

MEMS Inertial Rate and Acceleration Sensor

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ABSTRACT

Development of the μ SCIRAS™ (pronounced micro-Cyrus) multisensor for a period of over six years has produced a practical MEMS Inertial Measurement Unit (IMU). Using only three silicon sensors, a full-up IMU suitable for tactical grade navigation and guidance applications has been achieved. Iterative improvements in silicon sensor design and bulk micromachining processes have matured to the point where an IMU with an attractive price/performance ratio is now producible. This paper summarizes the design features and test results for an IMU with < 100 deg/hr performance. Test results are shown for rate bias and acceleration bias over temperature.

Production of this initial member of the μ SCIRAS product family begins this year to support applications including guided artillery shells, technology insertion to decrease missile costs, navigation of remotely-piloted vehicles, dismounted soldier location devices and other navigation aids. The small size of this silicon multisensor and its ability to measure both angular rotation rate and linear acceleration provides a useful advantage in product packaging, cost, size, and system testing. The μ SCIRAS Inertial Sensor Assembly (ISA) is housed in a 2 cubic inch

package weighing less than 5 ounces (140 grams) requires less than 0.8 Watts of power. Continuing development will lead to greatly improved performance on the order of 1 deg/hr at low prices in high-volume production.

INTRODUCTION

In the rapidly advancing world of Micro-Electro-Mechanical Sensors, or MEMS, there are many new design approaches used to achieve rate sensors. As sizes shrink, a new set of error sources come into play which ultimately set the limits of performance. Bulk micromachining offers the benefits of mass production, but not at the price of performance. By utilizing the full thickness of the silicon wafer, sensitivity to line width, mask alignment and flatness are greatly reduced. At the same time, the long term stability of the device is enhanced due to the low stress of the lightly doped layers. While bulk machined sensors are larger than surface machined, the cost to the user is minor due to the relatively higher costs of the electronics and packaging. Thus the performance is maximized without the need for mechanical or electrical trimming.

The development of μ SCIRAS is the culmination of six years of silicon work, and seven prior years of macro-size mechanisms. Leveraging off of the strength of three decades in the design of precision linear accelerometers, the rate sensor consists of two linear accelerometers etched within a unique dither mechanism. This produces a direct cost advantage in that both linear acceleration and angular rate are sensed by the same silicon and processing electronics. The dither drive mechanism was designed to not only provide a velocity

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perpendicular to the accelerometers sensitive axes to excite the Coriolis signal, but also to link the two accelerometer motions to be equal and opposite. This makes the dither drive reactionless and less sensitive to mounting, orthogonal axes dither and external vibration sources. This feature has been tested and refined to produce a vibration insensitive sensor which can meet performance in tough military vibration environments. The sensing element is sandwiched in between two cover plates which provide squeeze film damping in a 1 atmosphere, dry gas backfill. The damping adds a further measure of vibration reduction as well as providing shock stops for the accelerometers and rate sensor. This gives the sensor the capability to withstand 20,000 g shock loads along the accelerometer input axes.

The accelerometers use resonant beams as the sensing elements. The output of the accelerometer is a frequency proportional to the input acceleration. Two proof-mass sensing elements are constrained by a pair of resonant beams. They are arranged so that one beam goes into tension for a higher natural frequency while the other goes into compression. This push-pull arrangement produces a differential frequency output proportional to acceleration. The advantage is that common mode errors such as absolute clock frequency and second order non-linearities are reduced. The output of the rate sensor is a direct digital interface which takes advantage of the revolution in digital processing techniques. The use of the new fine-line digital Application Specific Integrated Circuits, ASIC, to convert frequency directly into a micro-processor digital word format eliminates the need for A/D or delta-sigma converters and their associated errors.

PRINCIPLE OF OPERATION

A simplified sensor mechanism is outlined in Figure 1. Multiple sensor elements are etched in a batch process from one piece of crystalline silicon. The sensor is comprised of three basic blocks: two resonant beam accelerometer, RBA, shuttles and an interconnecting link. Each shuttle is connected to the silicon frame by multiple high aspect ratio flexures. The link is connected to each shuttle and to the frame with three similar high aspect ratio flexures. The center flexure acts as a hinge which allows the link to rotate about an axis normal to the plane of the substrate and located at the flexure's mid-point.

