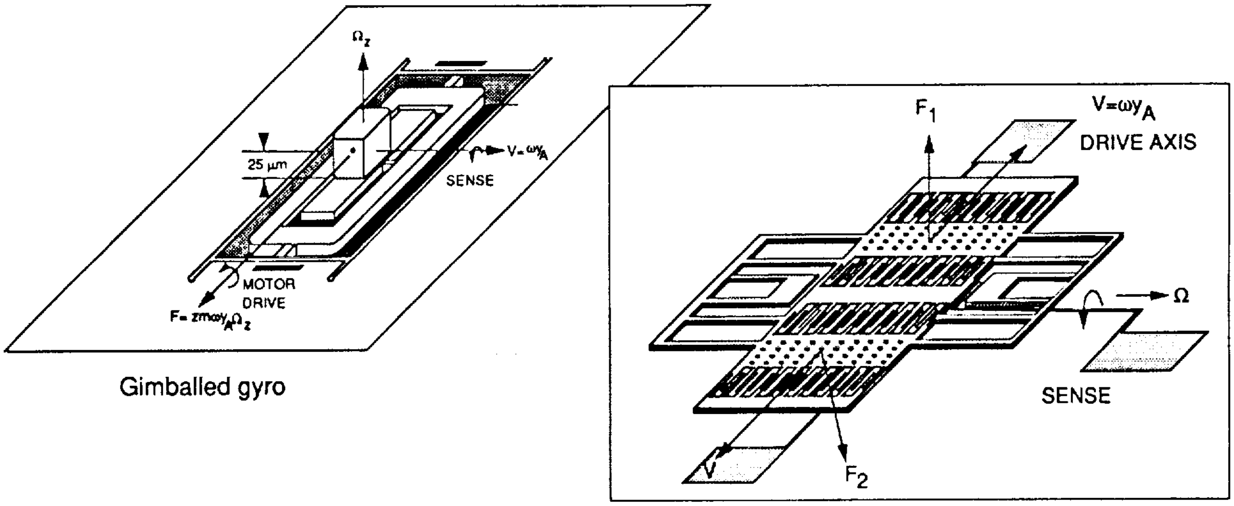


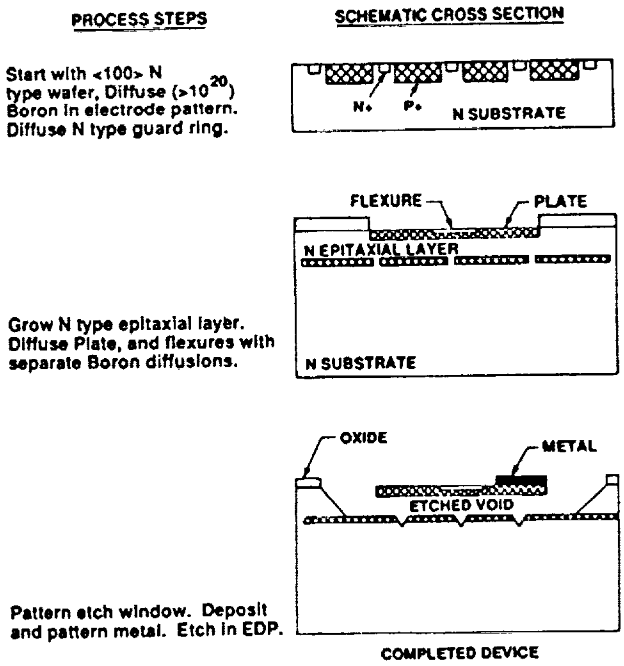
Figure 1. Silicon gimballed gyroscope.



Gimballed gyro

In plane gyro

Figure 2. Operation of gimballed and tuning fork gyro.



Start with <100> N type wafer, Diffuse ($>10^{20}$) Boron in electrode pattern. Diffuse N type guard ring.

Grow N type epitaxial layer. Diffuse Plate, and flexures with separate Boron diffusions.

Pattern etch window. Deposit and pattern metal. Etch in EDP.

Figure 3. Microfabrication in single crystal silicon.

