PACKAGING AND QUALIFICATION OF MEMS-BASED SPACE SYSTEMS

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ABSTRACT

The number of spacecraft designed and built over the next century will grow exponentially as communication satellite networks proliferate and NASA continues to push towards the development of many microspacecraft to replace its traditional "grand tour" crafts. Since costs in the space industry are measured in terms of weight (dollars per pound launched) and reliability, unit costs pale in comparison to launch costs and the cost of replacing an entire vehicle in the case of a catastrophic failure. Space systems present a unique application for microelectromechanical systems (MEMS) technology. MEMS technology can be applied to miniaturize many of the. subsystems in a space vehicle, and can improve overall reliability.

This paper will identify potential applications of MEMS in a space system, describe space environmental factors, and review efforts to develop appropriate packaging and space qualification methodologies. Finally, a flight experiment for testing the performance of typical MEMS devices and packages in the space environment will be described.

INTRODUCTION

Many fores of MEMS devices have been proposed for application to space systems in order to realize reduction in size, weight, and power consumption at the component level [1,2]. At the same time, significant issues remain to be examined that have critical influence upon the viability of MEMS devices for space. As a new technology, each individual MEMS device will need to go through some kind of a space qualification process to ensure its reliability and compatibility with the space environment. It is not clear, however, that the traditional qualification methods are applicable to MEMS, and in general these methods are perceived as far too costly. New approaches need to be developed for devices and packages.

The availability of miniature components have caused a shift in the way spacecraft are architected and designed. The traditional architecture involves a spacecraft bus connecting subsystems which themselves consist of individual packaged components. The new architecture aims at eliminating at least one of these levels of integration by packaging entire subsystems as highly integrated components, eliminating the spacecraft bus entirely in favor of a distributed architecture or integrating active components with structural elements.

Ensuring the reduction of life-cycle (i.e., development, qualification, integration, launch, and operation) cost is critical for justification of using MEMS on spacecraft Incremental reduction in total system mass to reduce launch costs is not a sufficient reason. There are conventional technologies that are miniature and space qualified (for example, the 25g Litton G2000 and the 77g AlliedSignal Minitact provide a 2 axis rate sensing in a hermetic, military-qualified package [3]). The advantage of MEMS lies in the ability to package many devices and their support electronics on a common substrate, significantly reducing mass, power and thermal control requirements of an entire subsystem.

Space qualification processes of such integrated modules will rely heavily on processes developed for microelectronics and multi-chip modules (MCMs). However, MEMS have a different set of failure modes requiring unique analyses and tests. Early flight demonstration will be critical for the reduction of qualification costs.

SPACE APPLICATIONS

MEMS sensors and actuators are most commonly considered in the context of either science instruments or inertial guidance, although they can potentially impact spacecraft subsystems such as propulsion, state-of-health monitoring, or active mechanical and thermal control structures.

Payload Sensors. Science sensors typically fall into one of two categories, remote sensors (for planetary or astronomical observation at a distance) and *in-situ* sensors (which measure the. physical environment surrounding the. sensor, including particles and fields). MEMS-based remote sensor elements might include infrared focal planes (bolometers, thermopiles, or

Golay cells), spectrometers (Fabry-Perot interferometers or gratings), shutters and filters (including microwave filters and resonators), pointing and steering devices, or adaptive optical elements. The typical remote sensing platform requires a large aperture, precision pointing and guidance, and the ability to process and transmit large amounts of data. In the foreseeable future, it is unlikely that such platforms will weigh less than 50 kg independent of the MEMS contribution, and the case of MEMS must be made primarily based on performance.

In situ sensors, on the other hand, are often deployed in remote environments under severe mass and power constraints. Since the sensor measures only a very local environment, there is typically an advantage to deploying large number of sensors. Incorporation of MEMS is usually justifiable simply on the basis of size, mass, power consumption, and cost. These sensors cover the entire scope of physical and chemical phenomena involved in the analysis of liquids, solids, gases, plasmas, or fields in free space. A comprehensive review is well beyond the scope of this paper, except to point out that small (<1 kg) autonomous scientific instruments with communication, data handling, power, and rudimentary mobility (the ability to be remotely deployed and to acquire samples) can revolutionize the study of planetary surfaces. Several small instruments are currently being developed, including miniature penetrators deployed directly from space, and tiny robotic rovers.