In operation, the two accelerometer shuttles are driven at resonance in opposite directions. The link insures that the phase and amplitude are exactly equal, even if there are mass or spring stiffness differences between the two shuttles. This feature has several advantages which allow the silicon processing accuracy to be relaxed. Minor processing gradients will cause the two accelerometer shuttles to be mismatched. If they were not interconnected, they could resonate at the average frequency between them, but with a leader / follower phase relationship. With high Q dither frames, small differences

rapidly grow to a substantial phase difference. This would lead to a sensor that is not reactionless and could lower the effective Q, induce base reactions that could couple to other sensors and leave it susceptible to input vibrations. The link prevents these adverse consequences and inhibits external vibration from inducing any differential shuttle motion. The shuttles are static g-balanced to prevent emitting reaction forces into the base mount that could otherwise couple into the other two channels.

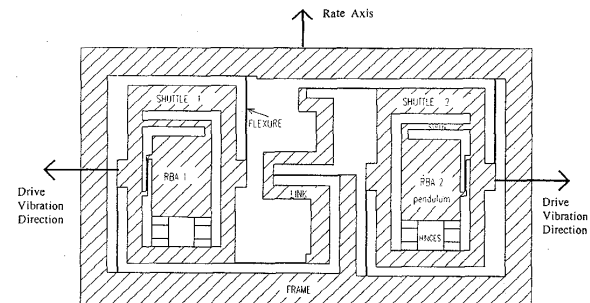


Fig. 1. Sensing Mechanism

The accelerometers are formed at the same time as the other elements. A pendulum is etched free from the substrate, except at five attachment points. The two flat flexures form a hinge at the bottom of the pendulum on the far side of the wafer. A horizontal hinge axis is formed through their mid-points, about which the pendulum can rotate out of the plane of the substrate. The pendulum is constrained against rolling about the rate axis by a strut, which remains flexible in the direction of pendulum motion out of the plane of the substrate. The pendulum is captured by the resonant beams used as the frequency sensitive output. These beams are located between the shuttle frame and the pendulum. Both pairs of beams are in a push-pull arrangement on the near side of the substrate. In Figure 1, an acceleration that is applied normal to the page causes RBA 1 beams to be pulled in tension while RBA 2 beams are pushed in compression. This configuration has the advantage of matching the accelerometer characteristics even when there are silicon process variations. The beams constrain the pendulum to a very small displacement even under high g-loads. The pendulum mass is levered to the axial spring rate of the beams. This increases sensitivity for a given proof mass by as much as ten to one. The advantage of driving a bulk etched proof mass is the greatly increased signal strength of the Coriolis acceleration relative to other error sources.

The sensor substrate is sandwiched between two silicon damping plates which are similarly bulk etched. In the central area just inside the outer frame of Figure 1, the damping plate is etched back to provide a stop for the pendulum and clearance for all the shuttle's moving parts. This gap also provides the squeeze film damping for the pendulum. The squeeze film damping prevents the pendulums from rattling against the stops during a

