Invited Paper

MEMS applications in space exploration

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ABSTRACT

Space exploration in the coming century will emphasize cost effectiveness and highly focused mission objectives, which will result in frequent multiple missions that broaden the scope of space science and to validate new technologies on a timely basis. Micro Electro Mechanical Systems (MEMS) is one of the key enabling technology to create cost-effective, ultra-miniaturized, robust, and functionally focused spacecraft for both robotic and human exploration programs. Examples of MEMS devices at various stages of development include microgyroscope, microseismometer, microhygrometer, quadrupole mass spectrometer, and micropropulsion engine. These devices, when proven successful, will serve as models for developing components and systems for new-millennium spacecraft.

Keywords: MEMS, micro, electro, mechanical, systems, space applications, technology, reliability, overview

1. INTRODUCTION

Space exploration has been, and will continue to be, an international enterprise. The activities in the United States, managed by the National Aeronautics and Space Administration (NASA), together with those in Russia, China, Japan, Canada, and many European and other countries, continue to contribute to the expansion of the final frontier. Since space exploration programs have always been high-profile human enterprises with international visibility, there is traditionally very low tolerance for failure due to significant political consequences. As a result, the traditional approach tended to rely heavily on well-proven technology when available, and costly redundancy when new technology must be introduced, to lower the risk of failure. Under intense competition between superpowers to demonstrate grand-scale technology and military mights, budgets for space missions took a very high national priority. But these costly international competitions have given way to concerns for national and international economic issues, grand-scale space missions must also give way to fast, efficient, cost-sensitive approaches that focus on the value of scientific discoveries. Mature but inefficient and inadequate technologies and costly system redundancy must be replaced with new technologies that enable the cost and science objectives of future space missions.

MEMS[1] is a miniature system that contains both electrical and mechanical components with characteristic sizes ranging from nanometers to millimeters. MEMS technology refers to the technology that creates these miniature systems. A great majority of MEMS technologies are based on photolithography used in the IC industry to achieve miniature sizes and to integrate electrical and mechanical components without post-processing assemblies. The term micromachining is sometimes used to refer to MEMS technology. In Europe, this field is more commonly called Micro Systems Technology, while in Japan, Micromachines and MicroRobots are more popular terms. This emerging technology has begun to impact not only research in the micron and sub-micron size regime, but has also been demonstrating its capability for drastic miniaturization, cost reduction, and performance improvement in several commercial products. For example, the use of a micromachined accelerometer has replaced the several mechanical acceleration switches in an airbag deployment system, substantially improving the functionality and lowering the cost of manufacturing. MEMS fabricated microinstruments are also being pursued and used in the human genome project to greatly accelerate the gene sequencing data collection steps. It is safe to assume that similar impact can happen to space exploration when MEMS technology is infused to replace decade old

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approaches. This paper aims at providing an overview of the activities within NASA that strategically apply MEMS technology to enable future space exploration.

2. SPACE EXPLORATION IN THE NEW MILLENNIUM

Space programs in the new millennium will continue to emphasize both robotic exploration and human exploration. Pioneering and discovery missions to distant planets, small bodies, solar probes are most strategically implemented with autonomous or semi-autonomous spacecraft. To perform highly intelligent and thorough investigation in near-Earth space and Mars, as well as to study the possibility of expanding human habitats beyond planet Earth, manned missions are needed. These two categories of space exploration are briefly reviewed in this section.

Robotic Exploration

Robotic space exploration in the next decade will be guided by the new philosophy of frequent and simultaneous missions, each at a drastically reduced cost and development cycle time compared to the traditional approach. For example, the Cassini spacecraft, which will be launched in October 1997 on a mission to Saturn, weights 5,630 kg, carrying 12 scientific experiments on the orbiter and 6 on the probe to the moon Titan. It cost $1.5 billion and 6 years to develop. A significant portion of the mission budget goes into the launch vehicle, which is the world's largest, the Titan IV Centaur (weighing 942,000 kg, 56 m tall). In contrast, the Mars exploration program contains 8 separate launches, 4 to carry landers and 4 for orbiters. Each orbiter or lander takes 2 to 3 years and around $150 million to develop. The total mass of the first orbiter is 1,050 kg, and was launched with a Delta II vehicle (215,000 kg, 38 m tall). Although it is less than 20% the weight of Cassini, it carries 6 scientific instruments. Subsequent Mars missions will be even lighter and smaller, while carrying the same amount of scientific experiments. The total scientific data to be collected from the Mars Exploration program will be significantly more abundant than those from Cassini about Saturn and its moon Titan, while costing less.

Other near- to mid-term robotic exploration missions are planned for Pluto, Jupiter, Europa, solar probe, small body exploration, comet nucleus sample return, and asteroid exploration and sample return. Beyond 2005, potential missions will include Mercury orbiter, Venus laboratory, Mars sample return, Europa lander, Io volcanic observer, Titan organic explorer, Neptune orbiter, and Triton exploration.

