

MICROMACHINED INERTIAL SENSORS FOR VEHICLES

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ABSTRACT

Micromachined silicon sensors offer tremendous cost, size, and reliability improvements for guidance, navigation, and control (GN&C). Currently the development of micro-electromechanical systems (MEMS) inertial sensors is largely supported by DoD; however, it will ultimately be driven by high-volume commercial markets with target prices below \$25 per instrument.

This paper describes recent advances in micromechanical gyro and accelerometer design and packaging. Performance of a prototype automotive traction control module, in pilot production, and a planned automobile suspension control module are described. The concept of a 3-cubic-inch, multi-purpose MEMS inertial system, based on a three-gyro, three-accelerometer system under development for a guided artillery shell, is discussed for automotive applications. Plans for future cost and size reduction are presented.

INTRODUCTION

Micromachined silicon inertial sensors are expected to have tremendous cost, size, and reliability advantages over many competing technologies. These sensors represent an important segment of an emerging microelectromechanical systems (MEMS) technology combining semiconductor materials and processing to create integrated mechanical and electrical systems. Inertial sensors, particularly gyroscopes, have long been an inherent part of platform stabilization and acceleration-sensing applications. A major drawback to the commercial use has been cost.

Most DoD/NASA GN&C applications require higher-performance, smaller multi-axis systems than commercial applications, and the expected production quantities will be small by

comparison. These applications include weapons safe-arming and fuzing, competent munitions, space and weapon platform stabilization, and personal/vehicle navigation systems. Currently the development of MEMS inertial sensors is largely supported by DoD; however, it will ultimately be driven by high-volume commercial markets with target prices below \$25 per instrument. The largest near-term market for these sensors is automotive systems. Consumer applications include video cameras, personal navigators, and various recreational and hobby equipment. Figure 1 illustrates the commercial dominance of future MEMS inertial markets. To achieve widespread special-purpose use, a flexible commercial production base that can be affordably directed toward the specific needs of military systems is being created.

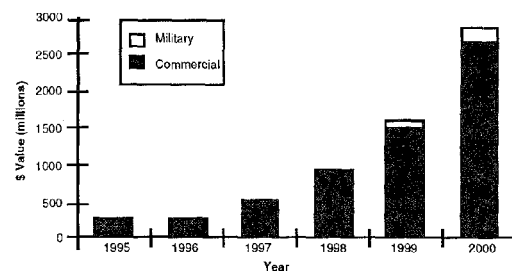


Figure 1. Worldwide MEMS inertial sensing products market.

Initial research on MEMS inertial sensors began at Draper Laboratory in 1984. In 1993, Draper Laboratory and Boeing North American (formerly the Rockwell Corporation) initiated an alliance to develop products for commercial and military systems. Currently, sensors for automotive applications are in pilot production at Boeing, while next-generation designs for improved performance and cost are being characterized at Draper. Joint development has already begun for higher-performance, miniature, multi-axis systems.

SENSOR DESIGNS

The MEMS gyroscope sensor is a Coriolis-force, comb-driven, tuning-fork design. Its principle of operation and construction features are illustrated in Figure 2. Two vibrating proof masses suspended by beam springs are driven in opposite directions by electrostatic comb drive motors to maintain lateral in-plane oscillation. When the device is rotated about its input axis (IA), which is parallel to the proof mass plane and normal to the vibration vector (V), the Coriolis effect causes the masses to oscillate out-of-plane. The resulting up-and-down motion, proportional to angular rate, is measured by capacitive sense plates underneath the proof masses. Closed-loop control nulls the output motion via rebalance electrodes; however, open-loop operation is adequate for many applications. Figure 3 is a scanning electron microscope (SEM) photograph of the MEMS gyroscope.

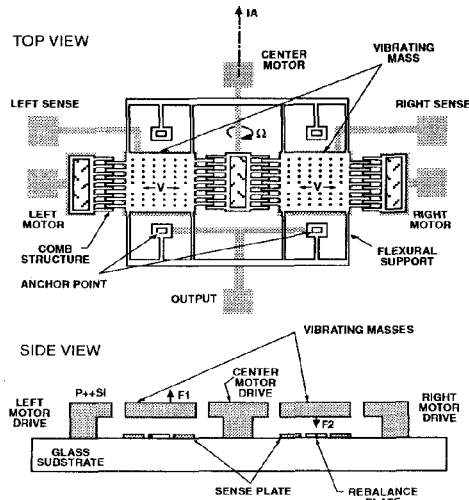


Figure 2. Micromachined gyroscope configuration.