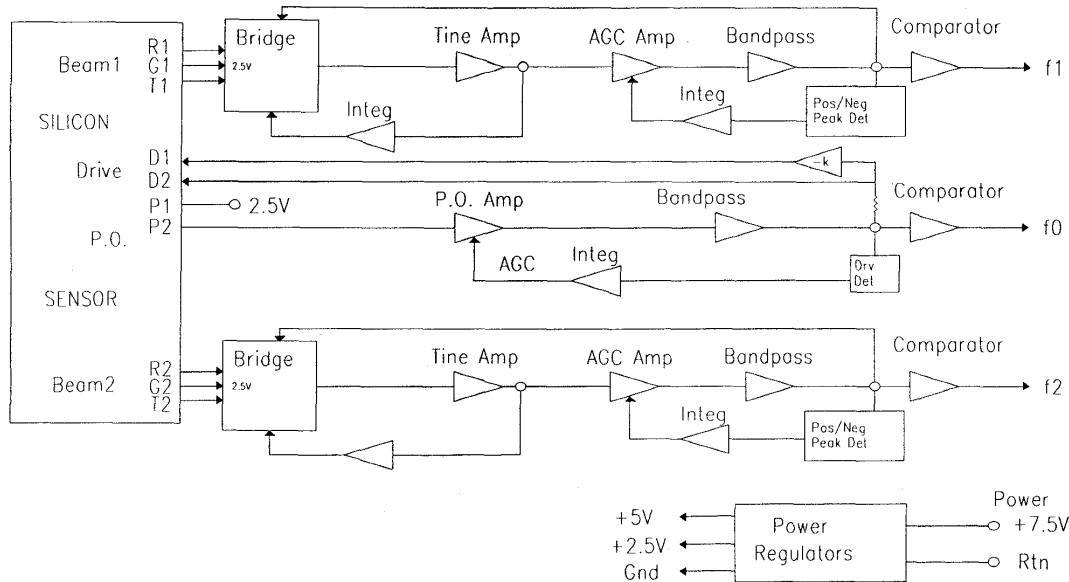


Figure 2. Hybrid Drive Electronics

vibration input. By using a 1 atmosphere backfill instead of a hard vacuum, the leak rate requirement is greatly reduced, thus further reducing processing and packaging costs. The gas damping also provides an extra measure of protection for shock overload in that the pendulum is cushioned as it approaches the stops. This prevents stress concentrations from damaging the pendulums during repeated shocks.

DRIVE ELECTRONICS

The drive electronics for the dither and two resonant beams is accomplished in a co-located ASIC hybrid circuit as shown in Figure 2. The two beam drive circuits are identical, each consists of a balanced bridge input formed by the tines and a matching reference resistor.

The difference is amplified with a variable gain, very low noise amplifier. This output is integrated and used to DC balance the bridge. The tine amp output is also bandpass filtered to reduce noise and then peak detected for input into an automatic gain control (AGC) loop. The output of the bandpass filter drives the top of the bridge to supply AC current to oscillate the beams. The output of the bandpass also drives a comparator to generate a logic level, frequency output signal. These two beam drive loops have local power supply regulation to reduce line sensitivity and to eliminate coupling to the other sensors in a triaxial unit.

The dither drive electronics is the middle block. The operation is similar to the beam drive loops except the velocity pickoff goes directly into the first amplifier without the bridge circuit. A bandpass amplifier which is

tuned loosely around the drive frequency supplies a signal the peak detector, motor drive amplifier and to the output comparator. The drive amplifier must supply the peak current to sustain the dither level and is run directly off of 5VDC power to avoid coupling into the beam drives. At the low drive frequency, the op amps have adequate power supply rejection to avoid coupling between the channels.

SIGNAL PROCESSING

Acceleration sensed by the rate sensor is:

$$a = 2\omega v \quad (1)$$

where

a = Coriolis acceleration

ω = Input angular rotation rate

v = Accelerometer perpendicular velocity

For a dithered accelerometer whose position input is a sine wave at the dither frequency, the perpendicular velocity is proportional to the cosine of the dither frequency. In order to extract the rate information from the accelerometer, a synchronous demodulator is used referenced to the cosine velocity. The advantage of an inherently digital system is the precision with which the demodulation can be done. Generating two equal periods with a digital phase lock loop allows precise cancellation of any constant term like accelerometer bias. This precision can be as good as the short term stability of a quartz crystal, on the order of one part in 5 billion per day.

A single channel of signal processing is shown in Figure 3. The resonant beam frequencies, f_i , are input into a digital ASIC which uses a 50 MHz clock as a fine