In order to meet the objective of cost efficiency, fast development, and frequent and simultaneous missions launches, the following strategies are being adopted. First, each mission is carefully selected to have focused objectives, carrying only several vital scientific experiments. This strategy leads to overall spacecraft size and weight reduction, and thus reducing assembly, handling, facility, and flight testing and qualification costs. It also leads to reduced on-board power requirements and, most significantly, launch vehicle requirement. Second, downlink requirements are minimized to reduce demands on telecommunications and supporting subsystems. Uplink requirements are minimized or completely eliminated by autonomous navigation and pre-programmed mission operation, further reducing demands on telecommunication. Third, invest in large-scale building blocks that can be designed once and then employed in multiple missions. These building blocks will include high capability and flexibility, and will also include advanced technology for miniaturization, performance improvements, and enhanced robustness. MEMS technology promises the potential of enabling miniaturization, autonomy, improved robustness, and increased functionality.

Human Exploration

The enterprise of Human Exploration and Development of Space (HEDS) within NASA has established several important goals for the coming decades, among which are to explore and settle the Solar system and to achieve routine space travel. The immediate challenge to reaching these goals is that the new capabilities that HEDS must provide to enable affordable, long duration manned space missions cannot be met with currently utilized technologies and system architectures. The current approaches are expensive and incompatible with current budget profiles; pose severe constraints on power, mass, and lift capability, are fragile and require redundancy to ensure reliability, and require significant human interaction to perform maintenance. Traditionally, well-proven technology is almost a mandate when implementing space missions that involve human exploration in order to guarantee safety, which has created a major hurdle that prevents new technology infusion. Among the several strategies to lower this hurdle without jeopardizing safety for human exploration, extensive ground testing and computer simulation of system robustness are needed. Also, new technology that has been used in robotic missions can be leveraged to implement human exploration. Among these new technologies, MEMS stands out as the prime enabling technology to meet cost and robustness goals. Several examples of potential use of MEMS for human exploration are in the miniaturization of health and environmental monitoring systems. In-situ instruments such as capillary zone electrophoresis systems, liquid chromatography systems, mass spectrometers, etc. have been demonstrated with drastic size and weight reduction with MEMS technology. These Earth-bound applications can be adapted for space flight verifications and then ultimately designed as part of the life sustaining and environmental monitoring systems.

3. MEMS TECHNOLOGY

The most common fabrication techniques for MEMS include three distinct categories: bulk micromachining[2, 3], surface micromachining[4], and high-aspect-ratio lithography and plating[5] (LIGA, a German acronym for Lithographie, Galvanoformung, Adformung, is commonly used to refer to this technique). The first two are sometimes mixed to create microstructures with specific functions. Integrated on-chip electronics have also been demonstrated for signal conditioning.

Figure 1 outlines the steps of a typical bulk micromachining process, in which anisotropic wet chemical etching is used to create structures from the silicon substrate. Surface micromachining steps are illustrated in Figure 2, where thin films are sequentially deposited and patterned on top of the substrate, with the final removal of the sacrificial layer to release the movable structures. The LIGA technique, in its most generic form, involves X-ray lithography of thick photoresist on conductive substrate, plating through the developed resist, and injection molding with the plated parts (Figure 3). These three techniques are compared and summarized in Table I. In addition, there are other micromachining techniques that have demonstrated usefulness and uniqueness for certain specific applications, such as the micro electro-discharge machining[6] (μEDM), laser micromachining[7], and polymer stereo lithography[8]. The selection and adaptation of these technologies is heavily dependent on the functional requirement and design constraints of the specific devices.