Guidance Sensors. Spacecraft attitude (orientation in free space) and position can be determined inertially, optically or by using known fields. A combination of these methods may be needed depending on the various mission phases. Inertial sensors include accelerometers with performance requirements of 1 µg for 0.1-300 Hz and gyroscopes with better than 1°/hr drift rate. Optically, attitude can be determined using star trackers with pitch/yaw accuracy better than 1 arc-sec and roll better than 10 arc-sec, and sun and horizon detectors with better than 1° accuracy. Finally, in satellites orbiting the earth, attitude can be determined using magnetometers with a 0.5-3° accuracy [4]. The goal is to integrate these into a single electronic package, similar to the packages used for the spacecraft's processor and memory, that can then be integrated into the main computer.

Propulsion. The attitude control of deep space vehicles and the orbit maintenance of satellites are traditionally accomplished by propulsive systems. There are two types of propulsion systems, electric and chemical. The simplest system would be based on a cold gas propellant, yet the implementation of MEMS in such a system does not seem like a reasonable goal at this point due to the high leakage rates in microvalves. Assuming that no more than 10% of the propellant can be lost during a 5 year mission, the required leakage rate cannot exceed 10^{-6} scc/sec for gas stored at greater than 1000 psi and working against vacuum [5]. Fluid flow controllers are still needed for propellants stored as liquids or solids. Even then issues still remain regarding propulsive efficiency of the system due to the dominance of the boundary layer and device survivability during thruster burns when flame temperatures are in the 1000°C range. Several micropropulsion system concepts for ion and chemical thrusters are currently being developed [5,6], however, major advantages over conventional technologies (such as Moog's 7g cold gas thruster/valve unit) will only be realized when many MEMS devices are arrayed and entire systems (tank, valves, thrusters) are integrated in a single compact unit with minimal transfer of fluid from storage to space.

SPACE ENVIRONMENT

In many respects the space environment is similar to the environment under the hood of an automobile. Unlike cars, spacecraft also experience severe shock and radiation environments. Moreover, the conditions greatly vary in different types of missions and different phases within a single mission. Table 1 presents a comparison of the automotive and space environmental parameters. The space parameters given are for the earth orbiting Space Technology Research Vehicle (STRV-2) mission which will host the MAPLE-2 experiment described later in this paper.

Table 1: The Automotive vs. the Space Environments

Environmental Parameter	**Automotive [7]**	Space **Example: STRV-2 [8]**
Operating Temperature	-40°C to 125 °C	-25°C to + 40°C
Thermal Cycling	> 1,000	**>5,000**
Humidity	Up to 100%	**35% - 60%**
Vibration	15 g, 10 200 Hz	Up to 0.4 g, 20-2000 Hz
EMI Protection	Up to 200 V/m	Up to 70 V/m
Shock	N/A	20 g, 100 Hz. 2000 g, 2 - 10 kHz
Radiation	N/A	10^6 rads/year
Depressurization	N/A	1 atm to vacuum at 1psi/sec

Delicate devices can be easily protected during the harsh launch phase by delaying power up until the end of the phase. Stops and other temporary means can also be used for additional protection. Such protection can not be used during a pyrotechnic separation event usually used for deployment or separation of various on board components. Traditionally, this shock has been attenuated through the various joints that separate the pyro device from other sensitive components, but as spacecraft shrink in size, the number of joints is reduced significantly increasing the. impact of the shock experienced by microdevices. Each shock presents an opportunity for an interconnect to fail or for a microcrack to form in the inheritantly stressed micro structure [9]. Such cracks can grow slowly and eventually lead to failure [10]. A typical shock response spectrum resulting from a small separation nut commonly used in space is shown in Figure 1.