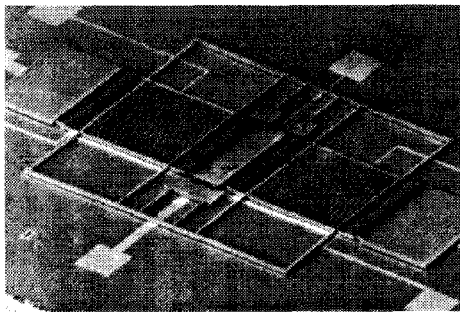


Figure 3. Micromachined comb drive tuning-fork gyro.

The companion accelerometer sensor is a pendulous mass displacement device. Its operation is illustrated in Figure 4. An unbalanced proof mass plate is suspended by torsional spring flexures in a seesaw-type configuration. When the device experiences an acceleration into the plane (IA), the proof mass rotates (or tips) around the flexure axis (FA). The resulting motion, proportional to acceleration, is measured by capacitive sense plates underneath the proof mass. For higher performance operation, torquer plates apply forces to rebalance the proof mass. Figure 5 is a SEM photograph of a MEMS accelerometer with dimensions similar to the gyroscope. Proof mass and flexure design variations yield devices with full-scale ranges from 1 to 100,000 g.

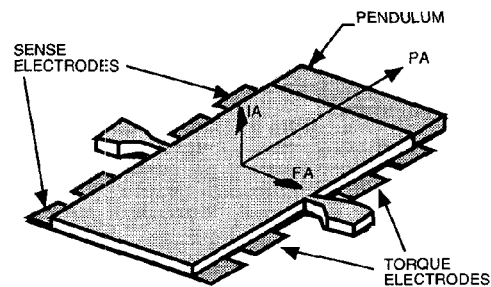


Figure 4. Accelerometer sensor configuration.

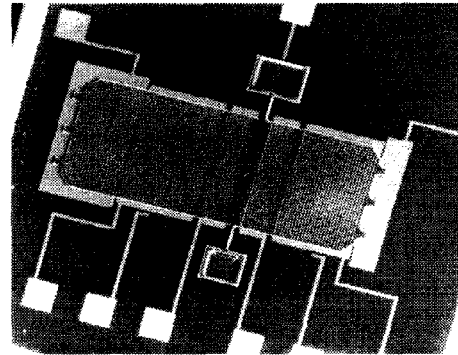


Figure 5. 100-g accelerometer sensor.

ELECTRONICS DESIGN

Electronic circuits are an integral part of the MEMS inertial instrument, as these provide the necessary sensor excitation and readout functions. The gyro electronics consist of a self-resonant motor loop to drive the proof masses and output processing to measure sense axis motion and provide a DC output proportional to angular rate. The accelerometer electronics form a differential capacitive measurement

system consisting of a carrier signal generator and demodulator circuitry, providing a DC output proportional to acceleration. For closed-loop operation, control compensation and torque drive circuitry are added.

Additional electronic functions include self-test and/or self-calibration, bias and scale-factor correction and/or compensation, and special application interfaces. Extremely low voltages are involved, and careful attention must be paid to sensitive preamplifier circuits and performance over temperature. Architectures target CMOS implementations for low power and cost.

MANUFACTURING

The key advantage of MEMS inertial instruments is the potential for low cost achieved through high-volume manufacturing and automated assembly and test methods. A simple dissolved wafer process is employed to micro-machine silicon sensors. This wafer-to-wafer bonding technique produces single crystal silicon structures on a glass substrate. Unlike most surface micromachining processes where sensor and electronics are cofabricated, separate processing of sensors and electronics optimizes the yield and performance of each component. Flexibility is afforded by matching different sensors and/or electronics for specific applications.

Both accelerometer and gyro sensor devices are sealed in hermetic packages that are designed to maintain a stable environment over a 20-year life, and the gyro requires a vacuum to obtain a high-Q resonance. Sensor chips are installed in leadless chip carrier (LCC) packages and aligned to a printed wiring board (PWB) containing the electronics. A cross-section diagram of the sensor LCC assembly is shown in Figure 6. This LCC is 0.25 inch square by 0.10 inches high.

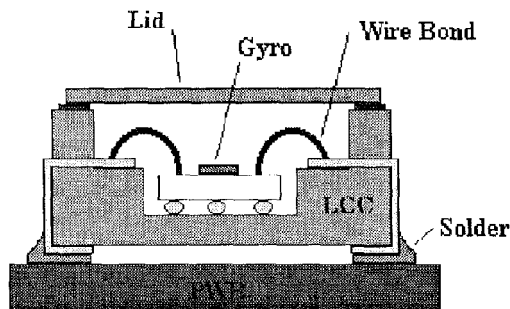


Figure 6. LCC sensor assembly.

