Chapter 2

VISION FOR MICRO TECHNOLOGY SPACE MISSIONS

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ABSTRACT

It is exciting to contemplate the various space mission applications that Micro Electro Mechanical Systems (MEMS) technology could enable in the next 10-20 years. The primary objective of this chapter is to both stimulate ideas for MEMS technology infusion on future NASA space missions and to spur adoption of the MEMS technology in the minds of mission designers. This chapter is also intended to inform non-space oriented MEMS technologists, researchers and decision makers about the rich potential application set that future NASA Science and Exploration missions will provide. The motivation for this chapter is therefore to lead the reader down a path to identify and

consider potential long-term, perhaps disruptive or revolutionary, impacts that MEMS technology may have for future civilian space applications. A general discussion of the potential for MEMS in space applications is followed by a brief showcasing of a few selected examples of recent MEMS technology developments for future space missions. Using these recent developments as a point of departure, a vision is then presented of several areas where MEMS technology might eventually be exploited in future Science and Exploration mission applications. Lastly, as a stimulus for future research and development, this chapter summarizes a set of barriers to progress, design challenges and key issues that must be overcome in order for the community to move on, from the current nascent phase of developing and infusing MEMS technology into space missions, in order to achieve its full future potential.

2.1 INTRODUCTION

We live in an age when technology developments combined with the innate human urge to imagine and innovate is yielding astounding inventions at an unprecedented rate. In particular, the past 20 years have seen the disruptive technology called Micro Electro Mechanical Systems (MEMS) emerge and blossom in multiple ways. The commercial appeal of the MEMS technologies are derived from their low cost in high volume production, their inherent miniature form factor, their ultra-low mass and power, their ruggedness, all with attendant complex functionality, precision and accuracy. The space community is exceedingly interested in utilizing MEMS technology for future missions for the very same reasons.

Recent dramatic progress has occurred in the development of ultra-miniature, ultra-low power and highly integrated MEMS-based microsystems that can sense their environment, process incoming information, and respond in a precisely controlled manner. The capability to communicate with other micro-scale devices and, depending on the application, with the macro-scale platforms they are hosted on, will permit integrated and collaborative system-level behaviors. Combine these attributes with the potential to generate power on the MEMS scale and one starts to see the potential for MEMS-based microsystems to not only enhance, or even replace, today's existing macro-scale systems but also to enable entirely new classes of micro-scale systems.

As will be described in detail in subsequent chapters of this book, the roots of the MEMS technology revolution can be found in the substantial surface (planar) micromachining technology investments made over the last 30 years by Integrated Circuit (IC) semiconductor production houses worldwide. Broadly speaking it is also a revolution that exploits the integration of multi-disciplinary engineering processes and techniques at the sub-millimeter (100's of microns) device size level. The design and development of MEMS devices leverages heavily off of well established, and now standard, techniques and processes for 2-D and 3-D semiconductor fabrication and packaging. MEMS technology will allow us to field new generations of sensors and devices in which the functions of detecting, sensing, computing, actuating, controlling, communicating, and powering are all co-located in assemblies/structures with dimensions on the order of 100-200 microns or less.

Over the past several years, industry analysts and business research organizations have pointed to the multi-billion dollar sized global commercial marketplace for MEMS-based devices and microsystems in such areas as the automotive industry, communications, biomedical, chemical and consumer products. The MEMS-enabled ink jet printer head and the digital micromirror projection displays are often cited examples of commercially successful products enabled by MEMS technology. The MEMS airbag micro-accelerometer and the tire air pressure sensors are both excellent examples of commercial applications of MEMS in the automotive industry sector. Implantable blood pressure sensors and fluidic micropumps for in-situ drug delivery are examples of where MEMS serves in the biomedical arena.

Given the tremendously rapid rate of technology development and adoption over the past 100 years, one can confidently speculate that MEMS technology, especially when coupled with the emerging developments in Nano Electro Mechanical Systems (NEMS) technology, has the potential to change society as deeply as the introduction of the telephone in 1876, the tunable radio receiver in 1916, the electronic transistor in 1947, and the desktop Personal Computer (PC) in the 1970's. In the not too distant future, once designers and manufacturers become more aware of the possibilities that arise from this technology, it may very well be that MEMS-based devices and microsystems become as ubiquitous and as deeply integrated into our society's day-to-day existence as the phone, the radio and the PC are today.

Perhaps it is somewhat premature to draw MEMS technology parallels to the technological revolutions initiated by such now commonplace household electronics. It is, however, very probable that as more specific commercial applications are identified where MEMS is clearly the competitively superior alternative, a confluence of two developments will occur: 1) the refinement of low-cost fabrication methods that will yield enhanced device quality/reliability, and 2) the formulation of industry standard packaging and integration solutions. Once these developments occur more companies focused solely on commercializing MEMS technology will emerge and rapidly grow to meet the market demand. What impact this will have on society is unknown but it is quite likely that MEMS (along with NEMS) will have an increasing presence in our homelife and our workplace as well as many points in between. One MEMS industry group has gone so far as to predict that before 2010 there will be at least five MEMS devices per person in use in the United States.

It is not the intention of this chapter to comprehensively describe the far-reaching impact of MEMS-based microsystems on human society in general. That is well beyond the scope of this entire book, in fact. The emphasis of this chapter is on how the space community might leverage and exploit the billion-dollar worldwide investments being made in the commercial (terrestrial) MEMS industry for future space applications. Two related points are relevant in this context. In the first place, it is unlikely that without this significant investment in commercial MEMS, we in the space community would not be even considering MEMS technology for use in space. Secondly, the fact that each year companies around the world are moving MEMS devices out of their research laboratories into commercial applications, in fields such as biomedicine, optical communications and information technology, at an increasing rate can only be viewed as a very positive influence on transitioning MEMS technology towards space applications. The global commercial investments in MEMS have created the foundational physical infrastructure, the highly trained technical workforce and, most importantly, a deep scientific and engineering knowledge base that will continue to serve as the strong intellectual springboard for the development of MEMS devices and microsystems for future space applications.

