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MICRO GUIDANCE AND CONTROL SYNTHESIS: NEW COMPONENTS, ARCHITECTURES AND CAPABILITIES

Edward Mettler and Fred Y. Hadaegh

Jet Propulsion Laboratory
California Institute of Technology

ABSTRACT

New GN&C (guidance, navigation & control) system capabilities are shown to arise from component innovations that involve the synergistic use of microminiature sensors and actuators, microelectronics, and fiber optics. Micro-GN&C system and component concepts are defined that include micro-actuated adaptive optics, micromachined inertial sensors, fiber-optic data nets and light-power transmission, and VLSI microcomputers. The thesis is advanced that these micro-miniaturization products are capable of having a revolutionary impact on space missions and systems, and that GN&C is the pathfinder micro-technology application that can bring that about.

1. INTRODUCTION

The general trend in communication, signal processing , and computation over the last two decades continues to be towards miniaturization for improved performance, higher reliability, and lower relative cost. However, the engineering difficulties and rapidly increasing expense of interfacing digital microelectronics with conventional sensors and effectors have not allowed this promise to be realized for space GN&C systems.

Research in micro-mechanics sensing and actuation has been very active in the past several years, both in industry and academia. Various commercial micro-sensors have been built to measure humidity, temperature, flow rate, viscosity, pressure, acceleration, chemical reactions, and many other physical parameters. At MIT, U. C. Berkeley Sensor and Actuator Center, the University of Utah Center for Engineering Design, and at Caltech, research is ongoing in integration of micromotors, micromechanical gearing, logic, and transducers.[1-12]

There have been recent advances in the micromachining of silicon through the use of anisotropic etchants with doping controls. These advances have led to the development of a new class of sensors composed entirely of surface micro- machined silicon. Surface micromachining is a much more sophisticated technique than bulk micromachining. Various beams, masses and other structures can be formed by depositing and etching multiple thin films and layers of silicon and silicon oxide. The feature dimensions of such devices are 1-2 μm, roughly the same as conventional electronic circuits.

Recent progress in the integration of established batch fabrication techniques for VLSI microelectronics with new silicon surface-micromachining methods has now made it feasible to incorporate on-chip the supporting circuitry for microsensors and microactuators (i.e., amplification, compensation, conversion, multiplexing, and interfacing functions). As an example, this technology has recently been used to develop the Analog Devices ADXL-50 accelerometer[13] shown in Figure 1.

While the present version of this sensor has an advanced level of integration, it is not an "inertial guidance grade" accelerometer in accuracy. It does represent the functional form of "smart" micromachined devices that are evolving rapidly through a marriage with VLSI microelectronics.

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The Analog Devices' part breaks new ground by using a surface micromachining process that lets the company integrate a capacitive, force rebalance, acceleration sensor, as well as control circuitry, on the same die. The device features on-chip signal conditioning and self-test circuitry. The sensor measures 500 μm x 625 μm. The capacitor plates are approximately 115 μm long and about 4 μm wide. The on-chip signal-conditioning circuitry produces a scaled-referenced and temperature-compensated output voltage. In addition, a digitally controlled self-test function lets the sensor deflect at any time, producing a precise output voltage corresponding to the equivalent g-force for a healthy sensor.

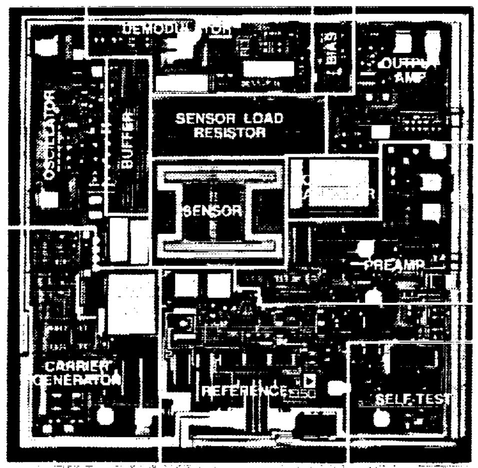


Figure 1. ADXL-50 Accelerometer

In this paper, these device features along with higher integration levels of micro-devices with local DSP for distributed architectures are proposed for new GN&C architectures.

2. SPACE APPLICATIONS

In the subsequent discussions, we present an advocacy for the development of micro-GN&C and describe an approach for the utilization of new microengineering technologies to achieve major reductions in GN&C mass, size, power, and costs to meet the needs of future space systems.

It would not be an overstatement to forecast the outcome of integrating the emerging fields of micro-optoelectronics and micro-electromechanics with advanced microelectronics as a revolutionary change, rather than an evolutionary improvement. The potential payoffs in the metric-space of cost-performance-risk are very impressive: 100/1 reductions in size, mass, and power; 10/1 reduction in recurring costs and cost growth-rates; solid-state reliability and lower performance risk; and robustness to temperature, vibration, and radiation environments.

To fully appreciate the impact that micro-miniaturization can have on intelligent-system implementation costs (i.e., systems like GN&C and robotics with sensors, computation/logic, and effectors), we have only to apply a conservative scaling to the dollars per kilogram and per watt for current unmanned spacecraft equipment: approximately 100 K $/watt and 100 K $/kilogram for today's planetary probes. Then, without even factoring in the multiplier for improved performance and reduced risk with a micro-technology implementation, we observe that the recurring cost improvement of 10/1 and greater can be taken as an achievable objective based only on the mass, power, and fabrication economics of microelectronics.

Several major NASA programs will directly benefit from these technology advances and therefore they provide an important motivation for this research: The Lunar and Mars Exploration initiatives contain both Micro-Spacecraft and Micro-Lander/Rover elements as key capabilities required to realize cost effective exploration and science return.

In a discussion of "micro-size" systems, we must define the metric that distinguishes "micro" from "small" or "light" spacecraft and rovers. As a reference, typical spacecraft fall into a range of 1500 to 3000 kg, and large rovers are in the 500 kg range. Then by "small" or "light" we mean a reduction of about 10/1 in mass, and by "micro" we mean a 100/1 or greater mass reduction. This scaling places the mass of micro-spacecraft in the range of 15-30 kg, and micro-rover mass at about 5 kg.

On the large space-systems scale, the future astrophysics advances from Space Interferometers and Multi-aperture Reflectors will be made feasible by the capability to actively control these spatially distributed optomechanical systems and integrated structures to nano-precision levels without imposing instrumentation mass, power and cost penalties proportional to system size and complexity.

