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Microelectromechanical Systems (MEMS) Technology Integration Into Microspacecraft

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ABSTRACT

The need to significantly reduce the mass, power, and volume of future scientific spacecraft has resulted in an increased interest on the part of NASA in the relatively new technology of microelectromechanical systems (MEMS). In addition to being light, compact and low-power-consuming, MEMS technology offers other advantages to space applications. Chief among these are robust performance with solid-state reliability. In addition, the ability to array many identical MEMS devices allows for very large scale integration (VLSI), fault tolerant, and distributed architectures. These micromachined, chip-level systems have been in the research stage for over a decade and are currently being developed commercially as such terrestrial applications as automotive and biomedical sensors.

Although MEMS technology is promising for space applications, it is relatively immature at this stage. Much work still needs to be done to take MEMS devices from the laboratory to the space environment. While space applications can leverage from the progress achieved by other industries, additional technical work is required to make these devices flight ready. This work includes consideration of such issues as space performance, survivability, and operation as well as space architectures and flight qualification methodologies. This paper identities the issues that, when resolved, would enable the incorporation of MEMS into space systems. It also describes various Jet Propulsion Laboratory (JPL) and JPL-funded activities addressing these issues.

INTRODUCTION

Microelectromechanical systems (MEMS) are mechanical devices manufactured using the same techniques developed for the manufacturing of integrated circuits (ICs). Although most MEMS devices today are fabricated on silicon wafers which makes them relatively simple to integrate with silicon-based control electronics, MEMS are not limited to these materials. Silicon carbide [1], nickel [2], ceramic, and other materials currently being researched may be important as Well .

Recent budgetary constraints in NASA resulted in a need to incorporate "leap-ahead" technologies, such as MEMS, to enable the realization of significantly smaller, lighter, cheaper and more capable spacecraft. MEMS technology can be applied in many of the subsystems on a spacecraft: Guidance sensors (such as microgyros and microaccelerometers), actuators (such as focal plane microactuators), fluid flow controllers (such as microvalves), and health monitoring sensors (such as pressure and temperature microtransducers). Other potential applications include microthrusters and ultra-fine actuated optical elements. These tiny devices and instruments enable not only the replacement of conventional sensors with miniaturized ones, but also new subsystems with unconventional architectures.

As promising as MEMS technologies seem today there remains a significant amount of work, both in basic research and applied areas, required to make them flight ready. In order to integrate MEMS into space systems several key areas need to be addressed. First, an understanding of the impact of the space environment on micromechanical structures and systems should be developed to aid in the design of MEMS for this particular application. 'l'his includes an understanding of material and structural properties as well as possible failure modes. Second, design methods and tools which address space requirements need to be developed and applied. Finally, testing methodology and packaging issues need to be resolved. In parallel with these activities, additional instrument and subsystem concepts utilizing MEMS need to be developed both on paper and in the laboratory.

Ibis paper will focus on identifying areas where further work is needed in order to enable the incorporation of MEMS technologies into microspacecraft. It will also outline ongoing JPL and JPL-sponsored activities in these areas.

LABORATORY TO FLIGHT

Flight qualification of new MEMS components and systems in the traditional sense may not be adequate and will certainly be too costly since this technology has no flight heritage. New approaches to flight qualification are required in order to make this technology feasible for space flight. An example for such a new approach is the Accurate, Cost-Effective Qualification (ACEQ™)

currently Wing developed at JPL for NASA Code Q and ARPA [3]. This approach is designed to identify redundancies and voids among mission requirements, failure modes, and available preventions, analyses and tests. Reducing overlap while continuing to fill the voids will significantly reduce the rigid, costly, technology-independent qualification process currently in place.

To support this type of advanced qualification approach, three primary activities are required:

1. Research leading to a better understanding of basic properties of MEMS materials, structures and devices.

2. Development of more accurate design methodologies and tools.

3. Development of advanced packaging to ensure space survivability.

In parallel with the activities mentioned above, earl y flight demonstrations are needed to gain experience with the integration of MEMS into a flight system, their space operation, and any unanticipated failures.

Understanding of Basic Properties

The paper that initiated the work leading to MEMS devices ("Silicon as a Mechanical Material" by Kurt E. Peterson [4] was published in 1982. During the past 13 years researchers have focused primarily on developing new devices and micromachining processes. The applied segment of this field has great momentum, often leaving basic research issues behind. A good example of this is the fact that the mechanical characteristics and failure modes of thin films manufactured from silicon, polysilicon, and other MEMS materials are still not well understood.