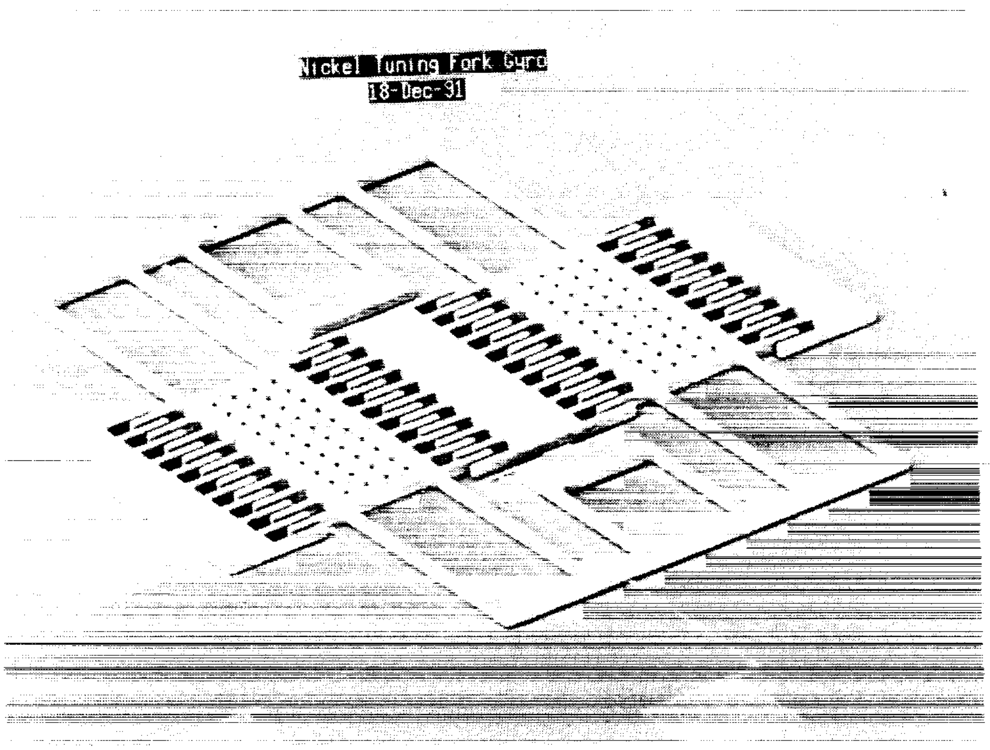


Figure 4. Nickel tuning fork gyroscope.

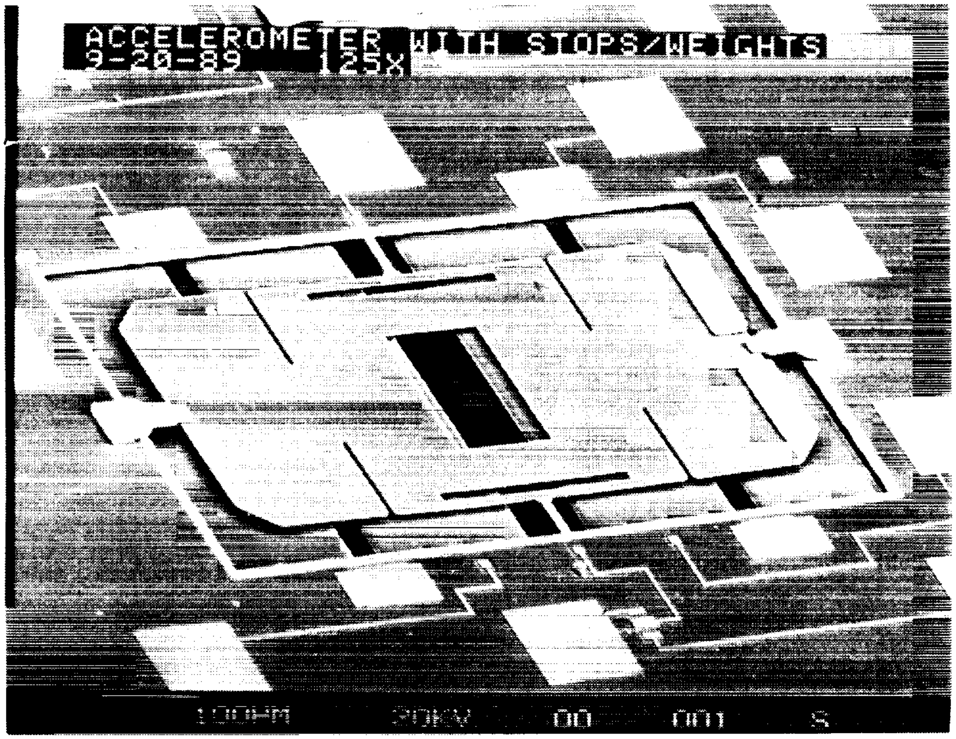


Figure 5. Silicon force rebalance accelerometer.