Cost-constrained remote sensing platforms, for both missions to planet Earth and deep space, and manned space stations will all benefit from the new microelectromechanics technology that will become ubiquitous in applications for both microsystems and macrosystems.

The GN&C application needs for these future space systems have been identified as follows:

Micro-Spacecraft, Micro-Landers, & Micro-Rovers
- Attitude & Maneuver Control System
- Micro-Inertial References
- Microelectro-optics for miniature cameras & remote sensors
- Inertial Navigation Systems
- Heading Reference Units
- Mini-Camera Pointing & Stabilization
- Antenna Pointing & Stabilization

Remote Sensing Platforms, Interferometers, & Deployable Reflectors
- Distributed Micro-Sensor System Identification
- Multivariable Control of Structural Dynamics
- Distributed Shape & Position Control of Mirror Arrays
- Embedded Stabilization of Telescope & Instrument Optics
- Distributed Micro-Inertial References
- Embedded Health Monitoring of GN&C Effectors

3. MICRO GN&C CORE INNOVATIONS

The core microengineering innovations needed to realize the above micro-GN&C architectures and functions can be combined into a set of six micro-technology products that would serve as enabling building blocks for the new GN&C subsystems. The following products include component and system implementations that are synergistic and would involve contributions and coordinated activities of NASA, industry, and academia.

- Massively distributed microsensing for system ID & control
- Light powered remote processing network for microsensing
- Micro-GN&C for microspacecraft and microrovers
- Six degree-of-freedom micro-inertial measurement unit

- Actively controlled micromachined deformable mirrors
- Embedded health monitoring for GN&C effectors

3.1 Massively Distributed Micro-Sensing for System ID & Control

For a massively distributed system ID-sensing approach for active structure control to be practical, the basic sensing system has to be, of necessity, mass efficient, low power, micro-g sensitive, of low complexity and cost, fault tolerant, and have generic applicability to future missions.

The fully integrated sensing system (Figure 2) will consist of high sensitivity micromachined sensing elements with distributed data communication, signal conditioning and processing electronics, connected together over a fiber-optic network. The high bandwidth fiber optic network provides digital data interfaces with high EMI immunity, and serves as the source for sensor power through optical to electrical power conversion. This obviates the need for multiple conductors for data and signal as in conventional networking technology. Fault tolerance and redundancy can be provided with multiple sensing elements per sensor as well as with a suitable choice of network topology and communication protocol.

The proposed smart sensor system will be implemented using a micro-accelerometer as the basic sensing element. Typical deployable space structures depend on flexible beam-truss structures assembled out of rod elements interconnected with joints (e.g., high gain communication antennas, instrument booms, basic truss support structures for segmented reflector telescopes, and spaceborne interferometers). Three-axis accelerometers will be mounted on the connecting joints of a truss structure, or single axis accelerometers will be installed along the length of flexible ribs.

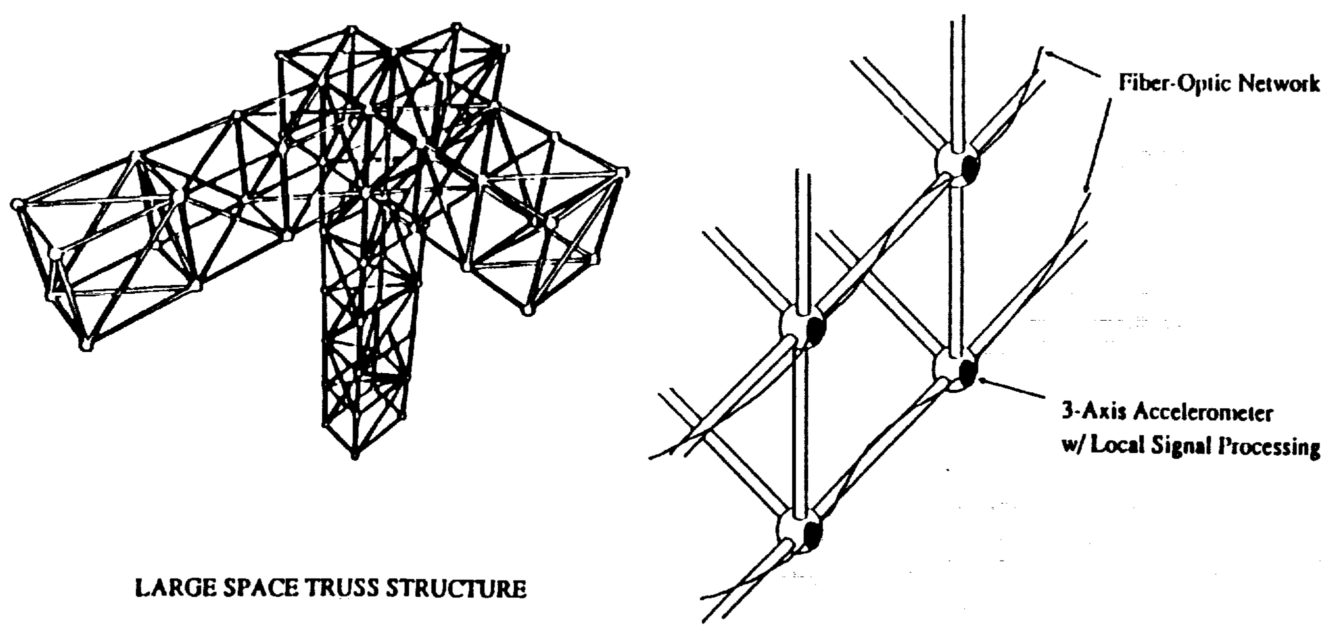


Figure 2. 3-Axis Integrated Sensing System

3.2 Light-Powered Remote Processing Network for Micro-Sensing

It will be necessary to develop the microtechnology that will enable the full integration of micro-sensors with their electronics, and will enable the adaptation of fiber-optic networks for communicating with, and powering of, microsensor systems. This work is described in two parts: **Microsensor Electronics**, and **Fiber Optic Networks**.

3.2.1 Microsensor Electronics

The development of integrated sensor electronics will provide a self-contained motion sensor with a very small form factor and low cost and power. This will enable the use of multiple sensors to sense three-axis linear accelerations. The system will read the multiple sensor outputs, process the information for velocity/ acceleration vectors, and format the output for serial I/O interfaces that transmit/receive information over fiber optics in a large massively distributed system. Figure 3 illustrates the various components of such a system. The amount of data management electronics will enable diverse system architectures to be produced from the same microelectronic building blocks.

