The Application of Micromachined Sensors to Manned Space Systems

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Abstract

Micromachined sensors promise significant system advantages to manned space vehicles. Vehicle Health Monitoring (VHM) is a critical need for most future space systems. Micromachined sensors play a significant role in advancing the application of VHM in future space vehicles. This paper addresses the requirements that future VHM systems place on micromachined sensors such as: system integration, performance, size, weight, power, redundancy, reliability and fault tolerance. Current uses of micromachined sensors in commercial, military and space systems are used to document advantages that are gained and lessons learned. Based on these successes, the future use of micromachined sensors in space programs is discussed in terms of future directions and issues that need to be addressed such as how commercial and military sensors can meet future space system requirements.

Introduction

The application of smart micromachined sensors to vehicle health management VHM is the focus of this paper. The paper presents examples of how smart micromachined sensors have been applied to VHM. Future uses of micromachine sensors are then discussed.

The VHM Requirements

The focus of VHM is to ensure that the system under management is available for mission use at scheduled times and has the ability to 'stay on course' during its mission. The requirements for manned launch systems include a high degree of operational readiness, efficient/automated ground servicing and inspection operations as well as a great deal of near real-time decision making and reaction capability to avert mission threatening events. Manned transfer/rescue vehicles pose additional requirements because they may remain in a dormant state for years, only to have operate normally on demand.

Studies are now deriving microsensor requirements from these large system level requirements[1 2 3 4 5 6]. Figure 1 represents one such derivation that is based on health management of the man-ratable NLS. Notice that from the system level requirements for reliability, distributed test and fault isolation, maintainability, autonomy, and low cost come microsensor requirements for data recording and formatting, time stamping, threshold detection, significant event detection, local data qualification, local processing, communication and fault detection.

Examples of Microsystems for Vehicle Health Monitoring

The following are three examples of complete Health Monitoring microsystems that combine the micromachined sensors with the signal processing, health monitoring data analysis, data reduction and data recording functions for failure analysis. The extremely small size and very low power requirements of these microsystems allow comprehensive vehicle health monitoring in applications where it was previously impossible or impractical. In a VHM application these microsystems, with the micromachined sensors in them, would be distributed throughout the manned space system.

Micro Time Stress Measurement Device

An example of a VHM microsystem is the Micro Time Stress Measurement Device (Micro TSMD)[7 8]. The Micro-TSMD is an integrated diagnostic system for embedding into electronic systems. It is packaged as a 1" x 2" x 0.2" hybrid. The Micro TSMD senses and records vibration, shock, temperature, voltage transients, and DC voltage stress events. These forms of external stresses can be correlated to system failures. This approach is key to solving persistent problems and "cannot duplicate" failures that are externally caused. Once failure causing environments are characterized the data can be used for prognostics of systems in use or dormant.

A photo and block diagram of the Micro TSMD is shown in figure 2. An internal micromachined accelerometer senses vibration and shock. An internal microcomputer processes the data. The stress data is time-tagged and histograms recorded for lifetime exposure. In the case of vibration, a fast-Fourier transform (FFT) is performed on the data, saving accumulated time exposure at different frequencies and energy combinations of vibration.

The Micro TSMD, developed under an Air Force contract, is targeted for avionics at the Line Replaceable Unit level, but its use is appropriate in any high-integrity, complex electronics system.

Environment Stress Monitoring Device

A Health Monitoring microsystem similar to the Micro TSMD is the Environmental Stress Monitoring Device (ESMD). The ESMD is smaller than the Micro TSMD and is designed to monitor at the module level. The ESMD is a hybrid ceramic 0.9". x 0.9 "in size (see figure 3). This ceramic can be used in a number of different application specific packages with micromachined sensors. The ESMD performs the sensor signal processing, data processing, and data storage. The device is suitable for placing in standard hybrid packaging and mounting on a circuit card assembly (CCA) or in a small stand-alone box customized for the user's application. The collected data is read out via a serial bus. A block diagram of the ESMD is shown on figure 3.

The ESMD requires no external components to monitor temperature, voltage transients and DC voltage. These sensing functions are designed into the ESMD In addition to these parameters the ESMD has seven analog inputs that can interface to many types of external sensors: temperature, humidity, corrosion, air flow, EMI detectors, strain gauges, electrochemical sensors, magnetic field, and electric current. Signals are multiplexed in the ESMD into a 10-bit analog-to-digital (A/D) converter with 4-V reference. To collect data from a specific external sensor, an embedded software modification would be prepared to scale and histogram the data recording.