While basic research into materials properties, behavior, and failure modes is currently taking place in academic and industrial research programs, it is not geared towards space applications. Thus it is important to conduct a parallel effort to examine the effects of the space and space-flight environments on MEMS materials and systems. The effects of three specific environments need to be more carefully considered:

Shock. While shock requirements in automotive application arc high (the ADXL50 microaccclerometer manufactured by Analog Devices can withstand 2000 g's in the unpowered state [5]) certain types of space systems arc likely to encounter much higher shocks. For example, the Mars Microlander, an advanced concept currently being proposed at JPL needs to withstand up to 10,000 g's [6]. Also, shocks resulting from pyro events are nearly unavoidable in space. In addition to separation from the launch vehicle and upper stage, some

space systems require additionat deployments during later parts of the mission. For example, the Mars Pathfinder mission (which carries a surface lander) has 80 scheduled pyrotechnic events. Pyro shocks release energy in all three axes and in a large range of frequencies. 'l"he higher the frequency, the higher the shock response. Microstructure, due to their small size, tend to have much higher resonant frequencies than macro structures and thus are immuned to darnage from low frequency (<10 kHz) response. However, the effect of the shock response due to higher frequencies is unknown, In macro scale systems, mechanical joints tend to attenuate the shock response at the higher frequencies [7], yet compact microspacecraft will undoubtedly have far fewer joints and far less distance between the pyro device and on board instruments. Regardless of the impact of the shock on the MEMS device, a jolt of any strength may create subtle changes in its micromechanics. MicroCracks in the material, that may result from successive pyro shocks throughout its life, can change important device characteristics, such as the resonant frequency of thes ystem, thus affecting the performance of the device [2].

Fatigue. While terrestrial applications arc also concerned with fatigue, space systems encounter a combination of effects that may make fatigue a more critical issue. While fatigue was not observed in silicon microstructure tested for 21 consecutive days [8], some space-bound devices and systems need to achieve much longer life-times in the presence of a significant thermal cycling which may accelerate fatigue of the system. Fatigue in materials causes change in dynamic properties of the structural components which in turn affect the dynamics of the device, thus degrading performance.

Radiation. Since MEMS are integrated electro-mechanical devices, all impact on electronics due to radiation still apply. However, it is also conceivable that radiation may affect the mechanics. Research on the effects of radiation on some material properties, such as hardness, have been conducted for a variety of materials [9]. Such change.s could potentiall y affect the characteristics of devices utilizing materials susceptible to such damage thus degrading their performance in the space radiation environment.

While all of these issues are critical to the success of Ml EMS operation in space, none make MEMS inheritantly inadequate for space applications. Designed and packaged properly, MEMS will provide the expected high performance and high reliability in a small and light-weight unit. Basic research into the effects of the space environment and associated failure modes will greatly assist all phases of design, from early conccptu-

alization to the packaging of MEMS for space.

Design Approaches

The difficulty in designing MEMS lies in the strong interaction between mechanics and electronics. One cannot be designed and analyzed without consideration of the response of the other. Short of running mechanical design tools (such as various CAD systems) and circuit simulation tools (such as SPICE) iteratively, no appropriate design tools are commercially available today. As a result, most design issues get resolved in the lab by actually manufacturing the device, testing its functionality, and modifying the design accordingly. However, several universities arc currently working on tools to alleviate this painstaking process. MIT's MEM-CAD, which was just released in a beta test phase, is a good example of such a tool. It combines three-dimensional, multi-energy-domain modeling with circuit simulation of integrated circuits [10]. Additional work will be needed to incorporate space-specific requirements and responses (such as radiation effects) into the design rules and simulation features already available.

Space Survivability and Packaging

The last step in the transition of MEMS from laboratory to flight environment is packaging and testing of the device as an instrument or a subsystem. Since MEMS are chip-level devices, often it would make sense to place thcm in a common package with other die. Multi Chip Modules (MCMs) designed for space application may provide adequate packaging for MEMS. I lowever, since MEMS technology encompasses many types of sensors with different requirements, other types of packages need to be considered. Depending on the failure modes of the individual device, appropriate packaging techniques need to be developed and implemented.