Two observations can be made concerning the differences between MEMS in the commercial world and the infusion of MEMS into space missions. Firstly, unlike the commercial marketplace where very high-volume production and consumption is the norm, the niche market demand for space qualified MEMS devices will be orders of magnitude less. Secondly, it is obvious that transitioning commercial MEMS designs to the harsh space environment will not be necessarily trivial. Their inherent mechanical robustness will clearly be a distinct advantage in surviving the dynamic shock and vibration exposures of launch, orbital maneuvering, and lunar/planetary landing. However it is likely that significant modeling, simulation, ground test and flight test will be needed before space qualified MEMS devices, which satisfy the stringent reliability requirements traditionally imposed upon space platform components, can routinely be produced in reasonable volumes. For example, unlike their commercial counterparts, space MEMS devices will need to simultaneously provide the following: 1) radiation hardness or, at least, radiation tolerance, 2) the capability to operate over wide thermal extremes, and 3) an insensitivity to significant electrical/magnetic fields.

In the remainder of this chapter there will be a discussion of recent examples of MEMS technologies being developed for space mission applications. The purpose of providing this sampling of developments is to provide the reader insight into the current state of the practice as an aid to predicting where this technology might eventually take us. A vision will then be presented, from a NASA perspective, of application areas where MEMS technology can be exploited for Science and Exploration mission applications.

2.2 RECENT MEMS TECHNOLOGY DEVELOPMENTS FOR SPACE MISSIONS

It is widely recognized that MEMS technology should have and will have many useful applications in space. A considerable amount of the literature has been written describing the ways in which MEMS technology could enable: 1) constellations of cost-effective microsatellites[1] for various types of missions, 2) highly miniaturized science instruments[2] for remote sensing applications and 3) unique, first-of-a-kind "Lab on a Chip" micro-sensors for in-situ chemical detection and analysis.[3]

Recently, several of the conceptual ideas for applying MEMS in future space missions have grown into very focused technology development and maturation projects. The activities discussed in this section have been selected to expose the reader to some highly focused and specific applications of MEMS in the areas of spacecraft thermal control, science sensors, mechanisms, avionics and propulsion. The intent here is not to provide design or fabrication details, as each of these areas will be addressed more deeply in the following chapters of this book, but rather to showcase the wide range of space applications in which MEMS can contribute.

While there clearly is a MEMS-driven stimulus at work today in our community to study ways to re-engineer spacecraft of the future using MEMS technology, one must also acknowledge the reality that the space community collectively is only in the nascent phase of applying MEMS technology to space missions. In fact our community at large probably does not yet entirely understand the full potential that MEMS technology may have in the space arena. True understanding and the knowledge it creates will only come with a commitment to continue to create innovate designs, demonstrate functionality and rigorously flight validate MEMS technology in the actual space environment.

2.2.1 NMP ST5 Thermal Louvers

The Space Technology 5 (ST5) project, performed under the sponsorship of NASA's New Millennium Program (NMP), has an overall focus on the flight validation of advanced Microsat technologies that have not yet flown in space in order to reduce the risk of their infusion in future NASA missions. The NMP ST5 Project is designing and building three miniaturized satellites, shown in **Figure 2.1**, that are approximately 54 cm in diameter and 28 cm tall with a mass less than 25 kg per vehicle. As part of the ST5 mission these three Microsats will perform some of the same functions as their larger counterparts.

One specific technology to be flight validated on ST5 is MEMS shutters for "smart" thermal control conceptualized and tested by NASA Goddard Space Flight Center (GSFC), developed by the Johns Hopkins University Applied Physics Laboratory (JHU/APL) and fabricated at Sandia National Laboratory. In JHU/APL's rendition, the radiator is coated with arrays of micro-machined shutters, which can be independently operated with electrostatic actuators thereby controlling the apparent emittance of the radiator.[1] The latest prototype devices are 1.8 mm x 0.88 mm arrays of 150 mm x 6 mm shutters that are actuated by electrostatic comb drives to expose either the gold coating or the high emittance substrate itself to space. **Figure 2.2** shows an actuator block with the arrays. Prototype arrays designed by JHU/APL have been fabricated at Sandia National Laboratories using their SUMMiT V process. For the flight units, about 38 elements with 72 shutter arrays each will be combined on a radiator and independently controlled.

The underlying motivation for this particular technology can be summarized as follows. Most spacecraft rely on radiative surfaces (radiators) to dissipate waste heat. These radiators have special coatings that are intended to optimize performance under the expected heat load and thermal sink environment. Typically, such radiators will have a low absorptivity and a high infrared emissivity. Given the variable dynamics of the heat loads and thermal environment, it is often a challenge to properly size the radiator. For the same reasons, it is often necessary to have some means of regulating the heat rejection rate in order to achieve proper thermal balance. One potential solution to this design problem is to employ the MEMS micromachined shutters to create, in essence, a Variable Emittance Coating (VEC). Such a VEC yields changes in the emissivity of a thermal control surface to allow the radiative heat transfer rate to be modulated as needed for various spacecraft operational scenarios. In the case of the ST5 flight experiment, the JHU/APL MEMS thermal shutters will be exercised to perform adaptive thermal control of the spacecraft by varying the effective emissivity of the radiator surface.

2.2.2 JWST Microshutter Array

NASA's James Webb Space Telescope (JWST) is a large (6.5 meter primary mirror diameter) infrared-optimized space telescope scheduled for launch in 2011. JWST is designed to study the earliest galaxies and some of the first stars formed after the Big Bang. When operational, this infrared observatory will take the place of the Hubble Space Telescope and will be used to study the Universe at the important but previously unobserved epoch of galaxy formation. Over the past several years scientists and technologists at NASA GSFC have developed a large format MEMS-based microshutter array that is ultimately intended for use in the JWST Near Infrared Spectrometer (NIRSpec) instrument. It will serve as a programmable field selector for the spectrometer and the complete microshutter system will be composed of four 175 by 384 pixel modules. This device significantly enhances the capability of the JWST since the microshutters can be selectively configured to make highly efficient use of nearly the entire NIRSpec detector, obtaining hundreds of object spectra simultaneously.