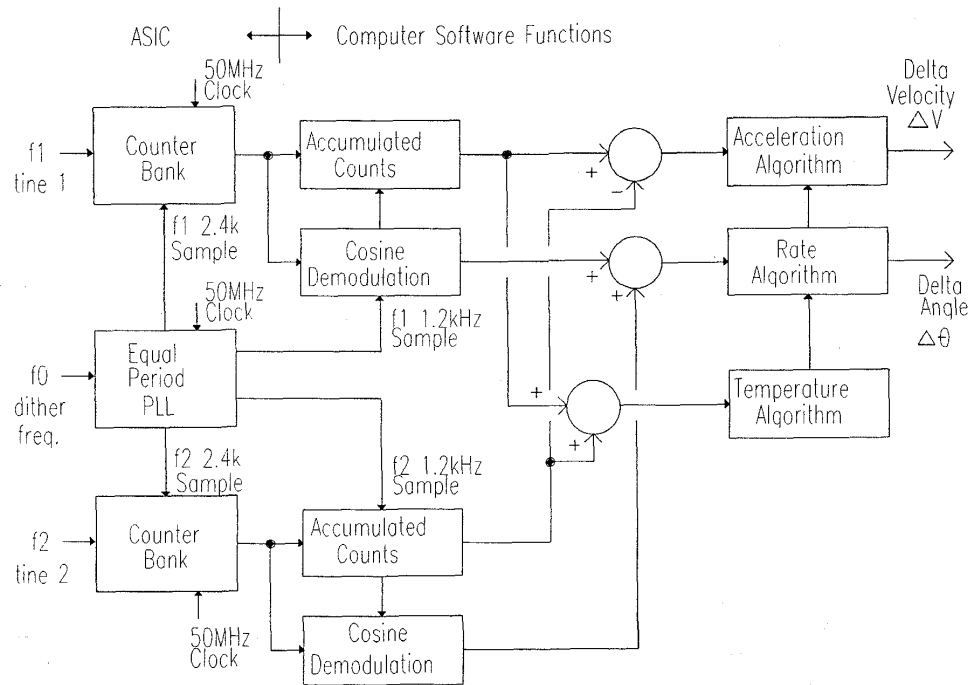


Fig. 3. Processing Block Diagram

reference. These frequencies are counted over a sample frequency of 1200 Hz. The data is taken each half cycle as determined by the input dither frequency and internal phase lock loop. If consecutive half cycles are added, the result is proportional to linear acceleration. The f2 counts are subtracted from f1 counts to form an input for delta velocity algorithm, ΔV . If two consecutive counts are subtracted, then a cosine demodulation is performed. Adding f1 and f2 demodulated counts forms an input to the delta theta algorithm, $\Delta \theta$. A signal proportional to temperature can be formed by adding accumulated counts.

The ΔV algorithm is:

$$\Delta V = A[\sum N_i + FT + B\Delta N_i] \quad (2)$$

where

A = Scale Factor

FT = Bias Frequency Constant

B = Correction Constant

N_i = Accumulated Counts per cycle

T = Dither Period.

Similarly, the $\Delta \theta$ algorithm is:

$$\Delta \theta = a[\Delta Di + ft + b\sum Di], \quad (3)$$

where

a = Scale Factor

ft = Bias Constant

b = Correction Constant

Di = Demodulated Counts per cycle

The coefficients in each algorithm are modeled over temperature and used to convert the digital counts directly into the ΔV and $\Delta \theta$ outputs at 1200 Hz. Subsequent operations include low pass filtering, coordinate transformation, axis-alignment corrections and non-linearity corrections. All of these operations are done at the 1200 Hz data rate and are available for auto-pilot functions as well as navigation. Lower rate navigation data at 100 Hz can easily be done by adding 12 frames of 1200 Hz data with appropriate scaling.

TRIAXIAL ISA

The Inertial Sensor Assembly (ISA), shown in Figure 4, on next page, consists of three silicon sensors mounted within a magnetic circuit. The magnets supply a field perpendicular to the silicon substrate so that by driving current along metalized paths atop the sensor flexures, a motive force can be generated. This provides the driving force for all the oscillators to run the tines and dither drive at their natural frequencies. The sensor assembly consists of only eleven parts. Three single-axis sensors are arranged in a triad as a "cube-on-corner" with equal angles of 35.26° with respect to the horizontal plane for each of the rate axes. This forms an orthogonal relationship between the rate input axes with a minimal volume. The accelerometer axes lie along the faces of the cube-on-corner in an acute skewed relation. Each of these

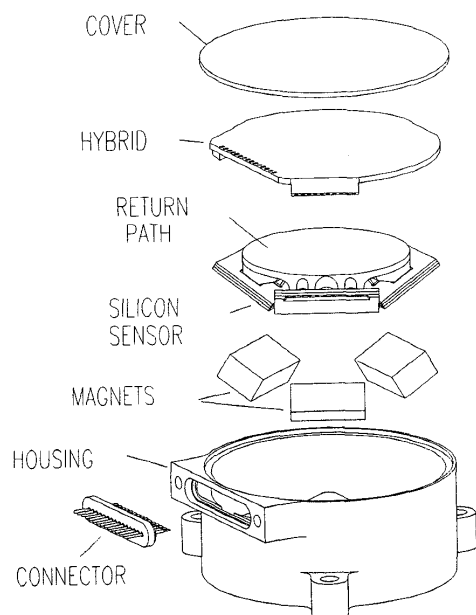


Fig. 4. ISA Exploded View

axes are 35.26° from the common vertical axis. The accelerometer axes are easily transformed to be co-located with the rate axes by a simple summing algorithm. Since the RBA's have excellent scale factor stability, this transform is accurate.