ACTIVITIES IN PROGRESS

In addition to NASA -- which through the "Better, Faster, Cheaper" approach has made a commitment to small and micro spacecraft -- other organizations are activcl y working towards flying MEMS. One of the leaders in this area has been the Aerospace Corporation which in 1993 published a document titled 'Micro- and Nanotechnology for Space Systems: An Initial Evaluation [1 1].' In addition, the biggest investors in the MEMS field, the Advanced Research Projects Agency (ARPA) and the Nationat Science Foundation (NSF), arc also gearing up to put MEMS in space. Recent interest for this application in several universities is accelerating the development of new subsystem concepts and

demonstration flight experience.

At the Jet Propulsion Laboratory (JPL), where the demands for smaller, lower-power devices and subsystems are even more critical due to the tighter mass and power margins available for deep space flight, MEMS technology has bccn specifically pursued for microspacecraft applications, Our activities are focused on developing systems concepts using MEMS, developing MEMS devices, developing an understanding of the impact of the space environment on MEMS and pursuing early flight demonstrations.

System Concepts

Among the system-level concept development efforts currently taking place at JPL are the Second Generation Microspacecraft, the Mars Microlander, and the Free Flying Magnetometer. These concepts all include MEMS sensors to enable their miniature size.

Second Generation Microspacecraft. The Second Generation Microspacecraft (SGM) is a technologically-aggressive concept for a 5.5 kg near-earth object flyby microspacecraft [12]. The SGM project developed spacecraft "building blocks" that can be implemented on an array of deep-space missions with a total wet mass of less than 15 kg. These building blocks include high levels of autonomy and an array of miniature sensors.

Mars Microlander. The Mars Microlander has been proposed as a secondary payload (under the auspices of the New Millennium Program) to the lander on the 1998 Mars Surveyor Spacecraft [6]. Shortly before the separation of the primary lander, the spacecraft will release a miniature microlander that will dive into the Martian atmosphere. The landed mass of 3.5 kg will include a forebody (penetrator) and an aftbody (lander). The lander will support two meteorological microsensors (pressure and temperature) while the penetrator will support an analytical microinstrrrmcnt to detect water at a depth of a meter bclow the Martian surface.

Free Flying Magnetometer. This silver-dollar-size free. flyer will include a micromagnctometer (see below) in addition to readout electronics, analog-to-digital conversion, data storage, power, telemetry and control electronics [13]. Many such spin-stabilized flyers could be released in the vicinity of planets to map their magnetic fields.

New MEMS Devices and Systems

Development of MEMS devices for space science and spacecraft applications is a primary charter of JPL's Microdeviccs Laboratory. Below is a description of several key developments currently being pursued:

Microaccelerometer. The microaccelerometer, shown in Figure 1, is&d on electron tunneling technolog y. It provides 10 to 100 times reduction in self-noise relative to comparable-size microaccelerometers and 50 times reduction in mass relative to comparable noise-floor accelerometers. A single axis accelerometer weighs 1 g and currently provides 10^{-7}g sensitivity [14].
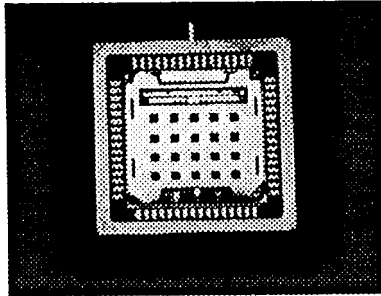

Figure 1: The JPL tunneling accelerometer set inside a pin dip. The tunneling tip is located near the top.

Microgyro. The vibratory microgyro, shown in Figure 2, is a joint JPL/UCLA project [13]. The device weighs 100 mg in a compact 5 cm x 5 cm x 5 cm package (mechanical device dimensions are 1.2 cm x 1.2 cm x 1.2 em). The power consumption is less than 1 W and the performance goat is 1 - 10 deg/hr bias stability.
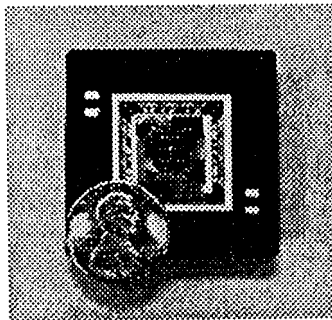

Figure 2: The JPL/UCLA vibratory microgyro relative to the size of a penny. The vibrating elements are the 4 pedals (squares) in the center of the chip.