Micromachined out of a silicon nitride membrane, this device as shown in **Figure 2.3** and **Figure 2.4** consists of a two-dimensional array of closely packed and independently selectable shutter elements. This array functions as an adaptive input mask for the multi-object NIRSpec providing very high contrast between its open and closed states. It provides high transmission efficiency in regions where shutters are commanded open and sufficient photon blocking in closed areas. Operationally, the desired configuration of the array will be established via ground command, then simultaneous observations of multiple celestial targets can be obtained.

Some of the key design challenges for the microshutter array include obtaining the required optical (contrast) performance, individual shutter addressing, actuation, latching, mechanical interfaces, electronics, reliability, and environment requirements. For this particular NIRSpec application, the MEMS microshutter developers also had to ensure the device would function at the 37 K operating temperature of the spectrometer as well as meet the demanding low power dissipation requirement.

Figure 2.5 shows the ability to address/actuate and provide the required contrast. These critical functions were demonstrated on a fully functional 128 by 64 pixel module in 2003 and development is proceeding on the 175 by 384 pixel flight-ready microshutter module that will be used in the JWST NIRSpec application. This is an outstanding example of applying MEMS technology to significantly enhance the science return from a space-based observatory.

2.2.3 Inchworm Micro-Actuators

The NASA Jet Propulsion Laboratory (JPL) is currently developing an innovative inchworm micro-actuator[5] for the purpose of ultra-precision positioning of the mirror segments of a proposed Advanced Segmented Silicon Space Telescope (ASSiST). This particular activity is one of many diverse MEMS/NEMS technology developments for space mission applications being pursued at NASA/JPL.[6]

2.2.4 NMP ST6 Inertial Stellar Camera

NASA's NMP is sponsoring the development of the Inertial Stellar Compass (ISC) space avionics technology that combines MEMS inertial sensors (gyroscopes) with a wide field-of-view Active Pixel Sensor (APS) star camera in a compact, multifunctional package.[7] This technology development and maturation activity is being performed by the Charles Stark Draper Laboratory (CSDL) for a Space Technology 6 (ST6) flight validation experiment now scheduled to fly in 2005. The ISC technology is one of several MEMS technology development activities being pursued at CSDL[8] and, in particular, is an outgrowth of earlier CSDL research focused in the areas of MEMS–based Guidance, Navigation and Control (GN&C) sensors/actuators[9] and low-power MEMS-based space avionics systems.[10]

The ISC, shown in **Figure** 2.6, is a miniature, low power, stellar inertial attitude determination system that provides an accuracy of better than 0.1 degree (1-Sigma) in three axes while consuming only 3.5 watts and packaged in a 2.5 kg housing.[11]

The ISC MEMS gyro assembly, as shown in **Figure** 2.7, incorporates CSDL's Tuning Fork Gyro (TFG) sensors and mixed signal Application Specific Integrated Circuit (ASIC) electronics designs. Inertial systems fabricated from similar MEMS gyro components have been used in Precision Guided Munitions (PGM's), autonomous vehicles, and other space related mission applications. The silicon MEMS gyros sense angular rate by detecting the Coriolis effect on a sense mass which is driven into oscillation by electrostatic motors. Coriolis forces proportioned to the rotational rate of the body cause the sense mass to oscillate out of plane. This change is measured by capacitive plates. A more detailed discussion of MEMS inertial sensors, both gyros and accelerometers, is presented in Chapter 10 (GN&C) of this book.

The ISC technology, enabled by embedded MEMS gyroscopes, is a precursor of things to come in the spacecraft avionics arena as the push towards much more highly integrated, GN&C systems grow in the future. There are a wide range of Science and Exploration mission applications that would benefit from the infusion of the compact, low power ISC technology. Some envisioned applications include using the ISC as a "single sensor" solution for attitude determination on medium performance spacecraft, as a "Bolt On" independent safehold sensor for any spacecraft, or as an acquisition sensor for rendezvous applications. It has been estimated that approximately 1.5 kg of mass and 26 Watts of power can be saved by employing a single MEMS-based attitude sensor such as the ISC to replace the separate and distinct star tracker and inertial reference units typically used on spacecraft.[11] So in this case, MEMS is an enhancing technology that serves to free up precious spacecraft resources. For example, the mass savings afforded by using the MEMS-based ISC could be allocated for additional propellant or, likewise, the power savings could potentially be directly applied to the mission payload. These are some of the advantages afforded by using MEMS technology.

2.2.5 Microthrusters

Over the past several years MEMS catalytic monopropellant microthruster research and development has been conducted at NASA GSFC.[12] MEMS-based propulsion systems have the potential to enable missions that require micro-propulsive maneuvers for formation flying and precision pointing of micro-, nano-, or pico-sized satellites. Current propulsion technology cannot meet the minimum thrust requirements (10-1000 μN), or impulse-bit requirements (1-1000 μN·sec) or satisfy the severely limited system mass (<0.1 kg), volume (<1 cm^3), and power constraints (<1W). When compared to other proposed micro-propulsion concepts, MEMS catalytic monopropellant thrusters show the promise of the combined advantages of high specific density, low system power and volume, large range of thrust levels, repeatable thrust vectors, and simplicity of integration. Overall this approach offers an attractive technology solution to provide scalable micro-Newton level microthrusters. This particular MEMS microthruster design utilizes hydrogen peroxide as the propellant and the targeted thrust level range is between 10-500 μN with impulse bits between 1-1000 μN·sec and a Specific impulse (I_{sp}) of greater than 110 sec.

Prototype MEMS microthruster hardware has been fabricated as seen in **Figure** 2.8, using GSFC's Detector Development Laboratory (DDL) facilities and equipment.

Individual MEMS fabricated reaction chambers are approximately 3.0mm x 2.5mm x 2.0mm. Thrust chambers are etched in a 0.5 mm silicon substrate and vapor deposited with silver using a catalyst mask.

2.2.6 Other Examples of Space MEMS Developments

The noteworthy space-related MEMS developments described above can be considered as very significant technological steps towards the ultimate goal of routine and systematic infusion of this technology in future space platforms. Clearly NASA researchers have identified several areas where MEMS technology will substantially improve the performance and functionality of the future spacecraft. NASA is currently investing at an increasing rate in a number of different MEMS technology areas. A review of the NASA Technology Inventory shows that in Fiscal Year (FY) 2003 there were a total of 111 distinct MEMS–based technology development tasks being funded by NASA. Relative to FY 2002, where 77 MEMS-based technology tasks were catalogued in the NASA Technology Inventory, this is over a 40% increase in MEMS tasks. It is almost a 90% increase relative to FY 2001 where 59 MEMS R&D tasks were identified. The MEMS technologies contained in the NASA inventory include:

- Stirling coolers
- Liquid-metal microswitches
- Inertial sensors
- Microwave RF switches and phase shifters
- Thrusters
- Deformable mirrors
- Pressure/temperature sensors

- Power supplies.