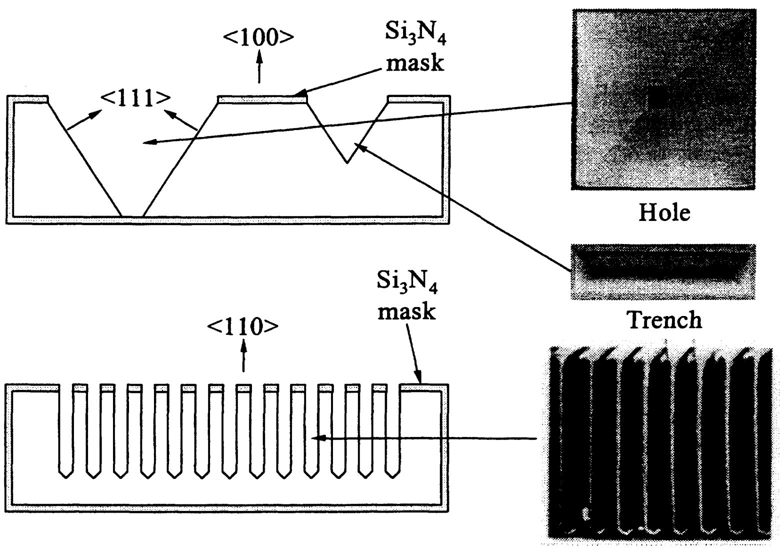


Figure 1 Anisotropic etching of monocrystalline silicon

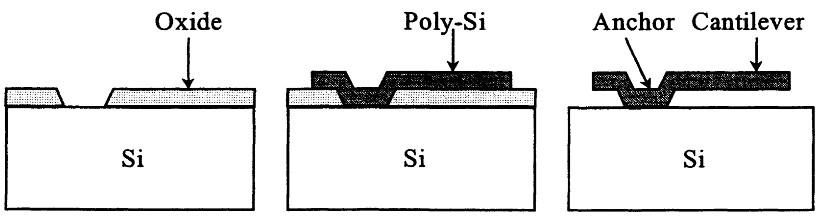


Figure 2 Typical surface micromachining

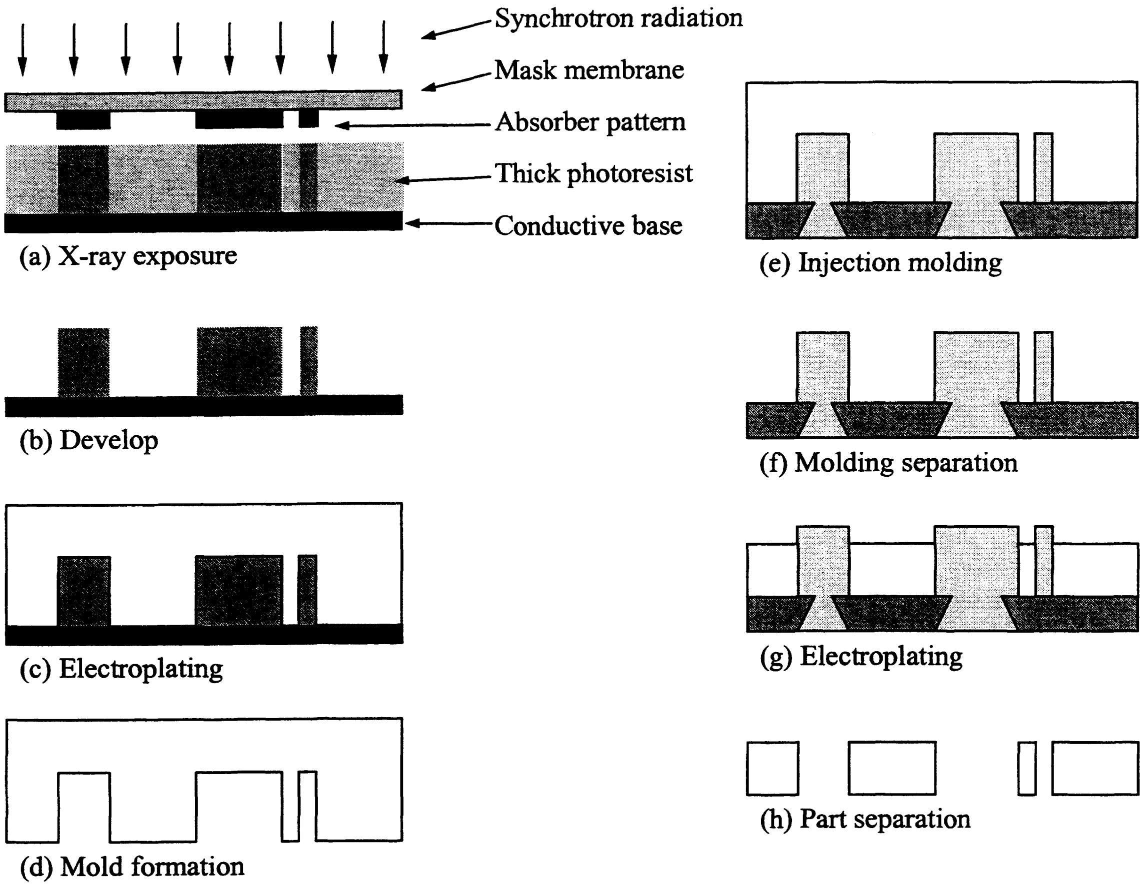


Figure 3 LIGA Process Steps

Table I. Comparison of MEMS Technologies

Capability	**Bulk (wet, 100 wafer)**	**Surface**	**LIGA**
Maximum structural thickness	wafer(s) thickness	<50 μm	500 μm
Planar geometry	rectangular	unrestricted	unrestricted
Minimum planar feature size	$\sqrt{2}$ × depth	1 μm	3 μm
Side wall features	54.74° slope	limited by dry etch	0.2 μm runout over 400 μm
Surface and edge definitions	excellent	mostly adequate	very good
Material properties	very well controlled	mostly adequate	well controlled
Integration with electronics	demonstrated	demonstrated	difficult
Capital investment & costs	low	moderate	high
Published knowledge	Very high	high	moderate

4. EXAMPLES OF MEMS DEVICES FOR SPACE EXPLORATION

Several microfabricated devices are described in this section to illustrate the special requirement for space exploration applications.