Infrared Sensor. The IR sensor, shown in Figure 3, is also based on tunneling technology and requires no cooling [13]. The 2 mm x 2 mm active array has a broad-bandwidth and high sensitivity. The theoretical Noise Equivalent Power (NEP) is 6 x 10^{-1}1 W/√Hz and the measured NEP is 3 x 10^{-10} The performance of this sensor is 2-3 times better than the best available pyroelectric sensor,

Micromagnetometer, The tiny magnetometer, shown in Figure 4, can be used as a science instruments as well as a component in an earth orbiting satellite's attitude con-
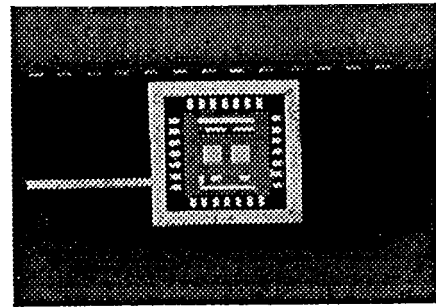

Figure 3: The JPL tunneling infrared sensor.

trol system. It has a predicted 2.5 nT vector sensitivity (for 100 loops) [13]. 'Ibis nanotesla sensitivity is not available in other state-of-the-ti uncooled, small (< 0.01 cm^3), low-power (mW range) magnetometers. A 50 kHz bandwidth, 100 dB dynamic range has already been demonstrated.
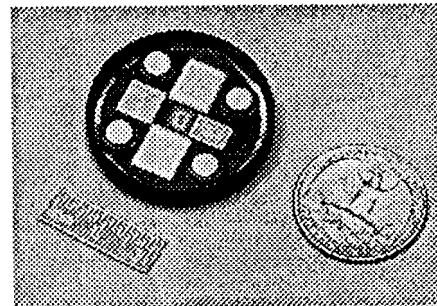

Figure 4: The JPL micromagnetometer shown in the center of the Free Flying Magnetometer prototype.

Micro Weather Station, The micro weather station is a collection of miniat ure sensors that provide in-situ measurements of temperature, pressure, wind speed, humidity and aerosol properties [131. Pressure is determined by measuring the deflection of a thin silicon membrane due to atmospheric pressure working against an evacuated chamber. The deflection of the membrane is measured using a capacitive circuit (as opposed to piezoresistive strain gauges used commercially) and allows for a dynamic range exceeding five orders of magnitude. The temperature measurement is accomplished by a thermocouple producing accuracies of 0.1 °c at temperatures between -70 and 70°c. Wind speed is determined using a single chip laser doppler anemometer. Wind speed accuracies are. as small as 0.1 m/s. Dewpoint is detected by frequency shifts of a surface acoustic wave oscillator coupled to a thermoelectric cooler.

A system concept for the micro weather station is currently under development. Recent efforts have focused on the individual sensor development.

Microseismometer. This 100 g seismometer, shown in Figure 5, performs equally to 5 kg commercial seismometers (10^{-9} g/$\sqrt{\text{Hz}}$ with a 4 Hz bandwidth) [13]. It has an ultra-high frequency capacitance transducer for required resolution and a stiff suspension requiring no adjustment after deployment.
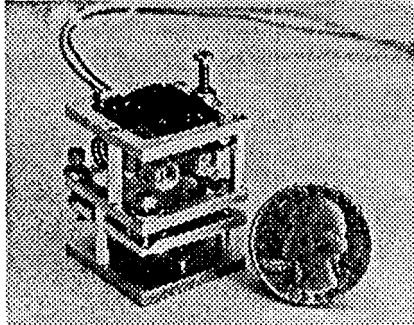

Figure 5: The JPL microseismometer relative to the size of a quarter.