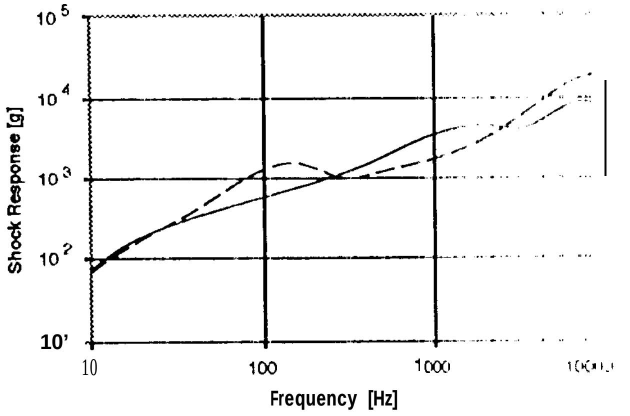

Figure 1: Shock response spectrum 1 foot away from separation nut. Dashed line presents response parallel to the line of separation, solid line presents the response at a 90° angle

The severe radiation environment in space causes various effects on microelectronic systems. Expected radiation levels for earth orbiters, measured in rads (1 rad = 6.25×10^7 MeV), vary with altitude and can reach up to 10^7 rads per year [11]. The total radiation dose is due to trapped radiation belts where electrons and protons are present, solar flares causing increase in heavy charged particles and galactic cosmic rays carrying high energy charged particles. The radiation issue is complicated by the fact that it is statistical in nature and that variation in dosage rate, along with total dose, cause different effects. The result of a recent paper showing enhanced damage at a lower dose rate raises a concern with the traditional radiation testing method of bombarding devices with particle at a high rate to accelerate life. [12]. The various types of radiation effects may impact prospective MEMS devices in up to three ways:

1. On-board analog and digital microelectronics, co-fabricated with the MEMS devices;
2. At the. transition points where MEMS sensors convert a particular form of energy to electrical energy or MEMS actuators convert electric.al energy to another form; and
3. Within the. MEMS device itself.

Table 2 presents the expected physical impact of each type of damage caused by radiation [13]. Proper packaging to protect devices from these effects may prove to be much heavier than the device. itself. However, proper design of devices and choice of materials can mitigate the risk of failure associated with these effects.

Table 2: Potential Impact on MEMS Due to Radiation

Radiation Effect	Physical Impact
Ionization damage (electrons, protons)	Charge trappings, interface state”-growth at oxide-silicon interfaces
Single Event Upset (protons, galactic cosmic rays)	Deposition of electron-hole pairs by single particle -- current pulse
Single Event Latchup (protons, galactic cosmic rays)	Localized, self-sustaining high current condition in semiconductor materials
Single Event Hard Error (protons. galactic cosmic rays)	Localized charge deposition results in permanent effect -- “microdose”, rapture
Single Event Burnout (galactic cosmic rays)	Single particle-induces collapse of large voltage across thin oxide
Displacement Damage (neutrons, protons)	Displacement of lattice atoms; minority carrier lifetime, doping level effects

PACKAGING AND QUALIFICATION

Packaging techniques for MEMS borrow heavily from those developed for microelectronics. Similarities include hermeticity and chip-level integration techniques such as MCMs; differences include a unique set of failure modes due to the mechanical nature of MEMS that are still not very well understood It is difficult to develop cost-effective qualification techniques when dedicated modeling and simulation tools are not yet available and no complete understanding of when and how macro scale laws break down.

Packaging for Reliability. Most packaging systems for space parts are hermetic due to a perceived increase in reliability, and to minimize the potential outgassing of materials otherwise encased in a hermetic enclosure. The latter concern is more relevant for contemporary spacecraft, since outgassing products that might evolve from polymeric materials could redeposit onto undesired surfaces, such as optics, solar cells, and instruments. By employing more advanced two and three-dimensional packaging approaches, a systematic reduction in the surface area that might contribute to outgassing can be achieved, since 10-100 times volume reductions in the total ensemble of circuit components and their associated connectors, boards, and harnesses may be realized. The latter (non-component-related packaging elements) create a large outgassing product control problem. Connectors and the associated cables, each of which contain polymeric material, can be reduced through advanced packaging. As such, the outgassing from level one packaging may be more than compensated by the systematic reduction throughout the packaging hierarchy.