Microgyroscope[9]

Gyroscopes are needed in all spacecraft with navigation systems, attitude and maneuver control, and instrument pointing and stabilization functions. A typical navigation grade gyroscope has a bias stability of around 0.01 to 0.001 °/hr. Those needed to augment external inertial reference systems such as the Global Positioning System (GPS) require 0.1 to 1 °/hr bias stability with a bandwidth from 1 to 60 Hz. Instrument pointing and stabilization usually need 1 °/hr performance level. Those performing with 10 °/hr bias stability can be used in spacecraft tumble recovery and attitude control and Δv maneuver. Traditional navigation grade gyroscope is usually based on the Sagnac effect, which is a general relativistic phenomenon. In a closed circular optical path, clockwise and counterclockwise propagating beams interfere to produce a fringe pattern. This pattern shifts in response to a rotation of the closed optical path along the axis perpendicular to the plane of the beam. Advantage of these optical gyroscopes include high dynamic range, high bandwidth, rapid start-up, little first-order sensitivity to acceleration, and low long-term drift. However, they require complex signal processing electronics, optical path length controller, high voltage power supplies, mechanical dithering, thermoelectric coolers, precision optical components, and complicated and delicate assembly processes. They consume lots of power (6 to 20 W) and are rather massive (0.2 to 20 kg). Therefore, they cannot be used in spacecraft weighing less than 20 kg.

Except for the most stringent requirement of navigation-grade gyroscopes, MEMS fabricated devices promise the potential to meet the requirement of other gyroscopic functions. It is highly desirable to achieve a low cost Micro Inertial Reference Unit (MIRU) that augment GPS for spacecraft navigation, instrument pointing and stabilization, as well as attitude control and Δv maneuver. One possibility is to perform rotation rate sensing based on Coriolis induction in a vibratory gyroscope. In such a system, a suspended inertial mass is driven into linear resonance in one direction, for example the x-axis. A rotation of the system along the z-axis causes the vibration to be coupled into the y-axis, so that the inertial mass will simultaneously oscillate in both x and y directions. The amplitude of the induced oscillation in the y-axis is proportional to the rotation rate, the initial oscillation amplitude in the x-axis, and the quality factor in the y direction. The rotation rate is conveniently inferred from the measured vibration amplitude in the y direction. This approach is amenable to miniaturization using MEMS technology, particularly when the drive and sense functions are implemented with electrostatic force and capacitive measurement, respectively. The JPL gyroscope, based on bulk micromachining, is the first MEMS fabricated gyroscope to demonstrate a bias stability of 29 °/hr. Figure 4 is the SEM picture and conceptual drawing of the device, which is based on a clover leaf shaped electrodes mechanically coupled to a metal post as the inertial mass. The structure is driven into rocking-mode resonance along the x-axis. Input rotation along the z-axis (Ω) is inferred by detecting the rocking-mode vibration amplitude along the y-axis. **Error! Reference source not found.** is a picture of the packaged device, which is orders of magnitude smaller in size and weight than conventional gyroscopes, and consuming less than 10% of the power. Further development is underway to meet the 1-°/hr requirement for MIRU implementation.