In addition to sensor development, JPL is also exploring other space systems applications of MEMS:

Micropropulsion. The components necessary for a micropropulsion system (such as microvalves, micropumps, micronozzles, and microchannels) are currently being developed primarily for biomedical and laserjet printer applications. JPL is currently supporting an activity to determine the feasibility of electrical and chemical micropropulsion. There are two primary concerns associated with MEMS-based propulsion systems (such as the one conceptualized in [20]). The first is the understanding of microfluidics. Fluids flowing through orifices and channels that are micrometers wide are operating within the boundary layer, and the tools and methodologies" that exist to evaluate fluid dynamics may not be applicable. JPL is currently funding a project at MIT to identify areas where current physical understanding is incomplete or uncertain and where future research and development is **needed** [21]. Examples include fluid-surface effects in MEMS devices, heat transfer and pressure drops in micro-flow systems, and phase changes in microcavities. The second concern is that of hermetic seals. There are many ongoing microvalve development efforts and some microvalves are even available commercially. These microvalves, however, have a high leakage rate. This problem is exacerbated when many such microvalves are arrayed to form a complete micropropulsion system.

Impact of Space Environment

In order to understand the specific failure modes of MEMS resulting from exposure to the space environ-

ment two types of tests need to be conducted, The first is to test materials and basic elements of MEMS and the second is to test completed devices. A recently formed activity at JPL, the MEMS Integration Task, has taken initiative in examining the impact of the space environment on MEMS. The main focus of this task is to test the behavior of basic MEMS elements under harsh environments Several devices currently under development at JPL are also being tested concurrently. The first of such environmental tests, a pyro shock response test, will be conducted at the end of August 1995. Other tests to determine the effects of radiation and thermal cycling, will follow.

For these tests a set of test structures was selected based on a literature survey of various MEMS devices. The basic elements of MEMS are cantilevers (usually on the order of 100 to 1000 μm long), bridges (commonly 300 to 1200 μm long) and membranes (square, 100 to 1000 μm on the side). Resonant frequencies range from 2 to 65 kHz for the first vibrational mode. The cantilevers and bridges are common in most MEMS devices while membranes are common in pressure transducers and fluid flow controllers.

Microstructures cannot be machined without defects, regardless of the fabrication process selected [2]. In addition, internal residual stresses tend to be high, For example, the measured residual stress for polysilicon fabricated using the low-pressure chemical vapor deposition (LPCVD) process is 0.1 - 0.3 GPa [22]. Thus it is important to test for impact of various dynamic environments and to develop a thorough understanding of failures, when they occur, and their effects on the entire system.

For the planned pyro shock test, we are comparing the resonant frequencies of the test structures before and after each shock to determine if microcracks resulted during, any of the three consecutive pyrotechnic events. Even a slight change in resonant frequency caused by microcracks or other forms of damage affect the performance of a MEMS device. The expected shock response spectrum of this testis shown in **Figure 6.** For the sake of comparison, it is plotted alongside the Mars Pathfinder shock response design requirements. Traditional dynamic tests (including the Pathfinder ones) have focused on the 100 to 10,000 Hz range. However, typical MEMS cantilevers, beams and membranes have resonant frequencies much higher than these and may be affected by dynamic responses in that regime.

The goal of this test is to provide designers of space-bound MEMS with a better understanding of the pyre-induced failure modes so that they can incorporate this data early on in their design process. Similar data from the environmental tests will further support this goal.
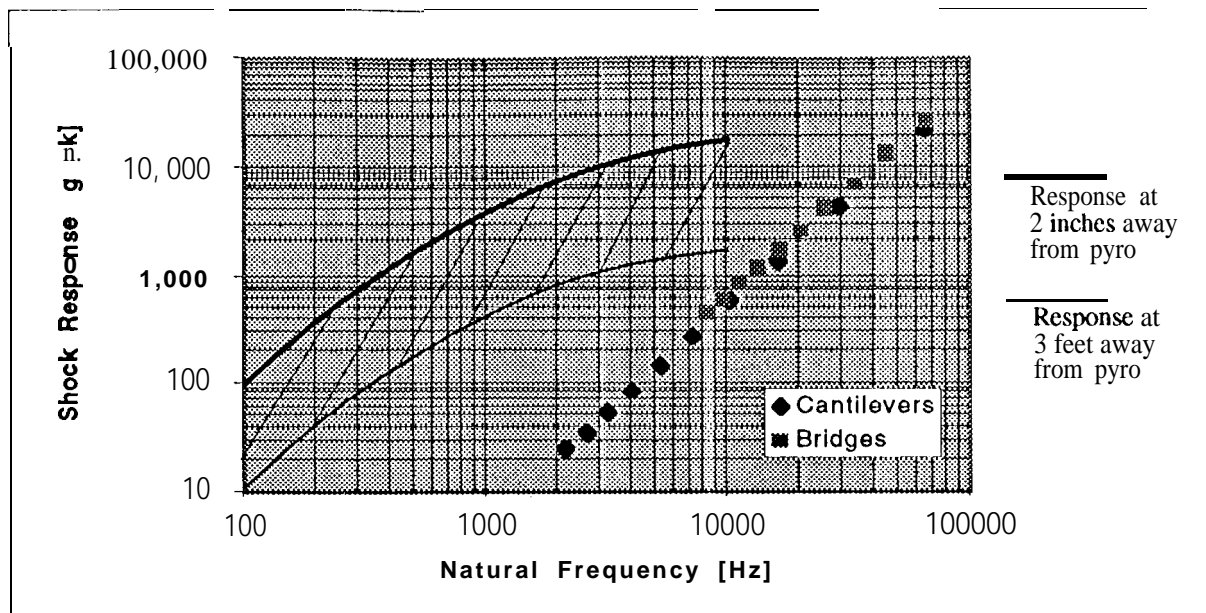
Figure 6: Shock response of test **structures** (calculated) relative to the Mars Path tinder mission design requirements.