Reliability Assessment Tool

A more general purpose health monitoring microsystem is the Reliability Assessment Tool (RAT). The module is only 2"x 3"x 0.5" in size. A photo and block diagram is shown on figure 4. The RAT is currently in development at Honeywell under an Air Force contract. The base line RAT will monitor three channels of vibration (continuously performing FFTs), temperature and electric power quality of the system being monitored. Additional sensors such as humidity, corrosion, air flow, EMI detectors, strain gauges, electrochemical sensors, magnetic field, and electric current can be used with it.

The RAT uses a 16 bit fixed point digital signal processor to preform analysis on three channels of vibration and shock data. This type of information can be used to monitor the health of many forms of mechanical and electrical systems. The health of rotating equipment would be a good example. Vibration spectrums can show the health of bearings or out of specification changes in loads. Three miniature accelerometers are included inside the RATs 2" x 3" x 0.5" package. Remote accelerometers can also be used. In addition to these sensors the baseline device has internal and external temperature sensors and the ability to capture the peak of voltage transients. It captures positive or negative voltage transients for two channels. This would be used to monitor power quality of a system being monitored. It also multiplexes in 4 general purpose analog signals. Two of these channels are used for temperature sensing in the package. One is connected to the case and the other is isolated from the case to measure ambient temperature.

In order to achieve this level of miniaturization Honeywell has developed a mixed signal CMOS IC which places all the analog and digital interface functions required for the sensors on to one chip. This IC can interface to three vibration sensors inside the package or three vibration sensors outside. These vibration signals are filtered to prevent alising errors and have a peak hold circuit to capture mechanical shock peaks.

Future Micromachined Sensors for VHM

The examples of Microsystems for Vehicle Health Monitoring presented above focuses on vibration, shock, and temperature sensors. These sensors are most often required for health monitoring applications. Beyond acceleration and temperature are a range of other sensors which are more systems specific. The following is a discussion of these parameters and their sensors.

Air Flow—The absence of proper air flow for cooling can cause failure due to over heating. In addition various stages of the environmental control and life support system should be monitored for proper correct flow. Honeywell has developed micromachined silicon airflow sensors[9]. These sensors operate as a hot thin film microanemometer. Their small size and long term stability make them ideal for use as a monitor in manned space applications.

Infrared Radiation—Placing temperature sensors on large systems of interest could be a problem due to cost, configuration management, interference with operation etc. Temperature can be remotely monitored with IR radiation sensing. Honeywell has developed an uncooled IR imaging array using an array of micromachined microbolometers[10]. These uncooled IR cameras could be used much like CCD video cameras to observe the IR radiation from a complete system. Less than a tenth of degree C resolution is possible.

Current—Current is a system parameter that identifies a problem's cause or source. An example would be IC failure leading to latchup, causing excessive current flow. Current spikes indicating arcing can occur in a traveling wave tube[11]. The spectrum of the current waveform of an electric actuator can be used to show degradation of the actuator. An integrated magnetic field sensor can sense the current without decreasing reliability by, adding another component electrically connected in the system. A hall-effect IC or one with a magnetoresistive thin film could be used.

Electrostatic Discharge—Electrostatic discharge can cause failure in the I/O circuits of microcircuit device by causing breakdown in the oxide insulation. Microsensors for ESD have been developed to show one time occurrences of ESD events (Zero Corp.). Interfaced to a health monitoring system the time and frequency of events can be recorded. With this information potentially damaged equipment can be identified and action can be taken to prevent further ESD.

Pressure—Examples of problems associated with pressurized systems include leakage of gases or fluids from sealed enclosures, rupture of sealed container, changes in properties of low-density materials, overheating due to reduced heat transfer, evaporation of lubricants, failure of hermetic seals and malfunction of equipment due to arcing. This is of key concern to systems that are dormant for many years. Micromachined silicon pressure sensors can be packaged in a small enough form to be embedded into systems to monitor their readiness.

Humidity—Moisture can cause physical and chemical deterioration of material. Temperature changes and humidity may cause condensation inside of equipment. Typical problems that can result from exposure to a warm, humid environment include swelling of materials due to moisture absorption, loss of physical strength, changes in mechanical properties, degradation of mechanical and thermal properties in insulating materials, electrical shorts due to condensation, binding of moving parts due to corrosion or fouling of lubricants, oxidation and/or galvanic corrosion of metals, loss of plasticity, accelerated biological activity, and deterioration of hydroscopic materials. Different types of integrated humidity sensors exist that would be applicable to health monitoring. The small size of integrated humidity sensor makes it possible to embedded them into the systems.