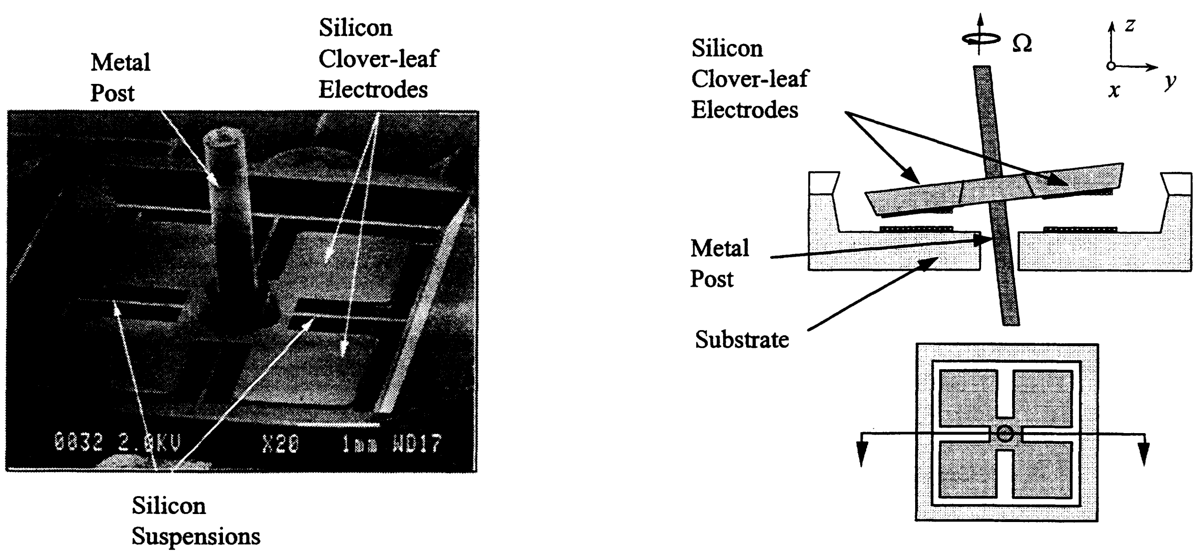


Figure 4 SEM and conceptual drawing of bulk micromachined vibratory gyroscope

Figure 5 Assembled gyroscope package

Microseismometer[10]

One of the key scientific interests in the study of Mars is seismic activity. Currently, there are no commercially available seismometers that are compatible with the strict mass, volume, power, and environmental requirements for future Mars landing missions. Furthermore, Mars is seismically quieter than even the quietest location on Earth, and thus requires more sensitive instruments than those deployed for Earth applications. It is desirable for Mars-bound seismometers to have sensitivities approaching 10^{-12} g/√Hz. They are required to measure long-period phenomena up to tens of thousands of seconds, so extremely low drift is a must. The principal source of drift in seismometers is thermal, and the Martian surface, with a diurnal temperature variation of tens of degrees, poses a serious challenge to seismic instrumentation. At depths greater than 50 cm below the Martian surface, however, the diurnal variation is less than 1°C, and the stability problem becomes simpler. This is a compelling argument for subsurface deployment. Of greatest importance, however, is the fact that subsurface deployment reduces the wind effects by several decades. The sensitivity requirement, together with the need for surviving penetration impact, poses a different kind of challenges, though. With drastic weight reduction and machining precision offered by MEMS technology, the chance of overcoming these challenges is greatly improved.

A miniature seismometer is under development by the In-Situ Exploration Technology (ISET) Group at JPL to meet these challenges. It is based on a precisely micromachined silicon proof mass weighing a few grams, combined with a novel capacitive transducer of sufficient sensitivity to measure the displacement of the proof mass (Figure 6). The completed package weighs only 100 g, which is contrasted with a 20 kg conventional seismometer. Figure 6 also shows a comparison of the seismic signals recorded by the JPL microseismometer and Streckeisen Model STS-2 field portable seismometer.

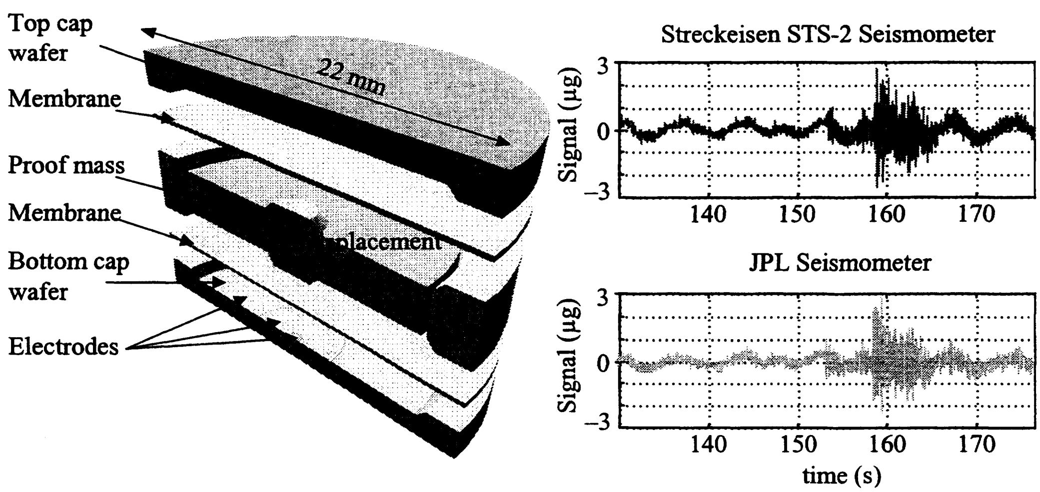


Figure 6 Blow-out drawing of the JPL microseismometer and output comparison

Microhygrometer[11]

There are several meteorological parameters that are important in Martian explorations. These include, among others, humidity, pressure, temperature, and wind. It is highly desirable to perform these meteorological measurements in a package that can be conveniently delivered to Mars and is robust enough to survive landing on the target sites. These *in-situ* measurements can serve as both the primary data source and ground-truth calibration for orbiting remote-sensor systems. Several MEMS-fabricated components that make up the micro weather station are at various stages of development at JPL. One of these components, the SAW hygrometer for humidity measurement, is reviewed here.