In closing this section, it should be stressed that the few selected developments highlighted above are not intended to represent a comprehensive list [13,14] of recent or on-going space MEMS technology developments. In fact, there are a number of other very significant space MEMS technology projects in various stages of development. Among these are:

- Flat plasma spectrometer[4] for space plasma and ionospheric-thermospheric scientific investigations
- Miniature mass spectrometer[3,4] for planetary surface chemistry investigations
- Switch-reconfigurable antenna array element[19] for space based radar applications
- Micro-heat-sinks for microsat thermal control applications
- Tunable Fabry-Perot etalon optical filters for remote sensing applications[5]
- Two-axis fine-pointing micro-mirrors for inter-satellite optical communications applications.[21]

2.3 POTENTIAL SPACE APPLICATIONS FOR MEMS TECHNOLOGY

It should be apparent that the near-term benefit of MEMS technology is that it allows developers to rescale existing macrosystems down to the microsystem level. However, beyond simply shrinking today's devices, the true beauty of MEMS technology derives from the system re-definition freedom it provides designers, leading to the invention of entirely new classes of highly-integrated Microsystems.

It is envisioned that MEMS technology will serve as both an "Enhancing" and an "Enabling" technology for many future Science and Exploration missions. Enabling technologies are those that provide the presently unavailable capabilities necessary for a mission's implementation and are vital to both intermediate and long-term missions. Enhancing technologies typically provide significant mission performance improvements, mitigations of critical mission risks, and/or significant increases in mission critical resources (e.g., cost, power, and mass).

MEMS technology should have a profound and far-reaching impact on a many of NASA's future space platforms. Satellites in low earth orbit, deep space interplanetary probes, planetary rovers, advanced space telescopes, lunar orbiters and lunar landers could all likely benefit in some way from the infusion of versatile MEMS technology. Many see the future potential for highly integrated spacecraft architectures where boundaries between traditional, individual bus and payload subsystems are, at a minimum, blurred or, in some extreme applications, non-existent with the infusion of multi-functional MEMS-based microsystems.

NASA/GSFC has pursued several efforts not only to increase the general awareness of MEMS within the space community but also to spur along specific mission-unique infusions of MEMS technology where appropriate. Over the past several years the space mission architects at the GSFC Integrated Mission Design Center (IMDC), where collaborative end-to-end mission conceptual design studies are performed, have evaluated the feasibility of using MEMS technology in a number of mission applications. As part of this MEMS technology "push" effort many MEMS–based devices emerging from research laboratories have been added to the IMDC's component database used by the mission conceptual design team. The IMDC also is a rich source of future mission requirements and constraints data that can be used to derive functional and performance specifications to guide MEMS technology developments. Careful analysis of this requirements and constraints information will help to identify those missions where infusing a specific MEMS technology will have a significant impact or conversely, identifying where an investment in a broadly applicable "crosscutting" MEMS technology will yield benefits to multiple missions.

The remainder of this section will cover some high priority space mission application areas where MEMS technology infusion would appear to be beneficial.

2.3.1 Inventory of MEMS–Based Spacecraft Components

It is expected that MEMS technology will offer NASA mission designers very attractive alternatives for challenging applications where power, mass, and volume constraints preclude the use of the traditional components. MEMS technologies will enable miniaturized, low mass/power, modular versions of many of the current inventory of traditional spacecraft components.

2.3.2 Affordable Microsatellites

A strong driver for MEMS technology infusion comes from the desire of some space mission architects to implement affordable constellations of multiple microsatellites.

These constellations, of perhaps as many as 30-100 satellites, could be deployed either in loosely controlled formations to perform spatial/temporal space environment measurements or in tightly controlled formations to synthesize distributed sparse aperture arrays for planet finding.

A critical aspect to implementing these multi-satellite constellations in today's cost-capped fiscal environment will be application of new technologies that reduce the per unit spacecraft cost while maintaining the necessary functional performance. The influence of technology in reducing spacecraft costs has been studied and carefully evaluated by NASA[22]. The through analysis of historical trend data has lead to the conclusion that, on average, the use of technologies that reduce spacecraft power will reduce spacecraft mass and cost. Clearly a large part of solving the affordable microsatellite problem will involve economies of scale. High volume production will serve to bring down the cost of the Nth unit built relative to the cost of the initial unit. Identifying exactly which technologies have the highest likelihood of lowering spacecraft cost is still a work in progress. However, a case can be made that employing MEMS technology, perhaps in tandem with the Ultra-Low Power electronics technology[23] being developed by NASA and our partners will be a significant step towards producing multiple microsatellite units in a more affordable way.

It should also be pointed out that another equally important aspect to lowering spacecraft costs will be developing architectures that call for the use of standard-off-the-shelf and modular MEMS-based microsystems. Also, there will need to be a fundamental shift away from the current "hands on" labor intensive limited-production spacecraft manufacturing paradigm towards a high-volume, more "hands off" production model. This would most likely require implementing new cost effective manufacturing methodologies where such things as parts screening, subsystem testing, spacecraft-level integration & test, and documentation costs are reduced.

So one can anticipate the "Factory of the Future" which produces microsatellites that are highly integrated using MEMS-based micro-subsystems, composed of miniaturized electronics, devices and mechanisms, for communications, power, and attitude control, extendable booms and antennas, micro-thrusters and a broad range of micro-sensor instrumentation. The multi-mission utility of having a broadly capable nano/micro spacecraft has not been overlooked by NASA mission architects. New capabilities such as this will generate new concepts of space operations to perform existing missions and, of greater import, to enable entirely new types of missions.