Electronics are implemented in an application-specific integrated circuit (ASIC). The ASIC is shown in Figure 7 on a 1-inch-square PWB with LCC gyro sensor and discrete components, making up a complete gyro instrument. These mixed-signal CMOS chips are being fabricated with a 0.5- μm class process on the 8-inch wafer line at the Rockwell Semiconductor Systems (RSS) Newport Beach facility.

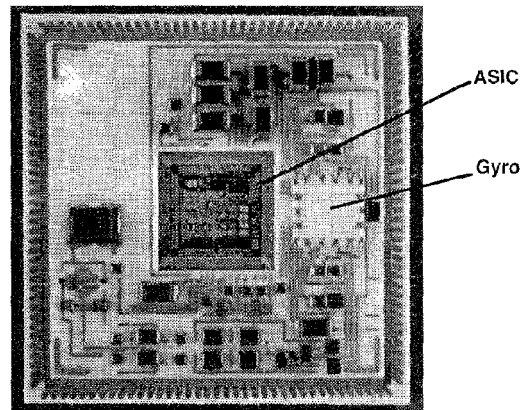


Figure 7. ASIC-based gyro instrument

PROTOTYPE AUTOMOTIVE TRACTION CONTROL MODULE

An early automotive application involves using the MEMS gyro as a yaw rate sensor for skid control in conjunction with the anti-lock braking system (ABS). Standard ABS uses wheel speed sensors to detect when one or more wheels are near lockup, and then pulses the brakes to increase overall braking efficiency. Split friction road surfaces with combinations of dry, wet, oily, or icy conditions can degrade ABS performance and cause a vehicle spin. Using a yaw rate gyro, vehicle spin is detected and corrected by differential wheel braking. Adding a lateral accelerometer and steering wheel inputs, brakes are actively adjusted to compensate for oversteer or understeer so that the vehicle follows the driver's intended path. These new safety features are now available only on high-end Mercedes Benz and Cadillac models, but like ABS and airbags, advanced steering controls will become standard on virtually all cars.

A prototype traction control module, containing a MEMS tuning fork gyro, is in pilot production at Boeing North American. Tested sensor packages and ASICs are assembled, along with discrete components, on a PWB using automated, high-speed, pick-and-place equipment. The

completed PWB is then installed in the final customer-defined module for delivery. For automotive applications, this module is a sealed thermoplastic enclosure with an integrally molded connector. The Pilot Production Automotive Traction Control Gyro Module is shown in Figure 8.

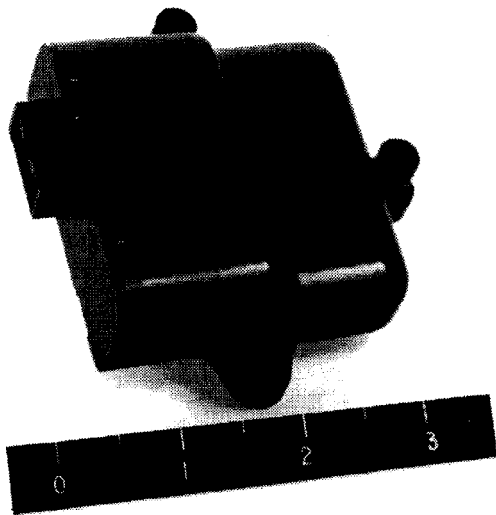


Figure 8. Pilot production prototype

Uncompensated gyro bias and scale-factor performance of 0.5°/s and 1.0% are nominally demonstrated over the automotive temperature range of -40°C to +85°C. Bias stability over the 0.5°C temperature range has surpassed 10°/h over 6-h tests. With compensation over the 125°C temperature range, the residual RMS errors for bias and scale factor improve to 60°/h and 400 ppm. Nominal resolution is 150°/h in a 60-Hz bandwidth, yielding an angle random walk of 0.25°/√h. The best resolution and angle random walk to date is 25°/h in 60 Hz and 0.04°/√h, respectively. These gyros have also demonstrated the ability to survive a high-g environment, operating after air gun tests in excess of 60,000 g.