Far from making a case for abandoning hermeticity, the balance of trade-offs suggest a careful consideration of factors. Simple edicts such as "no plastic packaging allowed" seem expedient, but may be short-sighted as a component selection strategy, as it may preclude the most promising options. New packaging approaches, of course, and new technologies in general require a certain level of understanding regarding system level reliability.

Space Qualification. Verifying reliability usually involves understanding failure modes in a hierarchical sense and establishing a means of systematically eliminating their occurrence in particular assemblies over a desired product and mission life. The understanding of failure modes can be very involved, and is usually based on a previous understanding of similar assemblies or elements. As such, new technologies create stress, as they require considerations beyond those associated with more conventional assemblies. Once the most important failure modes are identified they are reconciled against the likely environmental conditions associated the with mission or product life. If such a reconciliation cannot be satisfactorily performed, then the technology must be improved, disqualified, or its expected lifetime environmental conditions must be adjusted. From this point, an attempt is usually made to establish test methods that would aggravate any real failure modes if possible by subjecting assemblies or elements to similar conditions, usually in some "accelerated" or more intense manner. These screens may then be applied to each assembly or element.

in practice, developers apply sets of test methods, chosen as though from a palette, with one of the largest "palettes" being documents, such as the military standard MIL-STD-883. New technologies create stress by forcing developer to consider a choice of the set of test methods or the "palette" itself. To avoid the real work implied by developing such a qualification approach, it has often been the habit of space systems designers to simply insist upon compliance to a pre-ordained set of test methods in blanket fashion, such as prescribed by documents like. MIL-H-38534 (general qualifications of hybrid microcircuits), which has recently been evolving to reflect more. contemporary qualification approaches. Certainly the older compliance documents were reinforced by similarities across a great many monolithic integrated circuit or "chip-and-wire" hybrid processes. The advent of newer MCM, three-dimensional packaging, and MEMS technologies possess traits which do permit casual simplification of the reliability evaluation and assurance processes. Rather, more flexible compliance strategies are required, such as qualified manufacturers' line (QML) approaches, which not only allow for board-mediated adjustment of reliability determinations to occur in a continuous manner, but focus on the quality of the process through which assemblies are created, instead of relying on the results of the screens alone. In some cases, QML permits screens to be eliminated partially or completely.

FLIGHT EXPERIMENT

The lack of flight heritage is a major impediment to the. use of MEMS devices in space. While ground testing and other qualification techniques can assure the reliability of a device or an assembly, its space "worthiness" is not proven until it has flown in space. An early flight demonstration of a MEMS package is currently being developed cooperatively by Phillips Laboratory (PL) and the Jet Propulsion Laboratory (JPL). It is designed to fit in the electronics testbed on board the Space Technology Research Vehicle-2 (STRV-2, a joint U.K./U.S. mission) with its highly elliptical orbit, providing an unusual opportunity to explore the impact of harsh space environmental effects.

The experiment, Microsystems and Packaging for Low Power Electronics II (MAPLE-2), includes the integration of three Analog Devices ADXL02, three ADXL05 microaccelerometers, and a single tunneling microaccelerometer developed at JPL, [14]. The sensors are hosted by a low-mass (<1.5 lbs.), low-power (< 1.5 W) package that has a microcontroller-based data acquisition system. The experimental configuration provides in-situ monitoring capability for operating the accelerometers in a self-test mode, as projected satellite on-orbit accelerations may fall below measurement resolution.