Furthermore, because the per unit spacecraft cost has been made low enough through the infusion of MEMS technology, the concept of flying "replaceable" microsatellites is both technically and economically feasible. In such a mission concept, the requirements for redundancy/reliability will be satisfied at the spacecraft level, not at the subsystem level where it typically occurs in today's design paradigm. In other words, MEMS-based technology, together with appropriate new approaches to lower spacecraft-level integration, test and launch costs, could conceivably make it economical to simply perform an on-orbit replacement of a failed spacecraft. This capability opens the door to create new operational concepts and mission scenarios.

2.3.3 Science Sensors and Instrumentation

As described in Chapter 7 of this book, the research topic of MEMS-based science sensors and instruments is an incredibly rich one. Scientists and MEMS technologists are collaborating first to envision and then rapidly develop highly integrated, miniaturized, low mass and power efficient sensors for both Science and Exploration missions. The extreme reductions in sensor mass and power attainable via MEMS technology will make it possible to fly multiple high performance instrumentation suites on Microsatellites, Nanosatellites, planetary landers and autonomous rovers, entry probes and inter-planetary platforms. The ability to integrate miniaturized sensors into lunar or planetary In Situ Resource Utilization (ISRU) systems and/or robotic arms, manipulators and tools (i.e., a drill bit) will have high payoff on future Exploration missions. Detectors for sensing electromagnetic fields and particles, critical to several future science investigations of solar terrestrial interactions, are being developed in a MEMS format. Sensor technologies using micromachined optical components, such as microshutters and micromirrors for advanced space telescopes and spectrometers are also being matured. One exciting research area is the design and development of adaptive optics devices made up of either very dense arrays of MEMS micromirrors or membrane mirrors to perform wavefront aberration correction functions in future space observatories. These technologies have the potential to replace the very expensive and massive high-precision optical mirrors traditionally employed in large space telescopes. Several other MEMS-based sensing systems are either being actively developed or are in the early stages of innovative design. Examples of these include, but are not limited to, micromachined mass spectrometers (including MEMS microvalves) for chemical analysis, microbolometers for infrared spectrometry, and entire Laboratory-on-a-Chip device concepts. One can also envision MEMS-based environmental and state-of-health monitoring sensors being embedded into the structures of future space transportation vehicles and habitats on the lunar (or eventually on a planetary) surface as described in the following section on Exploration applications for MEMS.

2.3.4 Exploration Applications

There are a vast number of potential application areas for MEMS technology within the context of the nation's Vision for Space Exploration (VSE). We will explore some of those here.

In the Integrated Vehicle Health Management (IVHM) arena, an emphasis will be placed upon developing fault detection, diagnosis, prognostics, information fusion, degradation management capabilities for a variety of Exploration space vehicles and platforms. Embedded MEMS technology could certainly play a significant role in implementing automated spacecraft IVHM systems and the associated crew emergency response advisory systems.

Developing future ISRU systems will dictate the need for automated systems to collect lunar regolith for use in the production of consumables. Innovative ISRU systems that minimize mass, power, and volume will be part of future power system and vehicle refueling stations on the lunar surface and/or planetary surfaces. These stations will require new techniques to produce oxygen and hydrogen from lunar regolith, and looking further ahead new systems to produce propellants and other consumables from the Mars atmosphere will need to be developed.

MEMS technology should also play a role in the development of the space and surface environmental monitoring systems that will be supporting exploration. Clearly the observation, knowledge, and prediction of the space, lunar and planetary environments will be important for exploration. MEMS could also be exploited in the development of environmental monitoring systems for lunar and planetary habitats. This too would be a very suitable area for MEMS technology infusion.

2.3.5 Space Particles/Morphing Entities

Significant technological changes will blossom in the next few years as the multiple developments of MEMS, NEMS, Micro-Machining, and Bio-Chemical technologies create a powerful confluence. If the space community at large is properly prepared and equipped, the opportunity to design, develop and fly revolutionary, ultra-integrated Mechanical, Thermal, Chemical, Fluidic, and Biological microsystems can be captured. These are the type of systems that cannot feasibly be built using conventional space platform engineering approaches and methods.

Some space visionaries are enthused by this huge "blue sky" potential to blaze completely new design paths over the next 15-25 years. One can envision the creation of such fundamentally new mission ideas as, for example, MEMS-based "spaceborne sensor particles" or autonomously morphing robotic space entities that would resemble today's state of the art space platforms as closely as today's ubiquitous PC's resemble the slide rules used by an earlier generation of engineers. Swarms of these MEMS enabled "spaceborne sensor particles" could employ collaborative behaviors to perform very dense in-situ science observations and measurements. One can also envision these miniature robotic "spaceborne sensor particles" breaking the Earth-to-orbit (also known as the Access to Space) launch constraint, by being able to take advantage of novel space launch system innovations such as electromagnetic or light-gas cannon launchers where perhaps thousands of these MEMS-based "particles" could be dispensed at once.

2.4 CHALLENGES AND FUTURE NEEDS

In this section, it will be stressed that, while some significant advancements are being made to develop and infuse MEMS technology into space mission applications, there is much more progress to be made in this arena. There are still many challenges, barriers and issues (not all technical or technological) yet to be dealt with in order to fully exploit the potential of MEMS in space. The following is a brief summary of some of the key considerations and hurdles to be faced.

2.4.1 Challenges

History tells us that the infusion of new technological capabilities into space missions will significantly lag that of the commercial/industrial sector. Space program managers and other decision makers are typically very cautious about when and where new technology can be infused into their missions. New technologies are often perceived to add unnecessary mission risk.

Consequently, MEMS technology developers must acknowledge this barrier to infusion and strive to overcome it by fostering a two way understanding and interest in MEMS capabilities with the mission applications community. This motivates the need, in addition to continually maturing the Technology Readiness Level (TRL) of their device or system, to proactively initiate and maintain continuing outreach with the potential space mission customers to assure a clear mutual understanding of MEMS technology benefits, mission requirements/constraints (in particular the "Mission Assurance" space qualification requirements), risk metrics and potential infusion opportunities.

2.4.2 Future Needs

It is unlikely that the envisioned proliferation of MEMS into future Science and Exploration missions will take place without significant future technological and engineering investments focused on the unique and demanding space applications arena. Several specific areas where such investments are needed are suggested below.