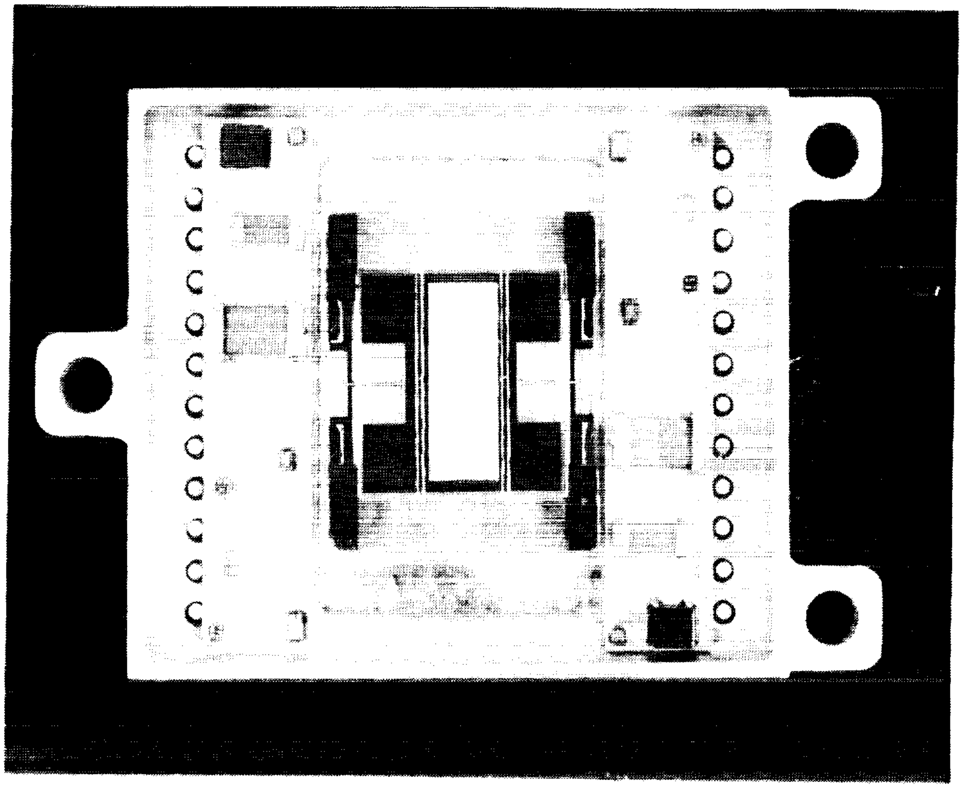
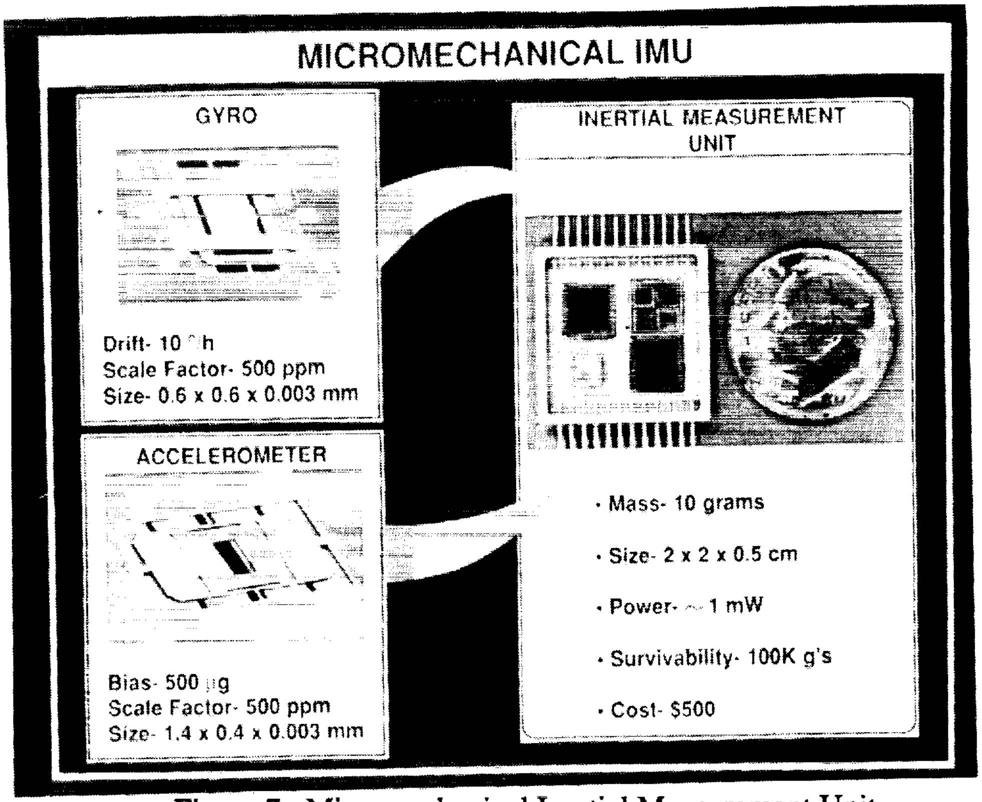


Figure 6. Quartz resonant accelerometer.



MICROMECHANICAL IMU

GYRO

Drift- 10 °/h
Scale Factor- 500 ppm
Size- 0.6 x 0.6 x 0.003 mm

ACCELEROMETER

Bias- 500 μg
Scale Factor- 500 ppm
Size- 1.4 x 0.4 x 0.003 mm

INERTIAL MEASUREMENT UNIT

- Mass- 10 grams
- Size- 2 x 2 x 0.5 cm
- Power- ~ 1 mW
- Survivability- 100K g's
- Cost- $500

Figure 7. Micromechanical Inertial Measurement Unit.