EMI— The presence of large amounts EMI can cause unexplained electronic system failures. Miniature broadband antennas and receivers can distributed in a system and made part of the health monitoring system. A failure can be correlated to a change in the local EMI. Action can then be taken to solve the problem.

Microcracks—Structural failure can be detected by monitoring of the acoustic emission caused by microcracks. Miniature smart acoustic emission sensors can be distributed through key structural components. The acoustic emission sensors can identify microcrack acoustic emissions. Recent Honeywell work has investigated using a micromachined sensor with a fiber optic interface to detect microcracks[12]. The health monitoring system would identify when the number of events reach an unacceptable threshold.

Microgravity - The quality of the microgravity environment can be considered important to health monitoring if the mission is performing microgravity experiments. Honeywell has twice flown on the shuttle a microgravity monitoring sensor[13]. This has been used with microgravity processing experiments to record the environment during the processing steps.

Single Event Upset (SEU)- SEU is a transient radiation effect. SEU is of concern for any space mission. An ionized atom can pass through an integrated circuit causing the state of digital data to change. The frequency of this occurring can change with solar activity, orbit or changes in equipment placement. A measure of SEU activity can be a useful input to the health monitoring system. RAM memories with known SEU sensitivities can be used as sensors.

Chemical Contaminants—Chemicals can cause many diverse failures in mechanical and electronics systems. These problems include corrosion of electronic or mechanical components or the contamination of parts of the crew systems. Salt Fog is a specific subset of chemical contamination. The effects of exposure of materials to an environment where there is an aqueous salt environment can be divided into corrosion, electrical, and physical effects. The effects include impairment of electrical equipment due to salt deposits, production of conductive coatings, corrosion of insulating materials and metals, clogging of moving parts, blistering of coatings, and formation of acidic/alkaline solutions. There are a wide variety of ways to sense different forms of chemical contamination. Micro versions of the sensors that measure the presence of chemicals are being developed by many sources. Recent work has used these types of sensors to detect the presence of a corrosive environment instead of the after effects[14 15].

Conclusion

This paper has presented examples of microsystems that use micromachine sensors for Vehicle Health Monitoring. Examples of VHM sensor needs for air flow, IR, electric current, ESD, Pressure, Humidity, EMI, Microcracks, SEU and Chemical Contaminants were also presented.

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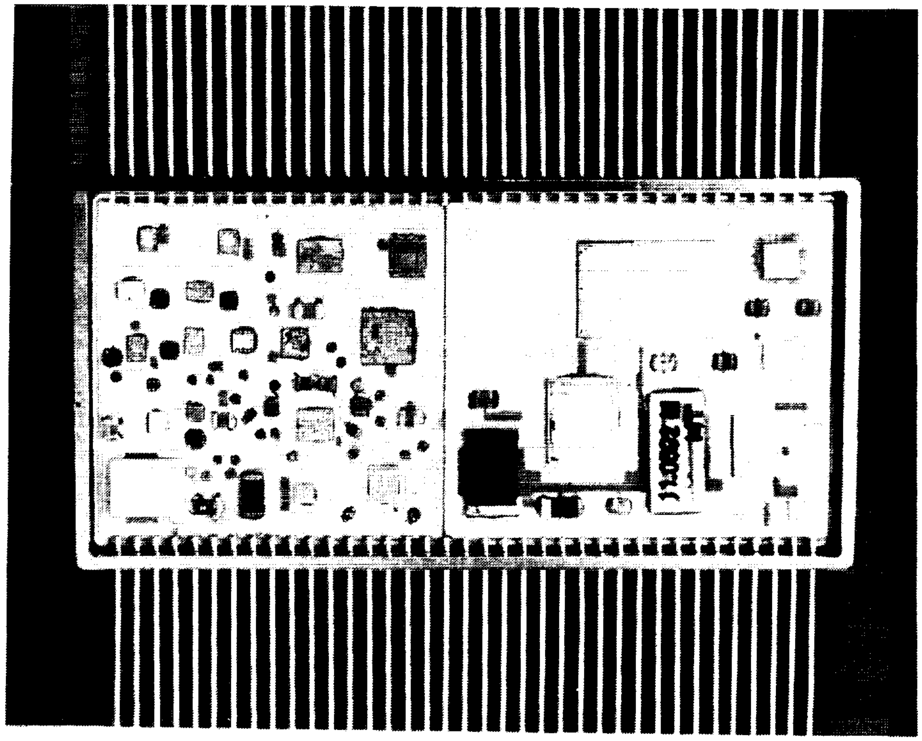
Vehicle Requirements
- Fault avoidance
- Reduced maintenance on schedule/demand