Transitioning MEMS microsystems and devices out of the laboratory and into operational space systems will not necessarily be straight forward. The overwhelming majority of current MEMS technology developments have been targeted at terrestrial, non-space applications. Consequently, many MEMS researchers have never had to consider the design implications of having to survive and operate in the space environment. An understanding of the space environment will be a prerequisite for developing "flyable" MEMS hardware. Those laboratory researchers that are investigating MEMS technology for space applications must first take the time to study and understand the unique challenges and demanding requirements imposed by the need to first survive the rigors of the short-term dynamic space launch environment as well as the long-term on-orbit operating environments found in various mission regimes. Chapter 4 of this book is intended to provide just such a broad general background on the space environment and will be a valuable reference for MEMS technologists. In a complementary effort, the space system professionals in industry and in government, to whom the demanding space environmental requirements are routine, must do a much better job of guiding the MEMS technology community through the hurdles of designing, building and qualifying space hardware.

The establishment of much closer working relationships between MEMS technologists and their counterparts in industry is certainly called for. Significantly more Industry-University collaborations, focused on transitioning MEMS microsystems and devices out of the University laboratories, will be needed to spur the infusion of MEMS technology into future space missions. It is envisioned that these collaborative teams would target specific space mission applications for MEMS. Appropriate mission assurance product reliability specifications, large scale manufacturing considerations, together with industry standard mechanical/electrical interface requirements, would be combined very early in the innovative design process. In this type of collaboration University-level pilot efforts would pathfind the development of viable low-cost production approaches. The expectation is that these pilot efforts would eventually result in standardized large volume industrial production processes yielding space-qualified Commercial-Off-The-Shelf (COTS) MEMS flight hardware.

On a more foundational level, continued investment in expanding and refining the general MEMS knowledge base will be needed. The focus here should be on improving our understanding of the mechanical/electrical behaviors of existing MEMS materials (especially in the cryogenic temperature regimes favored by many space sensing applications) as well as the development of new exotic MEMS materials. New techniques for testing materials and methods for performing standardized reliability assessments will be required. The latter need will certainly drive the development of improved high-fidelity, and test-validated, analytical software models. Exploiting the significant recent advances in high performance computing and visualization would be a logical first step here.

Another critical need will be the development of new techniques and processes for precision manufacturing, assembly and integration of silicon-based MEMS devices with macro-scale non-planar components made from metals, ceramics, plastics, and perhaps more exotic materials. The need for improved tools, methods and processes for the design and development of the supporting miniature, low-power mixed-signal (analog and digital) electronics, which are integral elements of the MEMS devices, must also be addressed.

The investigation of innovative methods for packing and tightly integrating the electrical drive signal, data readout and signal conditioning elements of the MEMS devices with the mechanical elements should be aggressively pursued. In most applications, significant device performance improvements, along with dramatic reductions in corrupting electrical signal noise, can be accomplished with moving the electronics as physically close as possible to the mechanical elements of the MEMS device. This particular area, focused on finding new and better ways to more closely couple the MEMS electronics and mechanical sub-elements, can potentially have high payoffs and should not be overlooked as an important research topic.

Lastly it is important to acknowledge that a unified “big picture” systems approach to exploiting and infusing MEMS technology in future space missions is currently lacking and, perhaps worse, non-existent. While there clearly are many localized centers of excellence in MEMS microsystem and device technology development within academia, industry, non-profit laboratories and federal government facilities, there are few, if any, comparable MEMS Systems Engineering and Integration centers of excellence. Large numbers of varied MEMS “stand alone” devices are being designed and developed but there is not enough work being done currently on approaches, methods, tools, and processes to integrate heterogeneous MEMS elements together in a "System of Systems" fashion. For example, in the case of the affordable microsatellite discussed above, it is not at all clear how one would go about effectively and efficiently integrating a MEMS micro-thruster or a MEMS micro-gyro with other MEMS-based satellite elements such a command/telemetry system, a power system, or on-board flight processor. We certainly should not expect to be building future space systems extensively composed of MEMS microsystems and devices using the integration and interconnection approaches currently employed. These are typically labor intensive processes using interconnection technologies that are both physically cumbersome and resource (power/mass) consuming. The cost economies and resource benefits of using miniature mass produced MEMS-based devices may very well be lost if a significant level of "hands-on" manual labor is required to integrate the desired final payload or platform system. Furthermore, it is quite reasonable to expect that future space systems will have requirements for MEMS-based payloads and platforms that are both modular and easily reconfigurable in some "plug and play" fashion. The work to date on such innovative technology as MEMS harnesses and MEMS switches begins to address this interconnection/integration need but significant work remains to be done in the MEMS flight system engineering arena.

In the near-term, to aid in solving the dual scale (Macro-to-MEMS) integration problem, researchers should pursue ways to better exploit newly emerging low power/radiation hard micro-electronics packaging and high density interconnect technologies as well as Internet-based wireless command/telemetry interface technology. Researchers should also evaluate methods to achieve a Zero Integration Time (ZIT) goal for MEMS flight systems using aspects of today's plug & play component technology which utilizes standard data bus interfaces. In the far-term, we most likely will need to identify entirely new architectures and approaches to accomplish the goal of simply and efficiently interconnecting MEMS microsystems and devices composed of various types of metals, ceramics, plastics, and exotic materials.

Balancing our collective technological investments between the intellectually stimulating goal of developing the next best MEMS stand-alone device in the laboratory and the real world problem that will be faced by industry of effectively integrating MEMS-based future space systems is a recommended strategy for ultimate success. Significant investments are required to develop new space system engineering approaches to develop adaptive and flexible MEMS flight system architectures and the supporting new MEMS-scale interconnection hardware/software building blocks. Likewise the closely associated need to test and validate these highly-integrated MEMS "System of Systems" configurations prior to launch will drive the need for adopting (and adapting) the comprehensive, highly autonomous Built-In-Test (BIT) functions commonly employed in contemporary non-aerospace commercial production lines.

Research in this arena could well lead to the establishment of a new MEMS Micro-Systems Engineering discipline. This would be a very positive step in taking the community down the technological path towards the ultimate goal of routine, systematic and straightforward infusion of MEMS technology in future space missions.