The sensor electronics are programmable in gain and mode of operation. The sensor output is digital so the sensor has a bi-directional digital interface. Enhanced versions of integrated sensor electronics will include:

- Standard serial and parallel interfaces.
- Two-wire interface where power is obtained from the interface.
- Signal processing on the sensor to integrate its acceleration signals for velocity, and correct for offsets in the system.
- Gain control of the sensor electronics to maximize their dynamic range.
- Optical power and interface designs that isolate the sensor from the control electronics.

The off-sensor control electronics will provide for the use of multiple-axis sensor systems and further enhance the sensor performance through hardware signal processing by special purpose local integrated circuits.

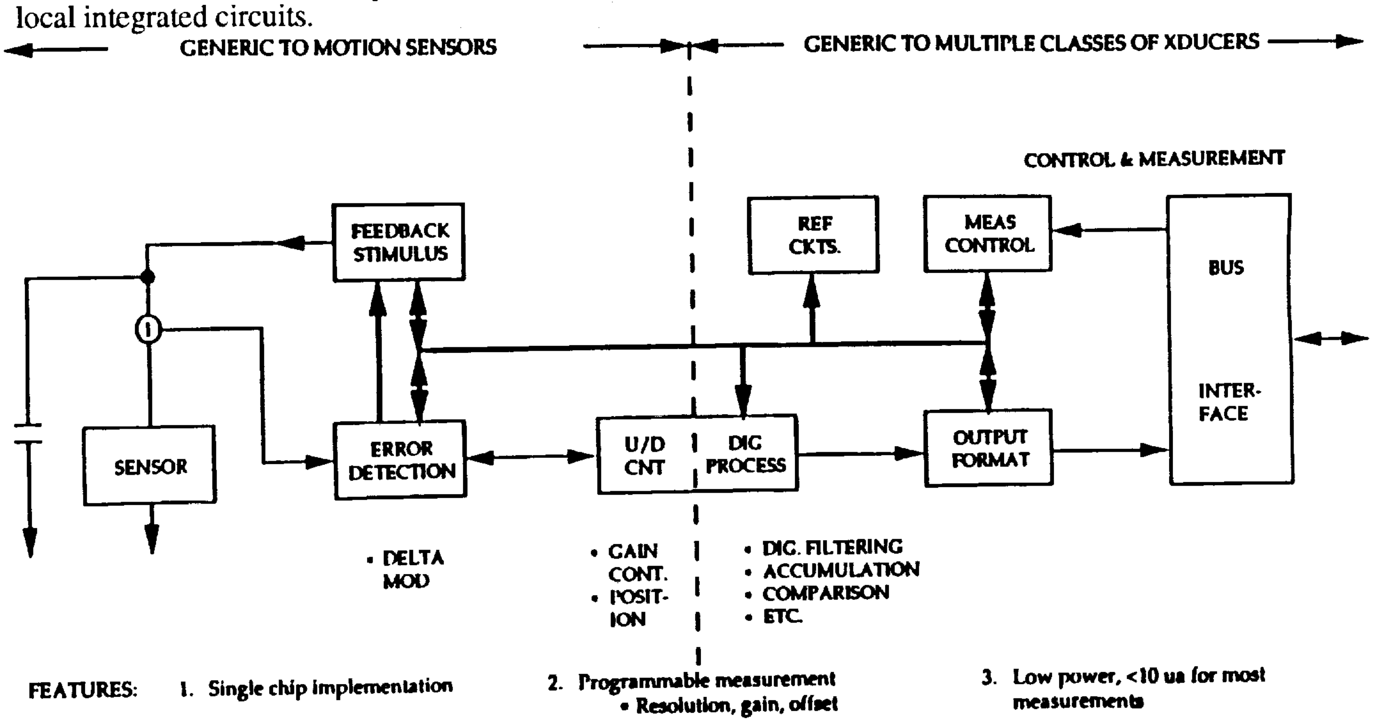


Figure 3. Remote Signal Processor for Motion Sensors

The development of on-chip electronics for the micromachined sensor will be directed toward generic electronics. These electronics will be integrated directly on the silicon sensor with conventional CMOS circuit fabrication technology. Their proximity to the microsensor mechanism will provide maximum overall sensitivity through noise minimization in the high impedance circuit; and equally significant, they will provide a small self-contained sensor at a low recurring cost.

These integrated sensor electronics will allow future system evolution so that on-chip enhancements will use the sensor as a cell, and external enhancements will have sufficient measurement and control interface access. In addition to low power, the design goal will include low voltage operation so that the chip can be powered from a single photo-detector which would be integrated on the sensor.

The addition of data management functions would include the further integration of sensor-specific processing functions and the interfacing with a distributed microcomputer. This microcomputer may make use of the technology that has been developed at JPL for a Common Flight Computer (CFC). The CFC makes use of a VLSI chip set jointly developed by Sandia National Labs and JPL. The CFC is a high performance computer contained on a single board. It will be further miniaturized by redesigning the packaging configuration to a high-density hybrid multi-chip module containing unpackaged chips on ceramic substrates.

The 16 bit data path computer is designed in a 1.25 µm CMOS (Complementary Metal-Oxide Silicon) technology and is based on Sandia's SA3300 microprocessor, a Rad Hard Single Event Upset resistant microprocessor which executes the National Semiconductor NSC 32016 instruction set. The chip set includes a Floating Point Unit (FPU), Interrupt Control Unit (ICU), two Direct Memory Access Co-processors (DMACs), Control Unit (CU), and Fault Management Unit (FMU). The FMU will transparently correct single-bit errors and perform bit-plane sparing to replace single bits of memory which might fail over time. Figure 4 shows a block diagram of the computer and its interfaces to other hardware functions.