System Requirements
- Automated checkout
- Real-time monitoring
- Integrated maintenance
- Fault prognosis/diagnosis
- Information management and control

Subsystem Requirements
- Remaining life measurements
- Fault prediction, detection, isolation
- Redundancy management
- Local data
- Local data management and control
- Timestamping of events

Smart Sensor
- Fault detection isolation
- Self-test
- Local data acquisition, filtering and processing/ health status assessment
- Timestamping of data

Figure 1 Derivation of smart micromachined sensors requirements for VHM



The internal accelerometer is in the lower left-hand corner.

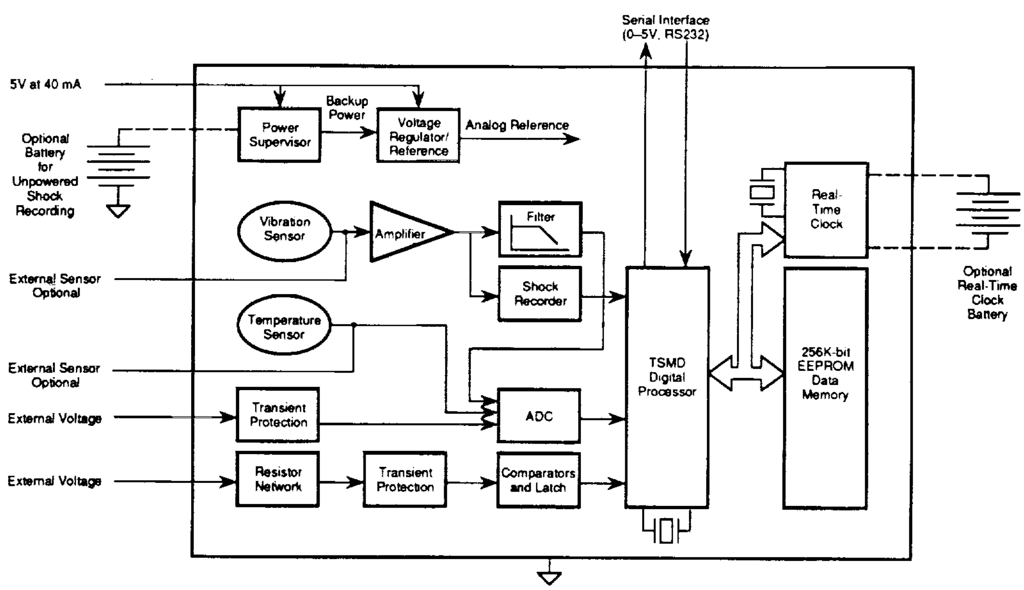
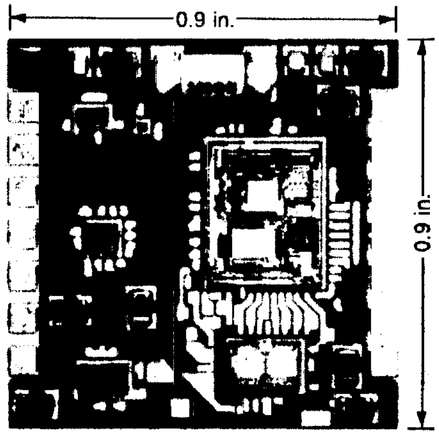


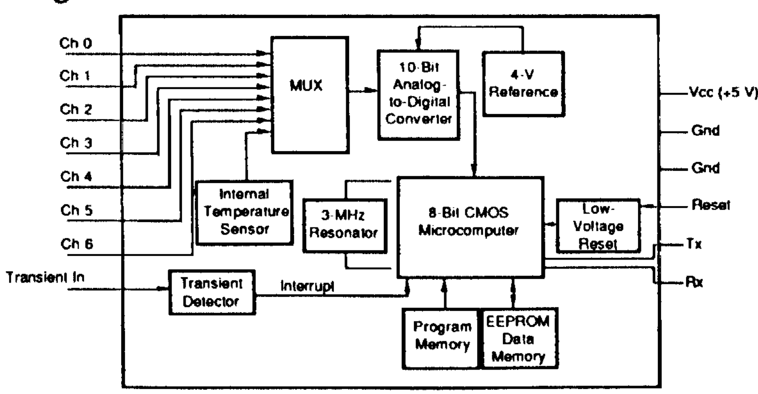
Figure 2 Micro-Time Stress Measurement Device photo and block diagram