There are several important inter-related common needs that span all the emerging MEMS technology areas. Advanced tools, techniques and methods for high-fidelity dynamic modeling and simulation of MEMS microsystems will certainly be needed, as will be multiple MEMS technology ground testbeds, where system functionality can be demonstrated and exercised. These testbed environments will permit the integration of MEMS devices in a flight-like Hardware-in-the-Loop (HITL) configuration. The findings and the test results generated by the testbeds will be used to update the MEMS dynamic models. The last common need is for multiple and frequent opportunities for the on-orbit demonstration and validation of emerging MEMS-based technologies for space. Much has been accomplished in the way of technology flight validation under the guidance/sponsorship of such programs as NASA's NMP but many more such opportunities will be required to propel the process of validating the broad family of MEMS technologies needed to build new and innovative space systems. The tightly interrelated areas of dynamic models/simulations, ground testbeds, and on-orbit technology validation missions will all be essential to fully understand and to safely/effectively infuse the MEMS into future missions.

2.5 CLOSING

The success of future Science and Exploration missions quite possibly will be dependent on the development, validation and infusion of MEMS-based microsystems that are not only highly integrated, power efficient and minimally packaged but also flexible and versatile enough to satisfy multi-mission requirements. Several MEMS technology developments are already underway for future space applications. The feasibility of many other MEMS innovations for space are currently being studied and investigated.

The widespread availability and increasing proliferation of MEMS technology specifically targeted for space applications will lead future mission architects to evaluate entirely new design trades and options where MEMS can be effectively infused to enhance current practices or perhaps enable completely new mission opportunities. The space community should vigorously embrace the potentially disruptive technological impact of MEMS on how space systems are designed, built and operated. Our space community should consider striving for a robust MEMS technology development approach along the lines adopted by the Defense Advanced Research Projects Agency (DARPA) to revolutionize military capabilities. It is well known that over the past several years DARPA has significantly invested in the development and widespread infusion of MEMS-based microsystems. Decision makers interested in sponsoring the development of innovative MEMS-microsystems for space mission applications would do well to study the DARPA approach. Multiple high risk/high payoff MEMS technologies have being aggressively pursued by DARPA to dramatically improve the agility, accuracy, robustness, and reliability of defense systems. There are lessons to be learned from this DARPA experience for the space community. Conceivably implementing a similarly strong MEMS technology "push" for space applications will directly support NASA's goals of improved system affordability, reliability, effectiveness and flexibility.

Transitioning MEMS microsystems and devices out of the laboratory and into operational space systems will present many challenges. Clearly much has been accomplished but several critical issues remain to be resolved in order to produce MEMS microsystems that will satisfy the demanding performance and environmental requirements of space missions. In the spirit of Rear Admiral Grace Murray Hopper ("If it's a good idea, go ahead and do it. It's much easier to apologize than it is to get permission") the community must continue to freely innovate with open minds. Otherwise, if we constrain our vision for MEMS microsystems in space, an opportunity may be missed to bend (or perhaps even break) the current space platform design and production paradigms.

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Figures 2.1- 2.8:

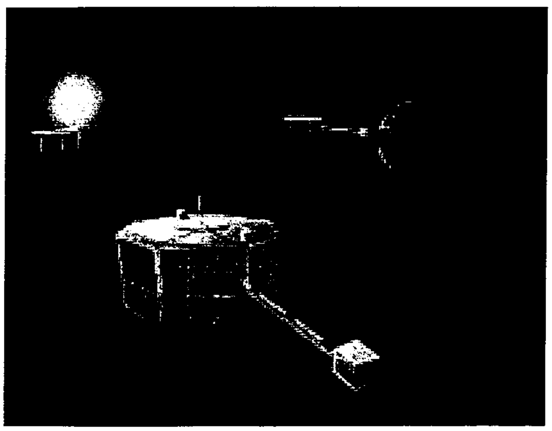


Figure 2.1: The NMP ST5 Microsats (Source: NASA)

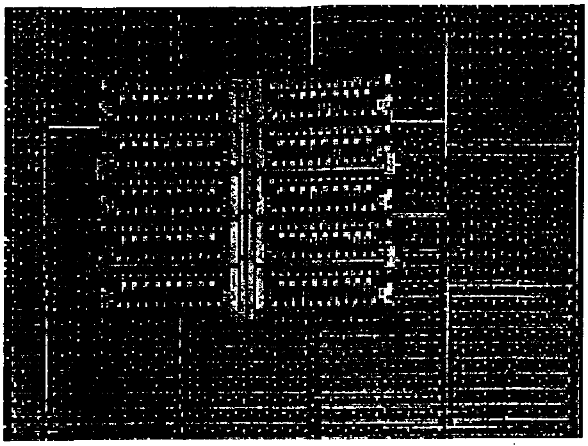


Figure 2.2: NMP ST5 MEMS Thermal Louver Actuator Block with Shutter Array (Source: JHU/APL)

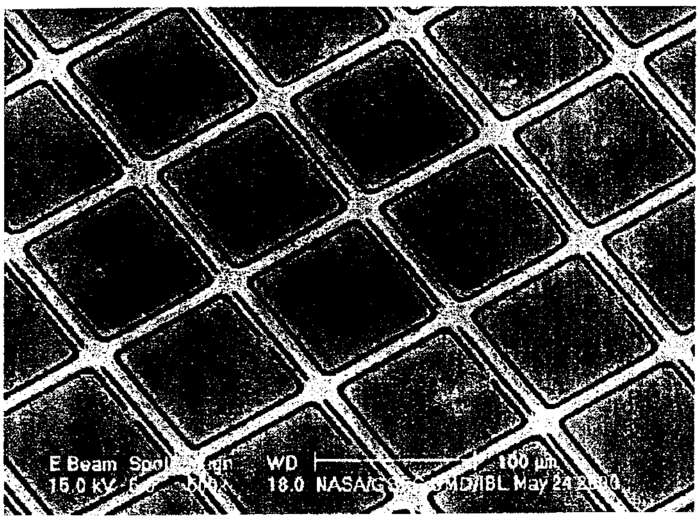


Figure 2.3: A Two-Dimensional MEMS Microshutter Array (Source: NASA)