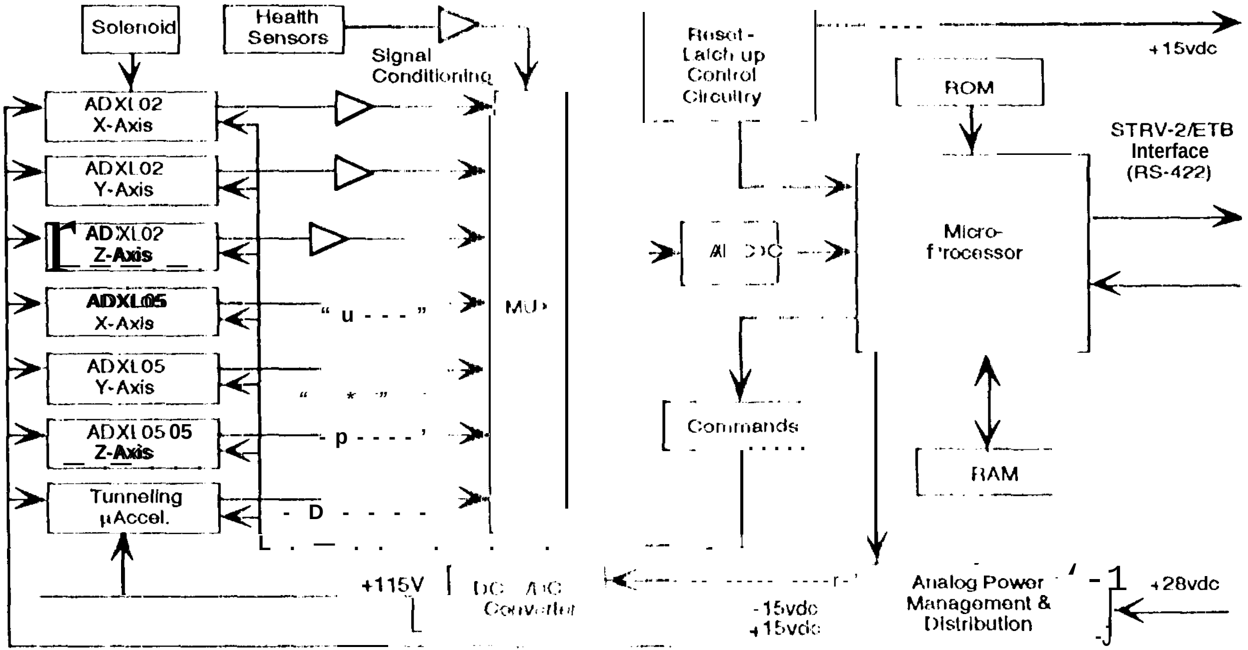

Figure 3: Schematic diagram of the MAPLE-2 flight experiment.

MAPLE-2's purpose is to evaluate the performance of commercial capacitive accelerometers and a tunneling accelerometer in the harsh space environment. It is expected to experience more than 5,000 thermal cycles, each correlating with a 90-minute orbital period. Temperature extremes are expected to be -25°C and +40°C and maximum total radiation dose is projected at upwards of 50,000 rads.

The MAPLE-2 block diagram is shown in Figure 3. Power conversion of a single 28 VDC input to 5, ±15 V, and +115 V is performed with custom conversion circuitry. The sensed accelerations of each accelerometer are scaled and multiplexed to an Analog Devices AD7572 12-bit analog-to digital converter (ADC), chosen based on recommendations by the manufacturer as a low-power ADC that had been found in one customer test to be tolerant to 15 25 krad total dose. The central processor in this case is a radiation hardened 8051 "clone," which operates from a hardened 2Kx8 Harris PROM and 8Kx8 hardened SRAM (based on a defunct TI SIMOX process). Other small scale analog and digital components were judiciously selected based on availability in a tested hard format.

Since the STRV-2 acceleration environment is projected to be nominally very low once the satellite is actually on-orbit, an artificial acceleration stimulus is provided to the MEMS devices through an onboard solenoid. The solenoid provides a convenient if not direct means of "injecting" known test impulses that allow performance degradations to be [illegible] accurately assessed. The experiment's timeline includes an initial 180 second warm-up period to permit initial diagnostics and trickle charge the solenoid firing circuitry. Then a solenoid discharge occurs, and all seven accelerometers are monitored for 3 seconds. Next, two 90 second idle/read cycles occur, during which the solenoid fire circuit is recharged and static environment readings are performed. MAPLE then idles until the host controller requests a download of signature information. The completion download signifies the end of the MAPLE experiment cycle, which is to be performed nominally 4 times per 90-min orbital period.