Each sensor is mounted on the magnetic field return path which is shaped to focus the magnetic flux. The return path supports the hybrid electronics and holds all three sensors in their magnet gaps. The entire assembly is bonded to a housing center support post. A top cover and connector are laser welded to the housing to seal in a dry nitrogen atmosphere which prevents moisture condensation at cold temperatures. The package is made from a magnetic grade stainless steel and serves as an EMI shield for both electric and magnetic fields. The ISA is a 1.72 inch diameter by 0.82 inch high (2 cubic inches) package weighing less than 5 ounces (140 grams) and requiring only 0.8 watts of power.

This configuration of sensor has been centrifuged to 15,000 g's and has worked before and after. The design is such that the inner sensor elements bottom out on the damping plates to protect the mechanism from excessive strain during high shock events. All of the package elements were designed to withstand 20,000 g's along the central vertical axis. This means that the device is rugged enough to be cannon launched and still provide a navigation function.

MICROPROCESSOR

A block diagram of the CPU circuit is shown in Figure 5. The major functions performed by the electronics

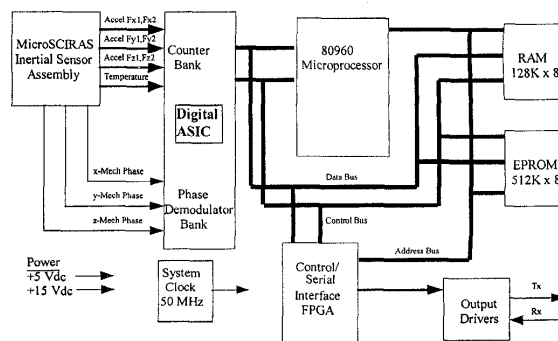


Fig. 5. Microprocessor

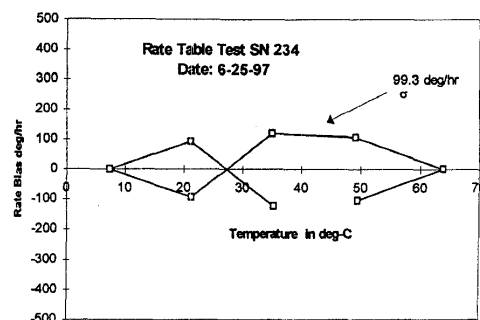


Fig. 6. Rate Sensor Residuals

are: inertial sensor interface, system processing, system timing and control, memory, and external interface. The digital ASIC provides the interface to the inertial sensors. The outputs are read by the micro-processor to derive synchronized, compensated accelerations and angular rates.

The processor loading is at 85% using an Intel 25 MHz 80960 Micro-processor. System memory consists of 512 Kbytes of EPROM and 128 Kbytes of RAM. System timing and control are achieved through the use of a field programmable gate array (FPGA) which can be mask programmed. This FPGA provides the signals necessary for the external interface. External interface signals flow to serial line drivers which interface to the host system.

A serial data output is implemented in the IMU as an RS-232 or RS-485 format. The CPU transmits six channels of inertial data over a serial data interface at 100 Hz update rate. Inertial data represents the delta linear velocity change and angular attitude change since the prior transmission.

THERMAL TEST DATA

Initial temperature test data shows good promise for tactile grade sensor performance. Rate sensor performance from 5°C to 65°C is shown in Figure 6. The rate sensor was calibrated and modeled over temperature. What is shown in Figure 6, are the residuals from the actual measurements minus a thermal model. The unit exhibits less than 100 deg/hr bias error in this test run.