AUTOMOBILE SUSPENSION CONTROL

As the applications of inertial sensors expand into other functions on the car, active suspension control will require sensors for various control systems. Specifically, accelerometers are used in automotive suspension systems to detect and measure the vehicle's dynamic movements. The suspension control systems receiving acceleration data compensates for yaw, pitch, roll, squat (the settling down of the vehicle's rear end as a result of increasing speed), and dive (the

lowering of the vehicle's front end due to braking) movements by altering shock absorber and strut pressures to maintain platform stability.

In one application, the auto maker uses a trunk-mounted accelerometer to sense road surface composition. In response to the severity of acceleration caused by road roughness, the control system softens or firms the vehicle's shock absorbers to maintain a consistent ride smoothness. In another application, an accelerometer mounted fore and aft measures squat and dive. The shock absorbers and/or struts are extended or compressed to compensate for these motions. In a third application, a lateral accelerometer is being evaluated for measuring roll as part of a vehicle dynamic control system. Side loading of the vehicle during turns causes the outward side of the vehicle to compress. A control system responding to side loading would activate shocks and/or struts to elevate the compressed side of the vehicle to maintain a level platform plane.

Like the traction control module described above, some of these features can be found now on high-end vehicles. However, unlike safety features (such as the traction control module), these performance-improving and ride-enhancing functions may never proliferate onto the low-end, least-expensive cars. But, as the systems mature over time, these functions should be found on all luxury and performance vehicles and probably on most mid-range vehicles.

Accelerometer bias and scale factor performance is nominally 50 mg and 0.5%, uncompensated over the -40°C to +85°C temperature range. Bias stability over the smaller 0.5°C temperature range surpasses 1 mg in 1- to 2-day stability tests. Bias and scale factor improves to under 5 mg and 500 ppm when compensation is applied. Nominal resolution in 60 Hz is 1 mg, yielding a velocity random walk of 0.05 m/s/√h. The best resolution and angle random walk to date is 400 mg in 60 Hz and 0.025 m/s/√h, respectively. These accelerometers are scaled using basic geometry modification, and have demonstrated 10^8 dynamic range, measuring from 100,000 g to under 1 mg.

MULTI-PURPOSE MEMS INERTIAL SYSTEM

MEMS inertial measurement units (IMUs) are currently being developed for military applications, requiring higher-performance gyro and accelerometer instruments designed to

exceed $1^\circ/\text{h}$ and $100\text{-}\mu\text{g}$ compensated bias stability. These IMUs consist of three individual gyroscope and accelerometer instruments, mounted orthogonally to sense three axes. This traditional configuration was employed for the first MEMS IMU integrated with GPS, which recently navigated three Extended Range Guided Munitions (ERGM) test flights. The next-generation MEMS IMU developed for the 5" Gun Competent Munitions Advanced Technology Demonstration (CM-ATD), although considerably smaller, also uses individual instruments. This IMU is part of an assembly designed to guide existing 5-inch gun rounds; the first flight is scheduled for 1998. The three gyroscopes and three accelerometers are laminated multi-chip modules, $\sim 1\text{-in}$ square, encapsulated to withstand $30,000\text{g}$ gun launch (Figure 9).

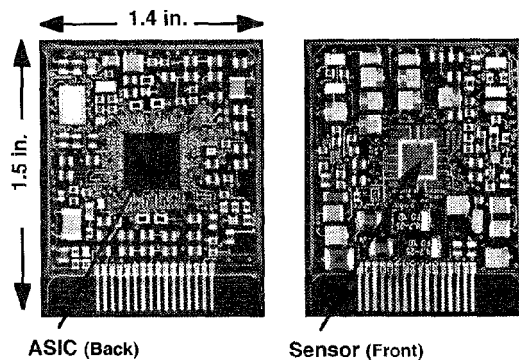


Figure 9. Gyro instrument multi-chip module

A potential automotive application of this inertial sensor assembly is its use as a multi-purpose MEMS inertial system, centrally located with shared electronics, to perform a wide range of operations, some of which are currently performed by separate distributed sensors. This integrated system could be used for: deploying air bags; controlling vehicle suspension for leveling; detecting rollover conditions to activate seat belt tensioners; four-wheel steering and skid control; braking and engine diagnostics; augmenting the GPS and map displays for navigation; and for an automotive equivalent of the aircraft black box recorder. The current 5-inch shell IMU including processor and voltage regulator is contained in a 3-cu-in volume and consumes less than 1 watt. A schematic is shown in Figure 10.