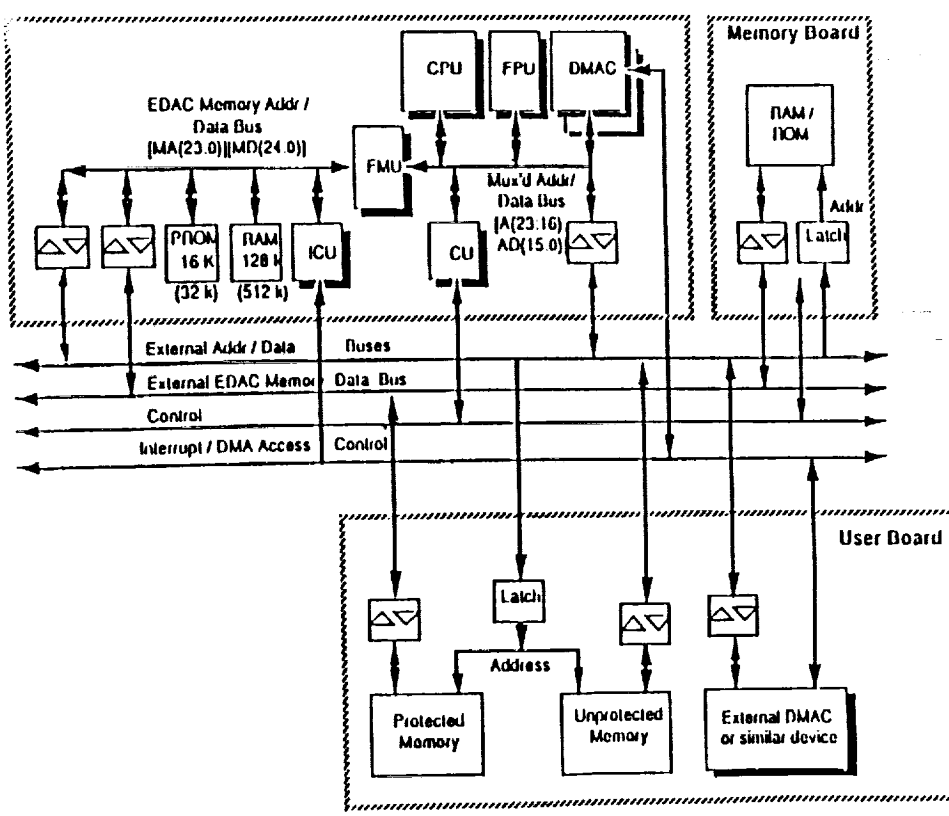


Figure 4. Common Flight Computer Architecture

3.2.2 Fiber Optic Networks for Microsensing

The general objective is to implement the remote-processing network with optical fiber rather than with electrical conductors. The small mass and low power consumption of microsensors make them the natural choice for many system-identification and control applications, and the use of remote processing enhances these advantages by a large factor. However, these advantages are largely lost if the interconnection must be done with conventional multi-conductor copper cable.

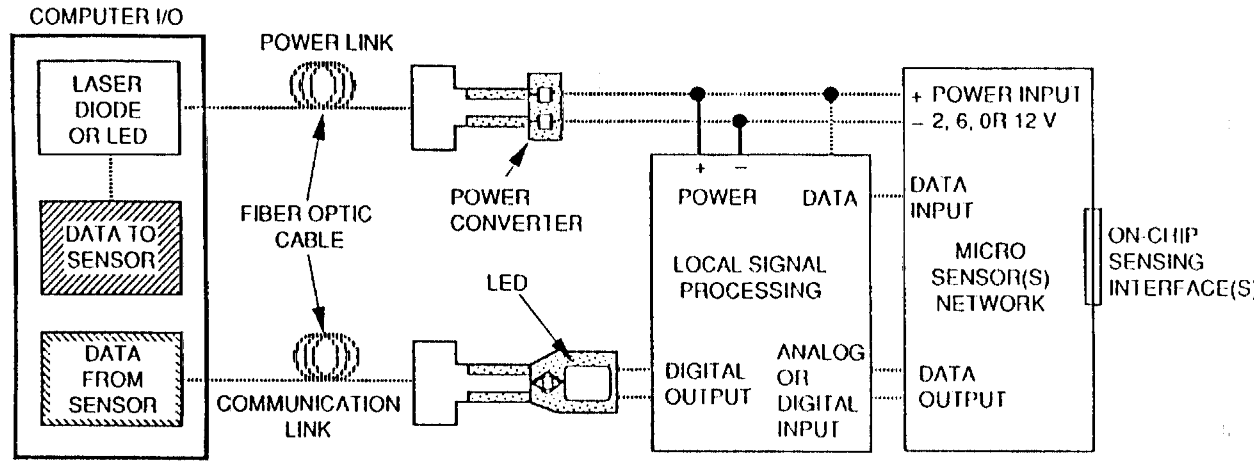
The network connects the microprocessors associated with each microsensor to one or more central processors. In this function it is a data bus of very high bandwidth. It is also a power-distribution system in which the power is distributed in the form of optical radiation. The optical power will travel through the same fiber as the data. The network will be constructed for the most part from existing components. These components include, besides the fiber itself, electrical-to-optical and optical-to-electrical interfaces as well as couplers, taps, etc. Although the optical powering of a pilot's headset, or the equivalent, has been demonstrated, the powering of an entire network has not been demonstrated, and some of the components may need continued development.

Semiconductors that convert light into electrical power have typically been characterized by a low output voltage that requires step-up transformers and amplifiers. Varian Research recently introduced its PR6C power converter[14] that offers a breakthrough solution. The monolithic device converts optical power into electrical power sufficient to drive ICs as well as sensors. When driven by light sources such as laser diodes, either directly or via fiber-optic cable, the new converter can produce an output power of up to 1 W, with output voltages up to 12 V. To generate such an increase in power output, Varian combined its GaAs solar cells with GaAs IC design and manufacture.

As an example, the 6-V version of the converter has an active-area diameter of 3 mm that is divided into six equal sections. Each section is essentially a GaAs solar cell, operating as an independent photodiode with an output of 1 V. These sections are electrically isolated by a trench measuring 20 μm. Interconnecting along the surface is not possible as the higher voltages require a topology too deep for this process. The solution is an "air bridge" or metal strip which spans the trenches, producing a sum of 6 V between the first and the last cell. The output voltage can be increased by simply increasing the number of 1-V cells. For a 6-V device, a 250 mW light input at a wavelength of 800 nm can produce an output power of about 111 mW at 5.8 V, giving an efficiency approaching 50%.

In one example of a "Power down/Data back" transmission strategy, light is sent from a control system, via fiber optics, to the converter. This light powers a sensor, as well as a diode, to send data back along the same fiber to be processed by the controller. Figure 5 shows a distributed microsensing system example based on Photonic Power Systems'[15] application of the power converter under license from Varian.

The overall topology of the network is also an important consideration. It is in part determined by the specific sensing problem being addressed, but it is also determined by reliability considerations. Figure 5.1 shows an example of network topologies. A linear bus implemented with two fibers is shown at (a). The use of dual fibers simplifies the design of the taps. A star network is shown at (b). The central star may be either active or passive depending on requirements. Ring networks both parallel and counter-rotating are shown at (c) and (d). The increased redundancy of the counter-rotating ring gives it improved reliability. A significant effort will be devoted to analysis of alternate network topologies for GN&C applications, including their effectiveness and their reliability.