Flight Demonstrations

The final step in making MEMS ready for space flight is a demonstration of their operation in space. JPL is currently working towards four such demonstrations:

Stanford OPAL Payload. Under contract from JPL, Stanford is designing a MEMS-based payload for Stanford's second student satellite, OPAL. This payload which includes an array of commercial MEMS sensors will monitor the deployment of the gravity gradient boom on-board the satellite. The off-the-shelf pressure microsensors, microaccelerometers, and micromagnetometers will be tested on the ground and evaluated in space to determine their compatibility with space missions.

Mars **Pathfinder Experiment. A** microgyro experiment has been proposed for an available slot in the Mars Pathfinder spacecraft's VME card cage. The microgym, designed jointly by JPL and UCLA, will be dormant during the cruise phase to Mars and will operate during the Entry, Descent, and Landing (EDL) phase to provide data about the dynamics of the entry vehicle. As a test payload, the microgyro will not be included in Pathfinder's control loop. However, it will provide important data for improved understanding of atmospheric entry dynamics.

STRV-2. The Space Technology Research Vehicle 2, sponsored by BMDO and NASA, includes an electronic test bed for the demonstration and evaluation of advanced electronic technologies. One of the five proposed demonstrations is a joint effort between the Air Force's Phillips Laboratory and JPL to evaluate the performance of two different types of microaccelerometers, Analog Devices' ADXL50 variable capacitance accelerometer [5] and JPL's tunneling accelerometer [14], during a highly-elliptical earth orbit flight.

New **Millennium. The New Millennium Program,** which tentatively includes three deep space flights and two earth orbiters in the. next five years, is committed to implementing revolutionary technology in order to significantly miniaturize spacecraft. Instruments and MEMS are the focus of one of its five Integrated Product Development Teams (IPDTs) which will develop this technology for space, and implement various MEMS on its flight demonstrations.

SUMMARY

Microelectromechanical Systems (MEMS) technology is an exciting and promising new field. There are many possible space system applications for this technology. Many more applications arc still yet to be identified, developed and evaluated. While the commercial MEMS industry (for terrestrial applications) has gained momentum over the past decade, there is considerable work to be done -- both in basic research and applied areas -- to ensure survivability and long-term operability y in space. JPL is currently exploring these issues as well as the development and implementation of advanced MEMS sensors. Space system developers should carefully monitor the developments in this dynamic field as it promises to significantly reduce spacecraft mass, power, and cost,

Acknowledgments

References

[1]   G. Muller, SiC as a New Sensor Material, *Proceedings of (he IEEE Micro Electro Mechanical Systems Workshop (MEMS '93),* Ft. Lauderdale, FL, February 1993.

[2]   S.B. Brown, G. Povirk, J. Connally, Measurement of Slow Crack Growth in Silicon and Nickel Micromechanical Devices, *Proceedings of the IEEE Micro Electro Mechanical Systems Workshop (MEMS '93),* Ft. Lauderdale, FL, February 1993.