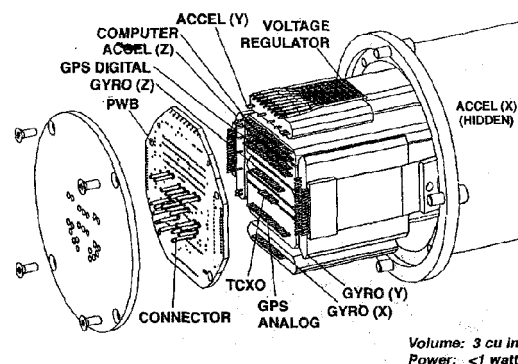


Figure 10. Multi-purpose MEMS inertial system schematic

COST REDUCTION

MEMS sensor packaging is currently a high-cost driver due to processes that now involve touch labor. Cost reduction development for MEMS packaging and assembly include on-chip sensor packaging and flip-chip assembly.

On-chip packaging places a hermetic cap directly on the sensor at the wafer level. This concept, illustrated in Figure 11, eliminates the cost of a separate LCC package, including assembly steps for die attachment, lead connection, and sensor-to-package alignment.

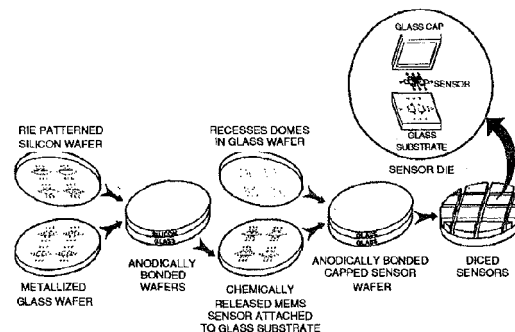


Figure 11. Sensor on-chip package sequence.

Inertial axis alignment with current die attach methods requires calibration with added cost for many applications. Flip-chip or bump bonding is a process employing conductive balls or bumps to replace wire bonds and/or provide mechanical attachment between stacked components. A unique feature of flip-chip bonding has been exploited to self-align sensors using capillary forces of the reflowed bumps. In addition to higher packaging densities and improved reliability achieved through bump

bonding, $<10^{-3}$ -rad misalignment has been demonstrated, eliminating the need for calibration in many applications.

The next step in achieving affordable, miniature MEMS IMUs is multi-axis instrument integration. Figure 12 shows four levels of integration recently studied.

The first level is an integrated instrument containing single gyro and accelerometer functions. This 2-degree-of-freedom (dof) configuration is desired by automotive manufacturers for steering control applications with a potential for high-volume production. Three identical 2-dof instruments are mounted orthogonally to achieve a three-axis IMU; however, the mounting block or frame increases IMU size. The second level uses sensor and electronics components from the first. The difference is that the MEMS sensor packages are rotated within the 2-dof instrument to obtain orthogonal sensing. The three 2-dof instruments can now be stacked to reduce overall size; however, each module is now a custom design.

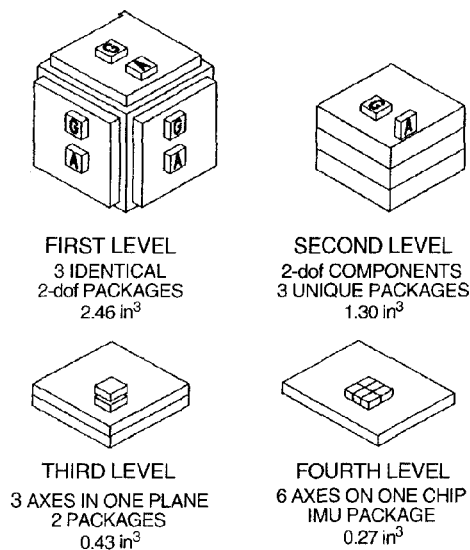


Figure 12. Integrated multi-axis ISA concepts.

The third level uses new MEMS sensor designs that have input axes orthogonal to those of existing tuning-fork gyroscopes and pendulous accelerometers. By combining in-plane and out-of-plane sensing designs, three-axis gyro and three-axis accelerometer instruments can be achieved in single plane resulting in two stacked modules. The fourth level is an extension of the

third, where the three gyro and accelerometer functions are integrated on one chip. Order-of-magnitude size reductions compared to latest designs are envisioned yielding an ISA less than 0.3 in³. Implementing the latest low-power electronic architectures will achieve a six-axis system at less than 0.1 W.

CONCLUSION

The introduction of silicon micromechanical gyroscopes and accelerometers into automotive applications has begun. These devices offer low-cost solutions to many safety, comfort, and diagnostics needs. It is expected that these inertial sensors will become standard features on virtually all automobiles, as well as other consumer products, in the very near future. Lowering production cost is the most critical factor for full commercialization of MEMS inertial sensors.

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