Humidity is a difficult parameter to measure in the cold, dry environment on the Martian surface, but measuring the amount of water on the planet is of great scientific interest. There are a number of conventional techniques available for measuring humidity, but none of which have the desired combination of low mass, low power, high accuracy, and fast response. Among various humidity measurement instruments, the dew-point hygrometer measures the amount of water in the atmosphere by cooling a surface and looking for condensation of water on the surface. One of the primary advantages of the dew point hygrometer is its accuracy and sensitivity at low humidity, and thus making it suitable for Mars exploration. The conventional approach is to cool a mirror down to the dew point, and optically measure condensation by detecting reflectivity on the mirror surface. The use of optical measurement techniques, however, suffers from high mass, high power, and possible long-term stability problems in the hash environments on Mars.

A micro hygrometer developed at JPL is built around a micromachined surface acoustic wave (SAW) device, which is cooled through the dew point using a small, two-stage thermo-electric cooler (Figure 7). The temperature of the device is determined with a co-mounted temperature sensor, and the frequency output of the SAW is measured as a function of this temperature. Any condensation on the SAW device is detected as a downward shift of the SAW frequency due to mass loading. During benchmark and calibration testing under controlled conditions, correlation between conventional, state-of-the-art, chilled mirror and the SAW hygrometer data indicate excellent agreement over the dew point between –40°C through +20°C. However, in field test, the SAW hygrometer shows performance superior to the chilled-mirror counterparts. Figure 7 also shows the dew point data taken from the NASA DC8 during descent. The SAW hygrometer is significantly faster and more accurate than the chilled mirror hygrometers in rapidly changing conditions. Furthermore, during periods of rapid rises in dew point, the chilled mirror hygrometers were unable to warm up rapidly enough to track the actual parameter, whereas the SAW hygrometer showed important details in the change. As a result, the SAW data reveals patterns in the dew point as a function of time that is either missed or inaccurately recorded by the chilled mirror counterparts. In addition, the drastic size and weight reduction with the SAW hygrometer makes it suitable for planetary exploration as well as upper atmosphere weather measurement on Earth.

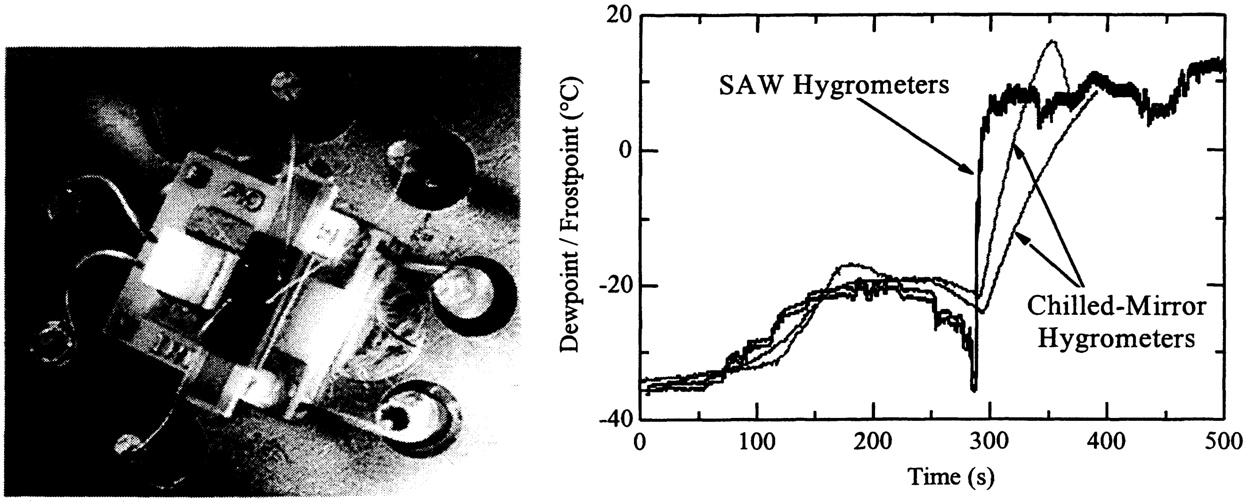


Figure 7 Photograph of the SAW microhygrometer and a comparison of outputs with state-of-the-art devices

Quadrupole Array Mass Spectrometer[12]