Environment Stress Monitoring Device (ESMD)

Photo of ESMD



ESMD Block Diagram



A low-cost device to accumulate long-term histories of failures that cause stress on an electronic system

Baseline Software Recording Functions

- Elapsed "power on" time monitor, (1-min resolution)
- Number of on/off cycles
- Temperature for the last 250 samples (samples selectable from 1–255 min)
- Temperature histogram (5°C bins)
- Temperature cycle histogram
- Voltage transient counter
- Temperature during voltage transient

Examples of Possible External Sensors

- Humidity
- Corrosion
- Strain gauges
- Air flow
- ESD
- Mechanical shock
- Current (dc and transients)

Applications

- Electronic assemblies
- Warranty verification
- Intrusion monitoring
- Product development testing
- Process trend monitoring
- Shipment monitoring
- Waste storage monitoring
- Equipment usage monitoring

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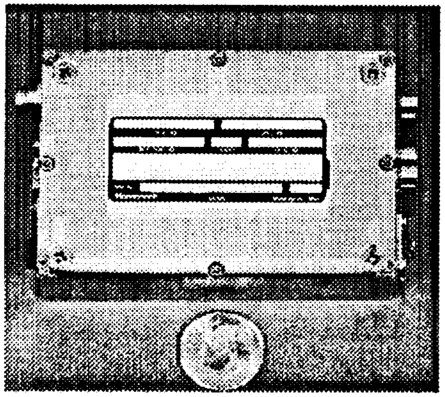
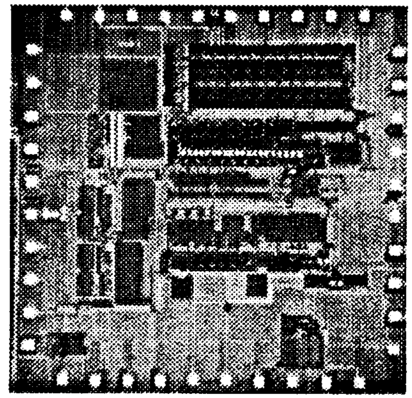
Figure 3 Environmental Stress Monitoring Device

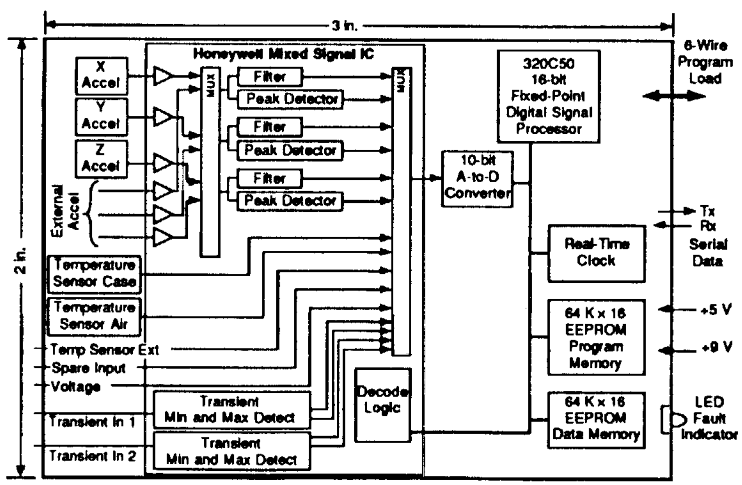
Vehicle Health Monitoring Microsystem with Internal Digital Signal Processor



Vehicle Health Monitoring Microsystem



Honeywell-Designed Custom CMOS Mixed Signal IC for Sensor Interfacing



Block Diagram

Function

Monitors 3-axis vibration, shock, temperature, voltage and voltage transient conditions of a system and can record a time history

Features

- Small size–2" x 3" x .05"
- Two internal temperatures
- Internal 3-axis vibration sensors
- 2-voltage transient detect
- 10-bit A to D converter
- 16-bit fixed point digital signal processor
- Nonvolatile data memory
- Real-time clock
- Serial interface

Applications

- System health monitoring
- System evaluation tests

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Figure 4 Reliability Assessment Tool

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