FEATURES:

- NOISE-FREE FIBER OPTICS FOR POWERING REMOTE SENSORS AND CONTROL SYSTEMS
- COMPLETE POWER ISOLATION, i.e., TOTAL AVOIDANCE OF POWER AND SIGNAL GROUND LOOPS
- TOTAL IMMUNITY TO NOISE CAUSED BY ELECTROMAGNETIC AND RADIO FREQUENCY INTERFERENCE
- NO VOLTAGE "STEP-UP" CONVERSION IS NEEDED SINCE VOLTAGE LEVELS ARE AVAILABLE AT 2, 6, OR 12V
- SENSOR INPUT POWER LEVELS AVAILABLE FROM 1 mW TO 150 mW DEPENDING ON LIGHT SOURCE
- MULTIPLEXING BOTH POWER AND SIGNAL FOR MULTIPLE SENSORS AND CONTROLS
- LIGHTWEIGHT CABLING

*COURTESY OF
photonic
POWER SYSTEMS, INC.

Figure 5. Light Power and Communication for Distributed Microsensing

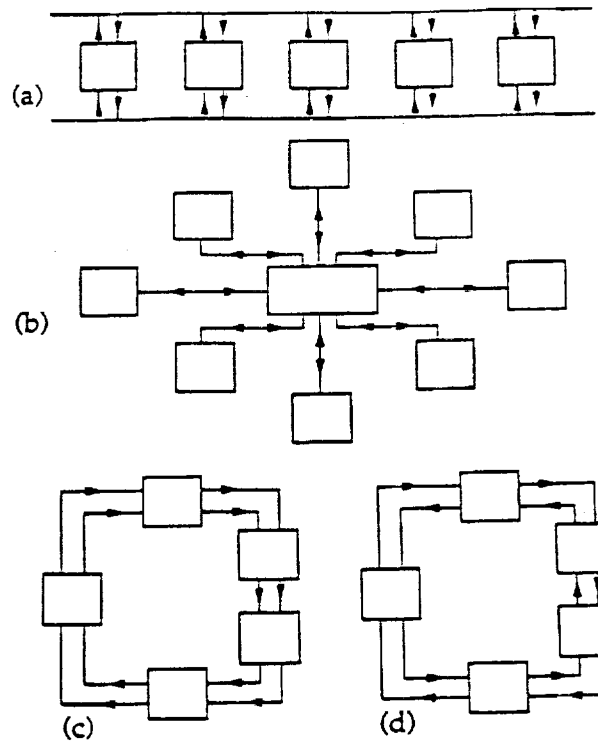


Figure 5.1. Candidate Network Topologies

3.3 Micro-GN&C for Micro-Spacecraft and Micro-Rovers

Advances in the miniaturization of sensors and computers with increases in performance allow the development of a miniaturized GN&C subsystem that enables a new class of micro-spacecraft and planetary roving vehicles.

3.3.1 Micro-Spacecraft

The functionality of an entire GN&C subsystem for a micro-spacecraft will be implemented in the miniaturized VLSI common flight computer. This includes the interfaces with CDS (the command and data subsystem), sensors, and actuators. Information will be processed into appropriate actuator commands (Figure 6).

The CDS interface will include input commands and output telemetry. The sensor inputs needed by the GN&C subsystem include gyros and accelerometers (from the 6-DOF IMU), star tracker or micro-imaging system (for attitude position and rate), sun sensor, and encoder position (for at least one articulating element). The sensor inputs and CDS commands will be processed by the computer to produce driver outputs suitable for actuators including reaction wheels, thrusters, and articulation motors.

The primary GN&C functions for a spacecraft are given below. The actual functions implemented in the micro-spacecraft GN&C subsystem will be a subset of these. The functions are broken up into three main areas:

Attitude Determination: This set of functions takes sensor data (such as sun sensor, IMU, and encoder information) and determines spacecraft attitude (to various levels of accuracy depending on the sensor), attitude rate, the articulation angle and rate of any appendages, and the vector (in the spacecraft frame of reference) to important bodies (sun/earth/bright bodies/target body).

Attitude Control: This includes various spacecraft functions such as sun acquisition and pointing, HGA pointing (pointing the radio antenna towards the earth), commanded turns, axial/lateral delta-v burn control, thrust vector control, and momentum unloading.

Articulation Control: Given an articulated appendage such as a camera, there are various modes that it needs to be commanded in, such as celestial pointing (based on inertial data), relative pointing (based on encoder data), target motion compensation, and closed loop target body tracking.

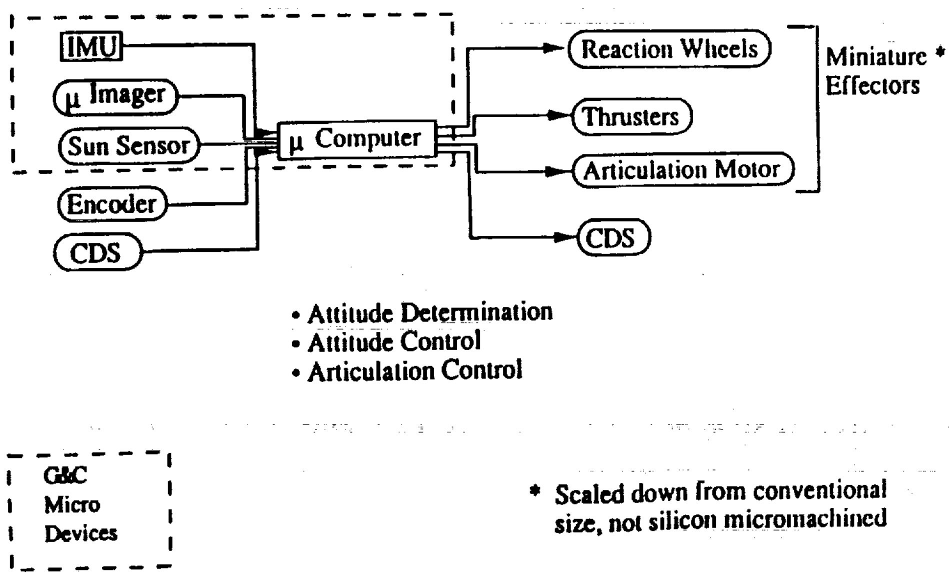


Figure 6. Micro-Spacecraft GN&C

3.3.2 Micro-Rovers

The GN&C functionality appropriate to a rover is quite similar to that for the micro-spacecraft, including an interface to CDS, sensors, and actuators (Figure 7). The CDS interface will include input commands and processed sensor information (such as processed landmark information from a micro-imaging system), and output telemetry and guidance information. The sensor input needed by the GN&C subsystem includes gyros and accelerometers (from the 6-DOF IMU), odometer, and encoder position (from an articulated appendage). The sensor inputs and CDS commands will be processed (in the common flight computer) to give articulation control commands, and navigation information suitable for processing to appropriate vehicle steering commands, path-planning, and telemetry.