The packaging techniques used in integrating the 7 MEMS devices and support electronics into the 5" by 6" printed wiring board include:

(to be added by Jim)

The following ground tests are planned for the MAPLE-2 experiment:

- (to be added by Jim)
- JPL also has the capability of independently assessing the radiation performance of components through its Co60, Cs161, flash x-ray, and low energy x-ray sources.

SUMMARY

Various MEMS applications for space can potentially provide a significant reduction in size and mass of scientific, remote sensing, and communication space vehicles. While this will reduce the cost of the launch phase, it may not reduce the total life cycle cost. The introduction of a new technology such as MEMS requires appropriate packaging and qualification to ensure reliability in the harsh space environment. This is a costly process that can only be justified for technologies that significantly increase performance or enable new functions not possible with conventional technologies. MEMS can revolutionize the way spacecraft are currently designed and built by enabling new architectures based on *in-situ* sensors, distributed sensors and actuators, and dense electronic packaging. To accelerate the space qualification process, we are conducting ground experiments and developing the first of many flight experiments.

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REFERENCES

[1] Proceedings of the Workshop on Microtechnologies and Applications to Space Systems held at the Jet Propulsion Laboratory 27-28 May 1992, JPL Publication, 93-8, 15 June 1993.

[2] Helvajian, H. and Robinson, E.Y. (eds.), *Micro- and Nanotechnology for Space Systems: An Initial Evaluation*, The Aerospace Corporation Report No. ATR-93(8349)-1, 31 March 1993.

[3] Personal communication with Dr. George Sevaston, Avionic Systems Engineering Section, Jet Propulsion Laboratory, 17 October 1995.

[4] Muller, L., and George, T., "MEMS for Space Applications," *Southern California Chapter of the American Vacuum Society Micromachining Workshop II: Technology & Applications, 27-28* September 1995.

[5] Personal communication with Dr. Juergen Mueller, Advanced Propulsion Technology Group, Jet Propulsion Laboratory, 14 November 1995.

[6] Jansen, S.W., "The Nanosatellite," in *Microengineering Technology for Space Systems* (Helvajian, H., ed.), Aerospace Corporation Report # ATR-95(8168)-2, pp. 214-216, 30 September 1995.

[7] Frank, R., "Sensors for the Automotive Industry," *Sensor Technology and Devices* (Ristic, L., ed.), pp. 380, Artech House, 1994.

[8] Brinza, D., Space Technology Research Vehicle (STRV-2) Interface Control Agreements Document, STRV-2 Doc. #206-310, Version 1.1 (draft), 29 November 1995.

[9] Hu, S.M., "Stress Related Problems in Silicon Technology," *Journal of Applied Physics*, *70 (6)* pp. 53, 15 September 1991.

[10] Brown, S.B., Povirk, G., and Connally, J., "Measurement of Slow Crack Growth in Silicon and Nickel Micromechanical Devices,"

[11] Wertz, J.R., and Larson, W.J. (eds.), *Space Mission Analysis and Design*, pp. 183-193, Kluwer Academic Publishers, 1991.

[12] Johnston, A.H., Rax, B.G., Lee, C.I., "Enhanced Damage in Linear Bipolar Integrated Circuits at Low Dose Rate," *IEEE Transactions on Nuclear Science*, Vol. NS-42, 19 December *1995.*

[13] Personal communication with Dr. Charles Barnes and Dr. Alan Johnston of the Electronic Parts Engineering Section Jet Propulsion Laboratory, October 1995.

[14] Rockstad, H.K., Reynolds, J.K., Tang, T.K., Kenny, T.W., Kaiser, W.J., and Gabrielson, T.B., "A Miniature, High-Sensitivity, Electron Tunneling Accelerometer," *8th International Conference on Solid-State Sensors and Actuators, Eurosensors IX*, 25-29 June 1995.