[3]   S.L. Comford, P.R. Barela, Accurate, *Cost-Effective Qualification,* JPL Office of Engineering and Mission Assurance (OEMA) Presentation, 16 June 1995.

[4]   K.E. Peterson, Silicon as a Mechanical Material, *Proceedings of the IEEE,* Vol. 70, No. 5, pp. 420-457, May 1982,

[5]   ADXL50 Monolithic Accelerometer with Signal Conditioning, Analog Devices Product Brochure, 16 February 1993.

[6]   Mars Microlander Status Meeting, Jet Propulsion Laboratory Internal Presentation to E. Kane Casani, 15 August 1995.

[7]   Personal Communication with Peter E. Rentz and Harry Himelblau of the Dynamics Environments Group, Jet Propulsion Laboratory, August 1995.

[8]   X.Y. Ye, Z.Y. Zhou, Y. Yang, J.H. Zhang, J. Yao, Determination of the Mechanical Properties of Microstructure, *8th International Conference on Solid-State Sensors and Actuators (Transducers '9.5), and Eurosensors IX,* Stockholm, Sweden, June 1995.

[9]   T. II. Blewitt and T.J. Koppenaal, Irradiation Hardening in Copper and Copper Alloys, *AIME Symposium on Radiation Effect,* Asheville, NC, 1965.

[10] S.D. Senturia, CAD for Microelectromechanical Systems, *8th International Conference on Solid-State Sensors and Actuators (Transducers '9.5), and Eurosensors IX,* Stockholm, Sweden, June 1995.

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

[12] Second Generation Microspacecraft, Final Reports for 1994. JPL Internal document no. D-12645.

Jet Propulsion Laboratory, Pasadena, CA, 1995.

[13] Display of current developments and achievements at the Microdevices Laboratory, Jet Propulsion Laboratory, Pasadena, CA, Ongoing.

[14] H.K. Rockstad, T.W. Kenny, J.K. Reynolds, WJ. Kaiser, A Miniature High-Sensitivity, Broad-Band Accelerometer Based on Electron Tunneling Transducers, *7th International Conference on Solid-Slate Sensors and Actuators (Traducers '93),* Yokohama, Japan, June 1993.

[15] Personal Communication with Tony K. Tang, Jet Propulsion Laboratory, 21 August 1995.

[16] T.W. Kenny, W.J. Kaiser, J.A. Podosek, II.K. Rockstad, J.K. Reynolds, Micromachined Electron Tunneling Infrared Sensors, *Proceedings of the Workshop on Microtechnologies and Applications to Space Systems, 1* Held at the Jet Propulsion Laboratory on May 27 and 28, 1992, JPL Publication No. 93-8, 15 June 1993.

[17] Personal Communication with Linda M. Miller, Jet Propulsion Laboratory, 21 August 1995,

[18] D. Crisp, W.J. Kaiser, T.R. VanZandt, J.E. Tillman, Micro-Sensors for in-situ Meteorological Measurements, *Proceedings of the Workshop on Microtechnologies and Applications to Space Systems,* Held at the Jet Propulsion Laboratory on May 27 and 28, 1992, JPL Publication No. 93-8, 15 June 1993.

[19] W.B. Banerdt, '1'. VanZandt, WJ. Kaiser, T.W. Kenny, A Broad-Band Microseismometer for Planetary Applications, *Proceedings of the Workshop on Microtechnologies and Applications to Space Systems,* Held at the Jet Propulsion Laboratory on May 27 and 28, 1992, JPL Publication No. 93-8, 15 June 1993.

[20] L. Muller, Miniaturization Methodology Applied to Deep Space Microspacecraft, M.S. Thesis, Massachusetts Institute of Technology, May 1994.

[21] K.S. Breuer, MEMS-based Spacecraft Propulsion, a research proposal submitted by MIT to JPL, 20 July 1995.

[22] S.M. Hu, Strms-Related Problems in Silicon Technology, *Journal of Applied Physics,* Vol. 70 (6), 15 September 1991.

Biography

Lilac Muller received her bachelor's and master's degrees from MIT's Department of Aeronautics and Astronautics. She was a technical intern at JPL's Spacecraft Systems Engineering section where she wrote her master's thesis on microspacecraft. Ms. Muller currently works at the JPL's Avionics Systems section and the Microdevices Laboratory to address issues related to MEMS in space.