The GN&C functions we will consider for the micro-rover are a subset of the following:

Attitude and Position Determination: This set of functions takes sensor data (such as IMU, odometer, landmark position information from an imager, and encoder information) and determines rover attitude, attitude rate, the articulation angle and rate of any appendages, and rover position.

Path Guidance: Given information on a path to be followed, and the current position, the path guidance function determines the high level steering commands needed to follow the path.

Articulation Control: Given an articulated appendage such as a camera, there are various modes that are required such as relative pointing (based on encoder data), rover motion compensation, and closed loop feature tracking.

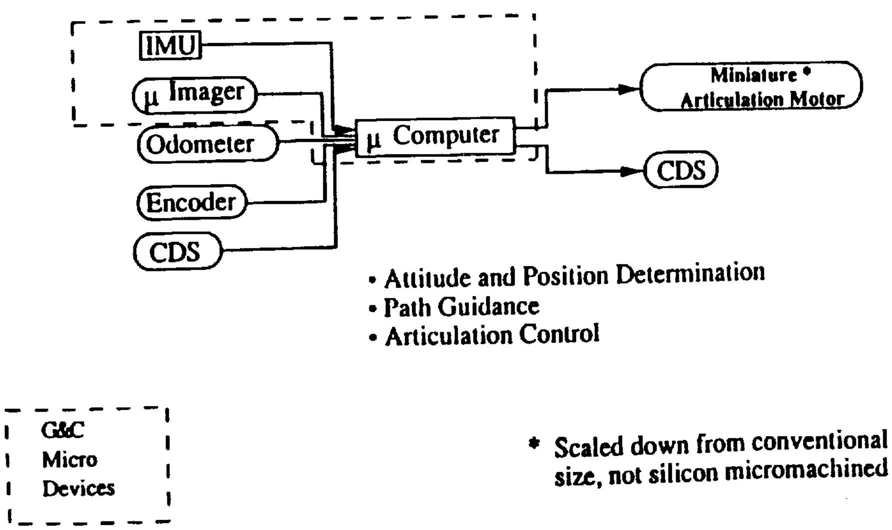


Figure 7. Micro-Rover GN&C

3.4 Actively Controlled Micro-Machined Deformable Mirrors

As the size and sophistication of optical instruments increases, instrument designers are turning to deformable mirrors as a means of compensating for distortions in elements of the optical train and/or in the instrument's field of view. The resulting adaptive optical systems have applications in large space interferometers and multi-aperture reflectors.

In the case of imaging instruments intended for space applications, a deformable mirror should be small, lightweight and highly pixelated (i.e., deformations having high lateral resolution can be made); it should also consume little electrical power, thereby minimizing undesirable thermal effects on the controlled surface as well as overall spacecraft power requirements. Figures 8 and 9 show an example construction.

This effort will exploit micromachining technology to develop a deformable mirror with the above characteristics. The mirror may be realized as a "flip chip" type assembly, consisting of two matched, micromachined structures mounted face-to-face and fused together along their peripheries. The key elements of the mirror will be simple, easily-replicated, capacitively-driven linear actuators, each responsible for pulling on a small section of a thin flexible mirror. Electronic element access, and perhaps even control circuitry, will be monolithically integrated into the mirror.

The initial performance goals for the mirror will be 10 nm control of a 32 x 32 pixel flat mirror. Once these goals have been achieved, efforts will be directed at extending the number of pixels/control elements until 10 nm control can be effected over a 1024 x 1024 pixel surface.