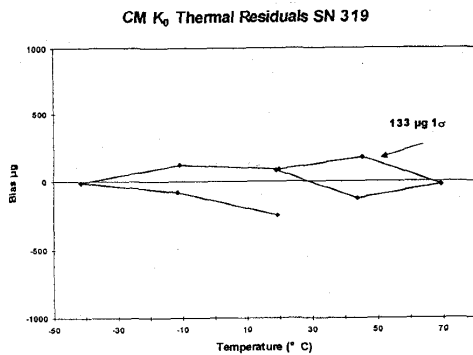


Fig. 7. Accelerometer Thermal Residuals

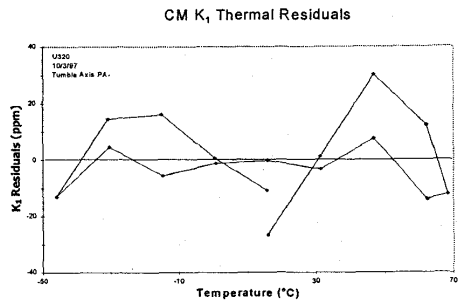


Fig. 8. Accelerometer K1 Residuals

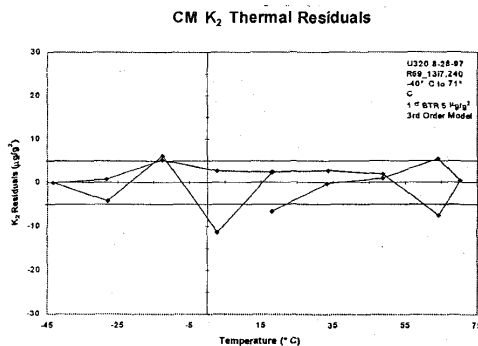


Fig. 9. Accelerometer K2 Residuals

Table 1.

Parameter	Current Target	Near Term Goal
Rate Bias	100 deg/hr	10 deg/hr
Rate Scale Factor	500 ppm	100 ppm
Random Walk	0.4 deg/√hr	0.15 deg/√hr
Accel Bias	1 mg	300 µg
Accel Scale Factor	100 ppm	25 ppm
Temperature	-40°C to 71°C	-55°C to 95°C

Accelerometer bias thermal testing was done from -40°C to 71°C. The residuals measured 133 µg, 1σ, over

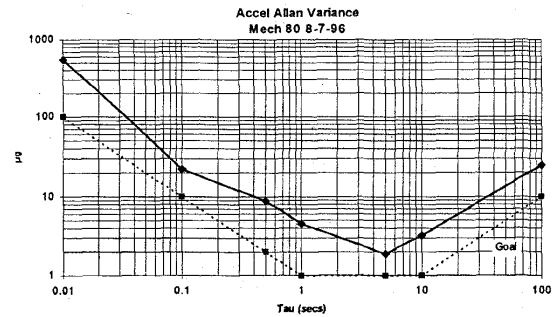


Fig. 10. Accelerometer Allan Variance

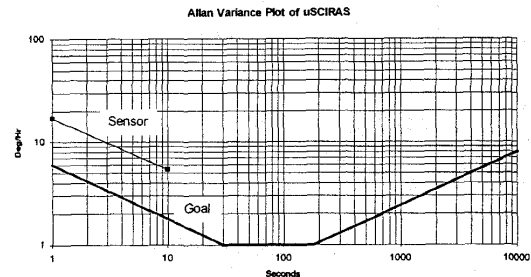


Fig. 11. Rate Allan Variance

temperature as shown in Figure 7. The scale factor 1σ residual was 16 ppm for K1 as shown in Figure 8.

The vibration rectification coefficient or K2 is used as the measure of vibration rejection. The K2 was measured and model residuals are shown in Figure 9. The residuals after modeling are less than 5 µg/g² over temperature.

The Allan Variance noise of the accelerometer and rate channels are shown in Figures 10 and 11. Both are within a factor of two of the theoretical limits.

FUTURE DEVELOPMENTS

The performance goals for the silicon sensor are summarized in Table 1. Long term goals include rate performance of 1 deg/hr and 0.1 deg/√hr random walk.

A major element of any IMU is the digital processing required to turn raw sensor signals into useful body rate information. Because the µSCIRAS sensor directly produces digital signals in frequency format, it is practical to condense the complicated front-end signal processing into an Arithmetic Logic Unit (ALU) based ASIC. Counters and simple arithmetic operations perform high speed demodulation operations that generate useful body rate information. Relegating this front-end digital processing to a low-cost ASIC yields impressive reductions in size and cost of the IMU. The basic size of an IMU with this condensed processing would be about 0.5 inches taller than the standard ISA. The interface would be a standard serial interface operating at user selectable baud rates. The signal processing ASICs embedded in the ISA would perform the

functions of an IMU, including operations such as temperature compensation and axis-alignment to achieving fully compensated ΔV and $\Delta \theta$ values.