Mass spectroscopy continues to be a standard method for the identification and characterization of gaseous chemical species, and is one of the most popular methods used in chemical analysis. It is highly desirable to include a mass spectrometer as part of an instrument suite for space exploration. There are a number of approaches to obtain the spectrum of mass distribution in a specimen. All of them combine ion formation, mass analysis, and ion detection. The specimen is first ionized, which is then passed through an electric or magnetic field. Based on the relationships between force, mass, charge, and applied fields governed by Newton's second law and Lorentz force law, the different constituents within the specimen are separated according to their mass-to-charge ratio. Finally, the quantity of each constituent is resolved in the ion detection stage. The various approaches in mass spectrometers differ mainly in the mass analysis, or mass filtration stage. Among the different approaches, quadrupole mass spectrometers are often found in benchtop systems due to the relatively small sizes and low-cost implementation. The most basic setup of a quadrupole mass filter stage is a parallel arrangement of four conductive cylindrical rods. A combined DC and RF potential is applied to the rods so that only a selected mass-to-charge ratio can pass through and eventually reach the ion detector. All other ions do not have stable trajectories through the quadrupole and collide with the rods. A reduced-size quadrupole mass filter has been fabricated using conventional machining and assembly techniques with pole lengths of approximately 25 mm and rod diameters of 2 mm. Limited resolution and dependence on energy, collision gas, pressure, and other factors are necessary trade-offs.

Because of the simplicity and small size of quadrupole mass spectrometers, a program at JPL was initiated to further miniaturize and ruggedize a quadrupole mass filter using MEMS techniques to make them suitable for space missions. The JPL program objective is to achieve a mass range of 1 to 300 atomic mass unit (AMU), with a full width at half maximum (FWHM) resolution of 0.5 AMU. This compares favorably with the 15 to 212 AMU range and a 1 AMU resolution of the mass spectrometers used on the Viking I and II spacecraft, which landed on Mars in 1976. In addition, the instrument must be able to survive a 50,000-g short-duration shock during penetration into Martian surface. LIGA technique was employed to create quadrupole rods 2.2 mm in length (Figure 8). To achieve the stated dynamic range and resolution, pole dimensions must be controlled to within 0.1%. Although this geometrical accuracy is yet to be demonstrated, it is within the theoretical limit of LIGA technique. Also, with the small mass, the shock survivability of the mass spectrometer is greatly enhanced.

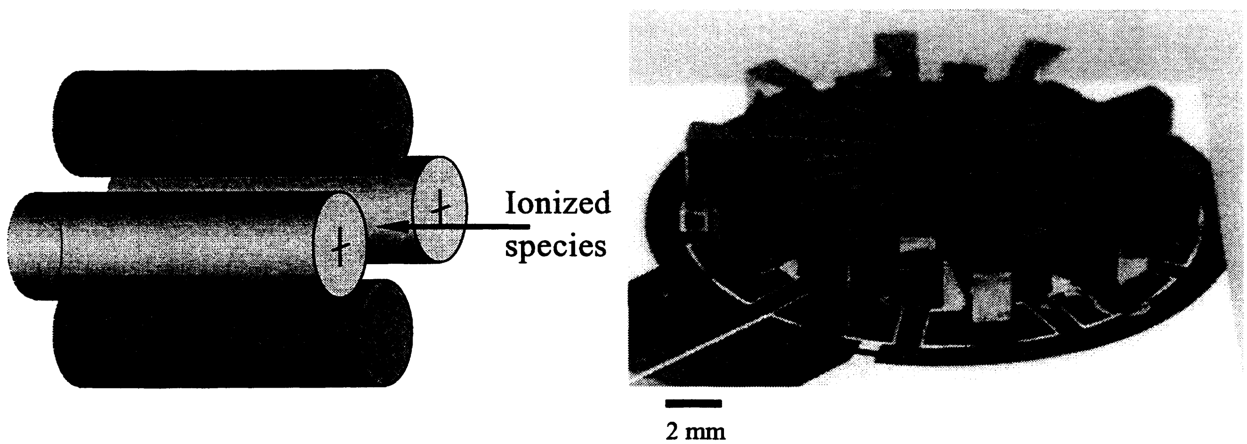


Figure 8 Conceptual drawing of quadrupole mass spectrometry and photograph of the LIGA fabricated device

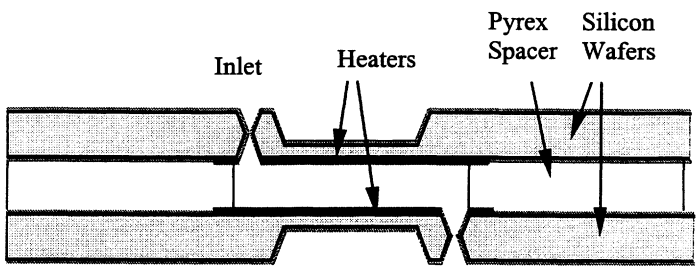
Micropropulsion Engine[13]