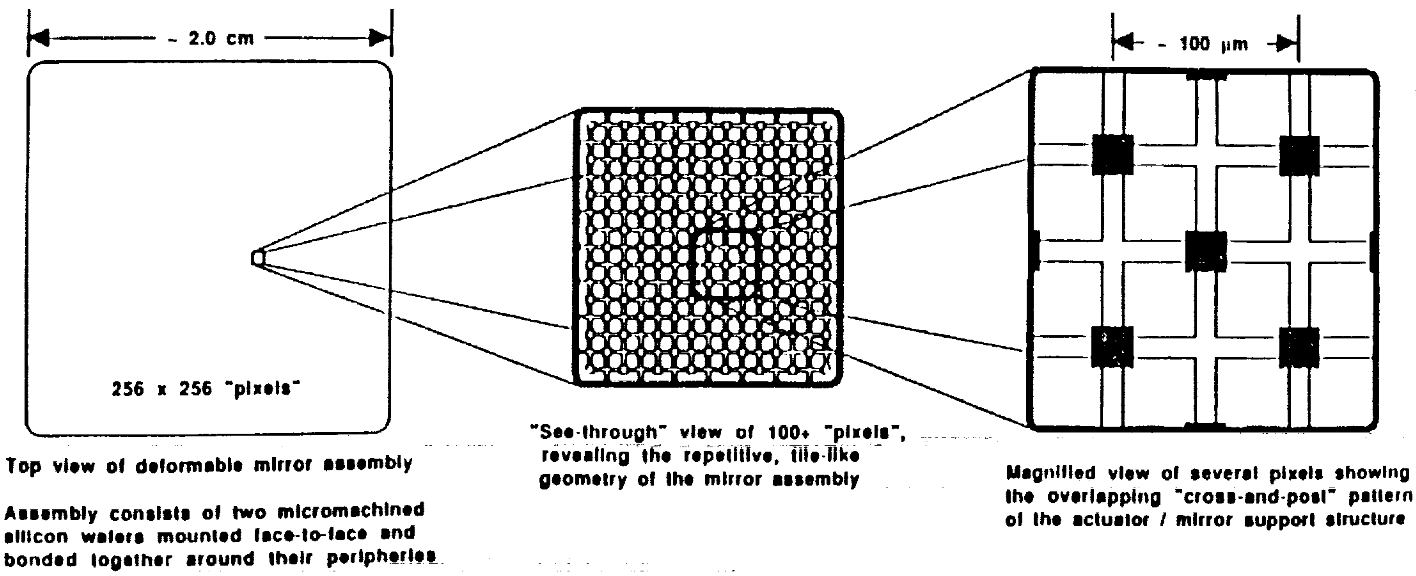


Figure 8. Micromachined Deformable Mirror

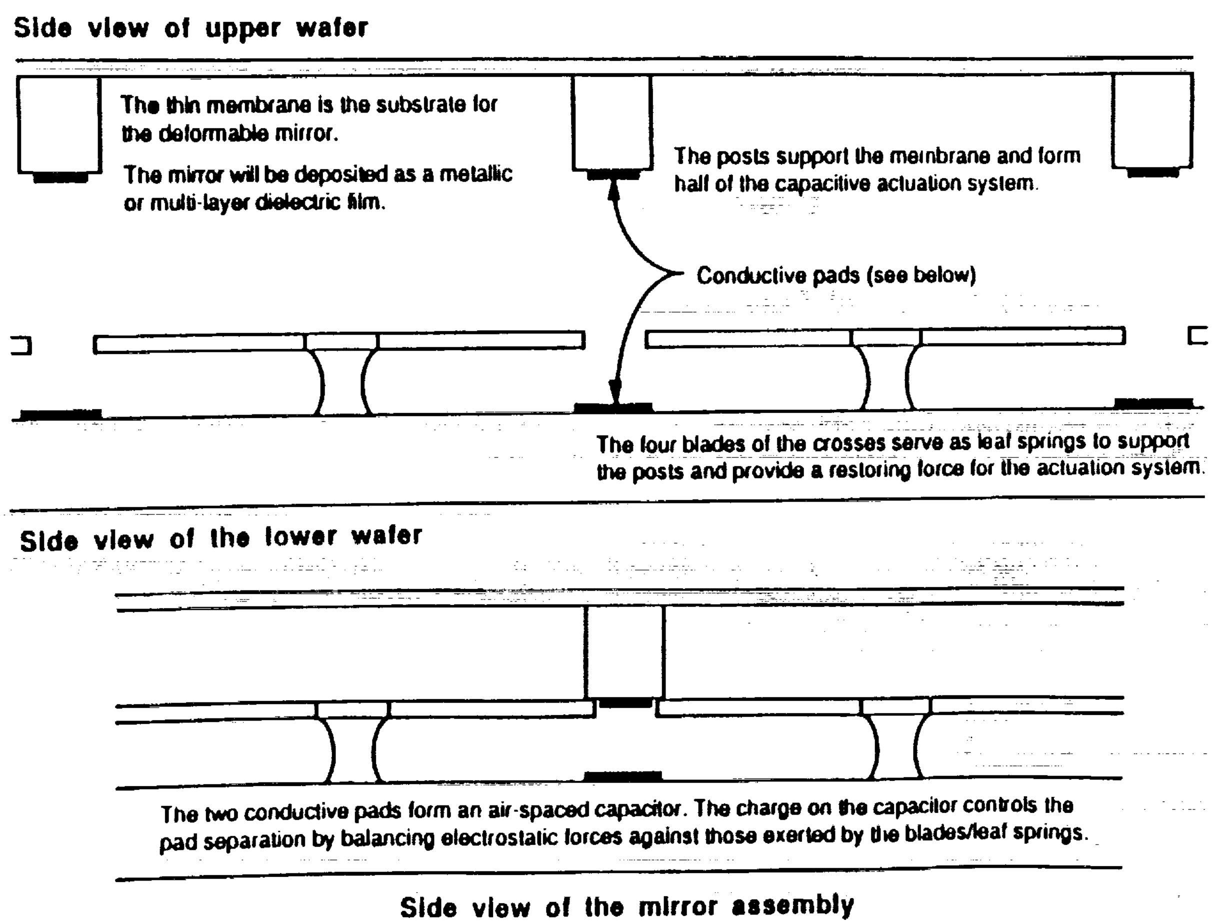


Figure 9. Micromachined Deformable Mirror

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3.5 Six-Degree of Freedom Micro-Inertial Measurement Unit

The IMU is composed of three orthogonal micro-gyros (micromachined devices integrated with VLSI sensor electronics), and three orthogonal micro-accelerometers with integrated sensor electronics. The sensor array mountings and 3-D packaging will be defined as part of the basic technology development effort. Functionally, the IMU will contain the necessary power and signal interfaces, conditioning electronics, the gyro and accelerometer capture loops, and any required local circuits for bias correction or temperature sensitivity compensation. The sensor outputs to the attitude determination and control, trajectory correction, and navigation functions of the micro-spacecraft or micro-rover will be delta (incremental) attitude angle and delta velocity in each axis with resolution dependent on the quantization achievable in the sensor capture loops.

3.5.1 Micromachined Vibratory Gyroscopes

Vibratory gyros are based on Coriolis-force-induced coupling between two modes of a two-dimensional mechanical oscillator. This basic principle has been extended to other two-dimensional mechanical oscillators to obtain gyros of greater utility than the elegant but unwieldly Foucault Pendulum. In particular, gyros have been based on tuning forks as well as vibrating strings, triangular and rectangular bars, cylinders and hemispheres. The performance capabilities of some of these gyros can be quite impressive. Hemispherical resonator gyro development has achieved navigational-grade performance: bias stabilities of 0.005 degree/hr, angular random walk levels of 6 x 10^{-5} degrees/square root hr, scale factor stability of 0.02 ppm, and readout noise of 0.02 arcsec.

Precise electron beam lithography and silicon micromachining capabilities, combined with high resolution interferometric displacement measuring techniques, suggest a new variation on the vibratory gyro theme. A micro-machined, vibrating silicon beam would serve as a rate-integrating vibratory gyro; readout of the integrated rotation angle would be performed by two orthogonal interferometric displacement measuring systems. The latter would be based on solid state lasers and fiber-optic/integrated-optics technology, and could be integrated with the vibrating beam into a very small package. Despite the gyro's small size and relatively simple design, impressive performance capabilities appear to be attainable: interferometric metrology systems are capable of measuring vibration amplitudes with precision on the order of 1 fm/square root Hz. Thus, given an overall vibration amplitude as small as 1 μm, the gyro would, in principle, be capable of nanoradian angular resolution at 1-Hz update rates.

Given the nature of the individual components, the gyros should also be relatively inexpensive, readily testable and highly reliable. The availability of unusually small, reliable and inexpensive navigational-grade gyros will have a profound impact on guidance and control applications. Inertial guidance systems will find entirely new uses in systems ranging from planetary microrovers to stabilized video cameras. Traditional gyro applications will enjoy the direct benefits of reduced mass, power, volume, and cost, and will further exploit these reductions to realize improved reliability and simplified environmental control requirements.