ACKNOWLEDGMENTS

A special word of thanks to the μ SCIRAS team for their hard work and dedication to make this happen. We

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IECEC-98 Global Warming, continued from page 16

Wang's better choice is a solid-oxide fuel cell with gas-turbine and steam bottoming cycles. The oxidizer and hydrogen are heated to the fuel-cell's working temperature, without flame, by a chemical-looping combustor, rather than by the fuel-cell's exhaust gas. This eliminates the loss in a high-temperature heat exchanger that would otherwise be needed. The fuel and oxidizer go through different reactors without flame; thus nitrogen-oxide formation is avoided.

Wang predicted that with progress in fuel cells and hydrogen production, this combined cycle will achieve record efficiency without nitrogen-oxide release.

Water Electrolyzer for Making Hydrogen

Hydrogen used in launching spacecraft is shipped from oil refineries to the launch pad. Hydrogen for a fuel-cell powered car is not conveniently available at a filling station. However, hydrogen can be available anywhere there is an electrical outlet!

Takahiro Nakanori has built a polymer-electrolyte water electrolyzer that makes hydrogen from water with an efficiency of 93.2% [4]. The 200 cm² five-cell stack operates at atmospheric pressure and a 7.850 stack voltage. The current density is 1.0 ampere per sq cm. If you are in a hurry, you can apply 9.308 volts and go to 5 amperes per sq cm. However, energy efficiency drops to 79.7%.

A gallon of gasoline contains around 120,000 Btu of energy. A gasoline engine delivers about 25%, or about 30,000 Btu, to the transmission. This same energy in hydrogen, made with a 93.2% efficient electrolyzer from 7 cents-per-kWh electric power, would cost 66 cents.

Fuel Cell Plus Gas Turbine Plus Steam Turbine – 81% Efficiency

Giacomo Bisio observed that 30% of fuel energy is destroyed in the combustion process used in today's electric power generation [5]. An additional 15% is lost during the transfer of heat from combustion gases to the working fluid, such as water vapor. A fuel cell is not a heat engine, so is not bothered by Carnot-cycle efficiency limits based on source and sink temperatures. Its exhaust gas temperature is related only to the energy that the fuel cell didn't extract from its fuel and oxidizer. "Indeed it is impossible by configurational adjustments to approximate a situation where the irreversibilities of both coupled phenomena (chemical and electrical) vanish," he observed.

Bisio's model showed that a power plant with a solid-oxide fuel cell with gas-turbine and steam-turbine bottoming cycles could have an efficiency of 81%. The best of today's natural-gas burning combined-cycle plants is 60%, and traditional steam plants are under 40%.

Combined Heat and Power: For Manufacturers It Saves Energy, Reduces Emissions

Power plants in the US generate power by burning fuel to produce heat for turbines. The combustion products, including carbon dioxide, go into the atmosphere. The nation's overall power generating efficiency is only 30%. That means 70% of the fuel energy heats our environment. In addition, we burn fuel to heat our homes, work places and malls.

Tina Kaarsberg evaluated alternatives that reduced both carbon discharge and energy cost [6]. District heating, in which the power plant generates electricity and delivers hot water to local residences is practiced in Europe. However, people in the US don't want to live near power plants. Also, in states like Texas cooling is needed more often than heating.

Quiet fuel cells and Stirling engines can deliver electric power, heating, and cooling to homes and small businesses. Mini-gas-turbines can do the same for industries and hotels. However this practice is discouraged by utilities and government regulations in the following ways:

- Complex "gold plated" interface equipment is mandated when local power is to be paralleled with utility power.
- Fees covering interest on utility power generators must be paid by anyone selling power to a utility.
- A permit is required when nitrogen-oxide can be emitted.
- Zoning restrictions effectively prohibit such installations.
- Skilled labor for installation and maintenance is not available.
- Some state laws require a power generator rated over 30 kW have a watchman on duty 24 hours a day.

Kaarsberg's suggestions for encouraging combined heat and power generation are:

- Relieve the regulation barriers.
- Create "technology incubators" that develop units in small sizes.
- Adapt combined-heat-and-power generation to commercial air conditioning.

The goal should be to generate 7 EJ of energy annually, and reduce the annual carbon release by 30 million tons.

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