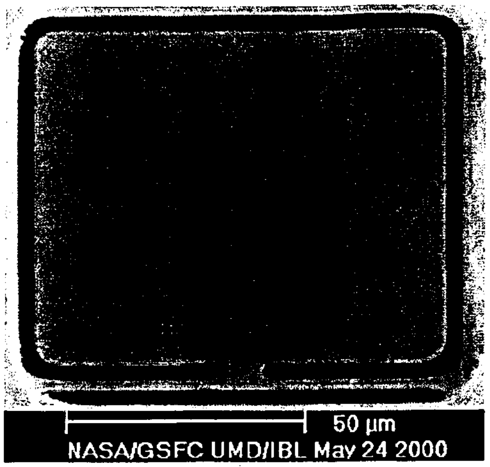


Figure 2.4: An Individual MEMS Microshutter Element (Source: NASA)

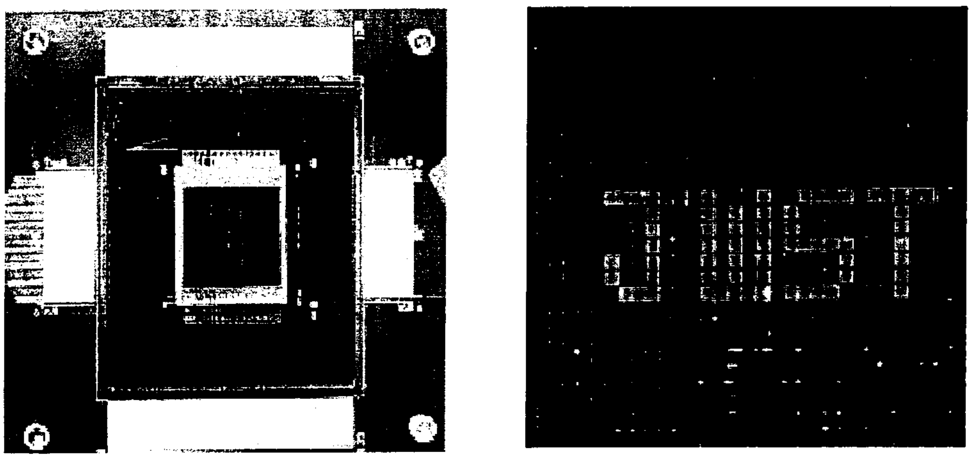


Figure 2.5: MEMS Microshutter Array 128 by 64 Pixel Demonstration Module Under Test (Source: NASA)

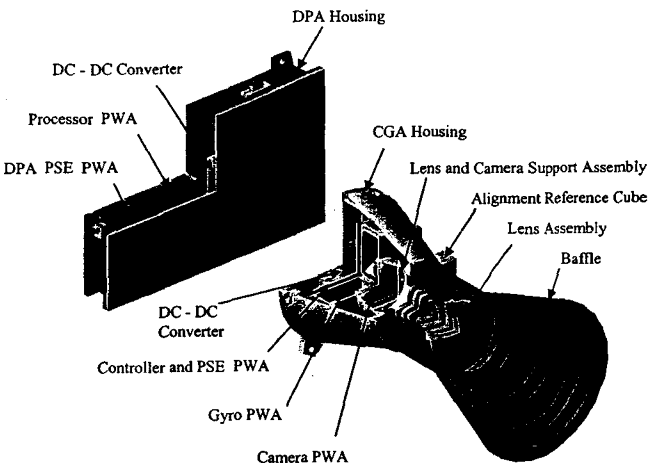


Figure 2.6: The NMP ST6 Inertial Stellar Camera (Source: CSDL)

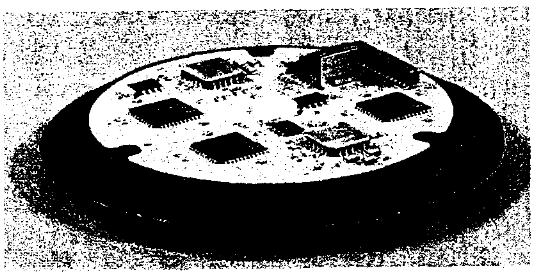
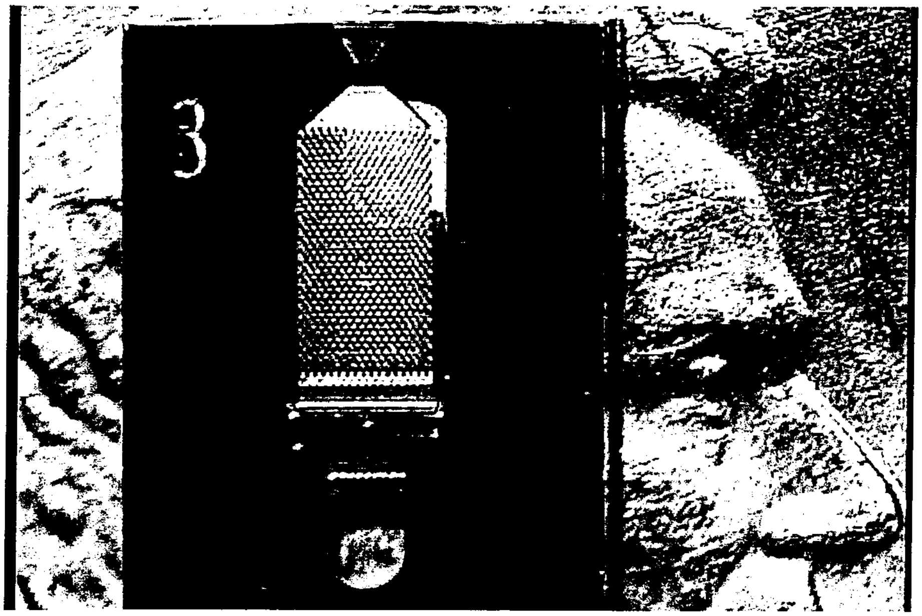


Figure 2.7: NMP ST6 ISC MEMS 3-Axis Gyro Assembly (Source: CSDL)

Figure 2.8: The completed MEMS "diamond pillar" monopropellant microthruster. A top view is shown, with the inlet at the bottom and the nozzle at the top of the figure. (Source: NASA)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