3.5.2 Micromachined Accelerometers

The designs for micro-miniaturized transducers have differed radically from scaled down versions of conventional sensors. The laws of scaling of the various physical phenomena have become critically important. For example, the scaling laws favor electrostatics over electromagnetics as the dimensions of a structure are reduced. In addition, the sensitivity of conventional sensors typically degrades with spatial reduction, and theoretical limits to transducer sensitivity impose practical constraints. The development of new transducers which scale favorably as the dimensions of the structure are miniaturized can allow substantial improvements over the performance of conventional technology.

At JPL's Center for Space Microelectronics Technology a breakthrough device has been designed and constructed -- an Electron Tunnel Motion Sensor with a currently measured noise floor of 1.0 E^{-8} g and near term capability of a nano-g[16].

This novel motion sensor takes advantage of the mechanical properties of micromachined silicon. For the first time, electrostatic forces are used to control the tunnel electrode separation, thereby avoiding the thermal drift and noise problems associated with all other tunneling devices which use piezoelectric control of the electrodes. The electrostatic forces induce deflection of a micromachined silicon cantilever spring with an integral tip electrode. For a typical construction, the tunneling current varies by an order of magnitude for each Angstrom change in electrode separation. Since tunneling only occurs in regions where the electrode tip is within several Angstroms of the other surface, the active area of the device is microscopic and relatively immune to radiation and charged particle environments common to space missions.

3.6 Embedded Health Monitoring for Electromechanical Effectors

Many spacecraft effectors, particularly rotating and scanning equipment, experience gradual bearing degradation rather than sudden catastrophic failure. For example, bearing wear can be due to micro-fatigue, contamination, hermetic seal leakage, lubricant chemical breakdown or thermal gradient driven migration, retainer whirl instability, and bearing resonances tuned to certain shaft rotation speeds or structural vibration modes. The torque noise produced by these phenomena is often a limiting condition on the jitter level of the spacecraft and its instrument-pointing-system precision.

There is a need for real-time methods to monitor and analyze the effector torque signature, vibrations of the bearings and structures, internal pressures and molecular by-products of chemical decomposition, temperature gradients, and motor current signatures to obtain an important advance in space system reliability and maintainability.

At present, health monitoring of these critical effectors (they are often not a block redundant resource) relies mainly on the download of telemetry reports. Often the only way the flight controllers have of detecting degraded performance of an effector is the indirect cause/effect behavior of the vehicle dynamics as measured by an attitude sensor or smear in a reconstructed imaging sequence. While telemetry may include data on temperature and motor current, these data are used in after-the-fact analysis and do little to predict the onset of poor health. The health-monitoring system would detect, identify cause, and select corrective actions for the spacecraft fault management system, whether located onboard or in the ground control center.

Important considerations in the design and implementation of a health monitoring system are that it should be embedded but non-intrusive, not draw significant power, not interfere with the primary function of the device being monitored, not impose significant mass and space penalties, and be highly reliable. We therefore see the direct compatibility of micromachined sensor technology with the practical constraints of an onboard health-monitoring system design.

3.6.1 Health-Monitoring Architecture

An architecture of embedded microsensors for health monitoring in the space environment will take advantage of integrated electronics to provide information not previously available to spacecraft operations. For example, monitoring of device parameters is available only at a very low bandwidth because of telemetry constraints, and monitoring bearing noise becomes impossible because of the bandwidth limitation. If processing of higher frequency data could be done on the spacecraft with a DSP chip designed for the particular application, the processed data could then be passed to the ground at the slower rate.

The case of health monitoring in a reaction wheel, depicted in Figure 10, is a particularly good example because the primary mode of performance degradation is bearing wear. The emphasis here is on designing the health monitoring by using existing bearing modeling and analysis techniques, while taking full advantage of microsensor and integrated electronics technology.

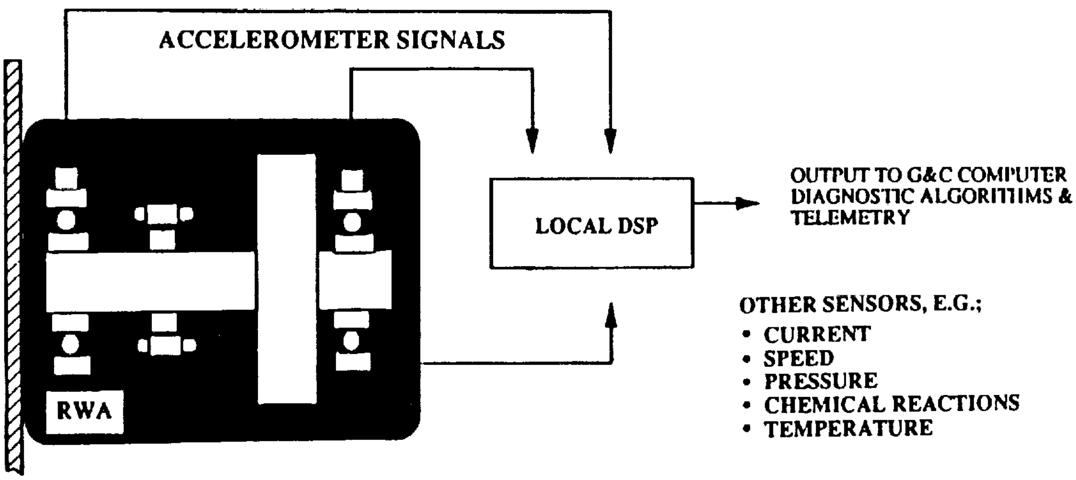

Figure 10. Reaction Wheel Health Monitoring

4. CONCLUSIONS

This paper has presented an advocacy for the development of micro-GN&C that would involve contributions and coordinated activities of NASA, industry, and academia. An approach has been described for the utilization of new microengineering technologies to achieve major reductions in GN&C mass, size, power, and costs to meet the needs of future space systems. New GN&C system capabilities were shown to arise from component innovations that involve the synergistic use of microminiature sensors and actuators, microelectronics, and fiber optics. Micro-GN&C system and component concepts were defined that include micro-actuated adaptive optics, micromachined inertial sensors, fiber-optic data nets with light-power transmission, and VLSI microcomputers. The thesis is advanced that these micro-miniaturization products are capable of having a revolutionary impact on space missions and systems, and that GN&C is the pathfinder micro-technology application that can bring that about.

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