Interplanetary missions based on spacecraft between 1 to 20 kg in weight require propulsion capability for course corrections and attitude control to accurately point the spacecraft for observation or communication. Often, these small spacecraft are launched as piggybacks to larger spacecraft to save launch costs. Therefore, propulsive capability is required to divert them to their own trajectories according to the desired mission objectives. In order to meet microspacecraft propulsion requirements, the use of lightweight, small sized, low-thrust and small impulse bit (I-bit) systems is needed. Microspacecraft with masses between 1 to 5 kg, in particular, pose severe volume and weight constraints on all its subsystems, including propulsion. Also, the precision of I-bit needed for maneuver and attitude control is higher than what the smallest conventional thruster can provide. For example, a 10-kg spacecraft attitude control system requires an I-bit of 5 μNs at a minimum thrust level of 1.8

mN. The Moog 58x125, a cold-gas thruster and the world's smallest rocket engine available today, measures 4.3 cm in length and 1.4 cm in diameter. However, it puts out an I-bit of 100 μNs and a thrust level of 4.5 mN, which are 20 times and several times higher than respective requirements. Furthermore, the tank volume required to contain the pressurized propellant will be bigger than a 10-kg spacecraft design. The use of MEMS technology to implement propulsion engines promises some potential to address those needs.

A vaporizing-liquid micro-thruster was recently proposed, in which a liquid propellant (ammonia or hydrazine) is heated with a thin-film heater on a silicon substrate (Figure 9). Two silicon wafers patterned with thin-film heaters and micro-nozzles are anodically bonded to a pyrex spacer, which is sandwiched between the two silicon wafers. The liquid propellant, which is pressure fed through the inlet into the chamber, is vaporized as it flows between the heaters. Propellant vapor is then exhausted through the precisely micromachined nozzle. A recess machined into the silicon on the other side of the heater creates thermal chokes near the heater edges, and thus reduces conductive thermal loss to the structure. A key advantage of this design is its simplicity. It does not require any complex moving parts such as pumps and turbines, which could pose reliability challenges. The design objective is to achieve a thrust level of 0.5 to a few mN. If it can be interfaced with a fast acting valve, then the low I-bit requirement can also be met. Disadvantages of this design are its low performances (50–75 s of estimated specific impulse) and propellant toxicity.

Other micro propulsion approaches are also possible, such as the subliming-solid micro-thruster[14]. The key advantage of this design, like vaporizing-liquid micro-thruster, is its simplicity. Also, storing propellant in the solid phase minimize loss of propellant due to leakage. Solid propellant with a high sublimation pressure, such as ammonium hydrosulfide (NH_4HS) or ammonium carbamate ($NH_4CO_2NH_2$), is heated to generate vapor pressure inside the propellant tank and the vapor is vented through a valve and a nozzle to produce thrust. However, the success of this design, like that of the vaporizing-liquid microthruster, hinges upon the availability of a fast-acting, low-leak microvalve, which is yet to be demonstrated.



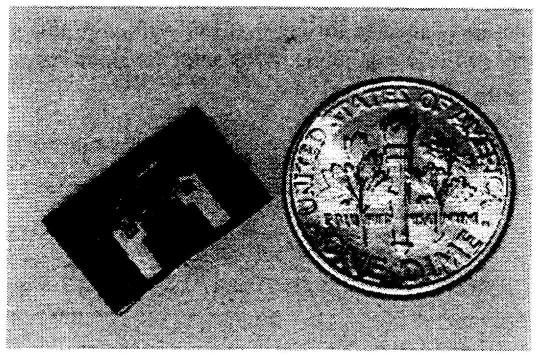


Figure 9 Vaporizing-liquid microthruster: conceptual drawing and size comparison with an American dime

5. CONCLUSION

Space exploration in the coming century will be significantly different than the traditional approach, with a very strong emphasis on cost effectiveness and highly focused mission objectives. The strategy to implement these objectives is to develop drastically miniaturized and functionally specific micro and nano spacecraft for robotic exploration, and to infuse high technology to enable safe and cost-effective human exploration. Infrequent grand-scale missions will be replaced by multiple small-scale missions that are cost-effective enough to be launched frequently. As a result, new technology can be infused and verified on a timely basis to enable gradual but significant technological improvement on subsequent missions. Among various new technologies, MEMS stands out as a prime candidate to enable drastic spacecraft miniaturization and functional enhancement. Examples being investigated include spacecraft and instrument orientation with micro gyroscope, in-situ planetary and small solar body exploration with microseismometer, microhygrometer, and quadrupole mass spectrometer, as well as attitude control and Δv maneuver for micro spacecraft with micro propulsion thrusters. These examples are in various stages of development and some of them are at the verge of flight validation. If their flight readiness is verified, microfabricated devices and systems will become standard components in future spacecraft.

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