IAA-B3-1004

AN OVERVIEW OF MEMS-BASED MICROPROPULSION DEVELOPMENTS AT JPL

Juergen Mueller, Colleen Marrese, James Polk, Eui-Hyeok Yang, Amanda Green, Victor White, David Bame, Indrani Chakraborty*, Stephen Vargo*
Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA
Point of Contact: juergen.mueller@jpl.nasa.gov

Robert Reinicke
Moog Inc., Space Products Division, 27281 Las Ramblas, Suite 207, Mission Viejo, CA 92691, USA

This paper is dedicated to the memory of our teammate, Russell Lawton.

Abstract - Development of MEMS (Microelectromechanical Systems) micropropulsion at the Jet Propulsion Laboratory (JPL) is reviewed. This includes a vaporizing liquid micro-thruster for microspacecraft attitude control, a micro-ion engine for microspacecraft primary propulsion or large spacecraft fine attitude control, as well as several valve studies, including a solenoid valve studied in collaboration with Moog Space Products Division, and a piezoelectric micro-valve. The solenoid valve features much faster actuation (as little as 1.5 ms to open) than commercially available MEMS valves and showed no detectable leak (< 10^{-4} sccs GN_2) even after 1 million cycles. The solenoid valve weighs 7 gram and is about 1 cm^3. A micro-isolation valve, aimed at sealing propulsion systems at zero leak rates, was able to show burst pressures as high as 3,000 psi even though entirely machined from silicon and Pyrex. It could be actuated with energies as little as 0.1 mJ.

I. INTRODUCTION: THE MICROSPACECRAFT BACKGROUND

Propulsion is a key subsystem to most spacecraft, having significant impacts on spacecraft volume and mass. Small (<100 kg) or microspacecraft (<20 kg), however, appear to have been an exception in this regard in the past, often making do with either no propulsion system at all, or requiring only very limited propulsive capability[1]. As small and microspacecraft continue to develop, however, one might expect such spacecraft to exhibit increasing degrees of capability and complexity, mirroring similar such trends in virtually every branch of technology.

Specifically, small and microspacecraft will likely continue to evolve beyond the status of mere technology demonstrators, which represent a fair fraction of today's microspacecraft (see below). They increasingly may have actual primary missions to fulfill that may require high degrees of maneuverability, necessitating the use of propulsion systems. For example, small and microspacecraft may be deployed in constellations for earth observation or communication, as in the case of the Air Force TechSat 21 mission[2,3], consisting of a multitude of 100-kg class spacecraft (Fig. 1).

Microspacecraft may also be deployed for "tensor-mapping" missions[1], such as magnetic field mapping around Earth (see Fig. 2), the Sun, or other planets, as currently envisioned in the National Aeronautics and Space Administration's (NASA's) Sun-Earth Connection theme of

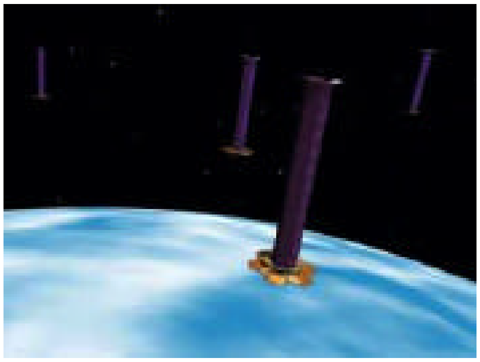


Fig. 1: Future Air Force TechSat 21 Earth-Orbiting Constellation of 100-kg Spacecraft.

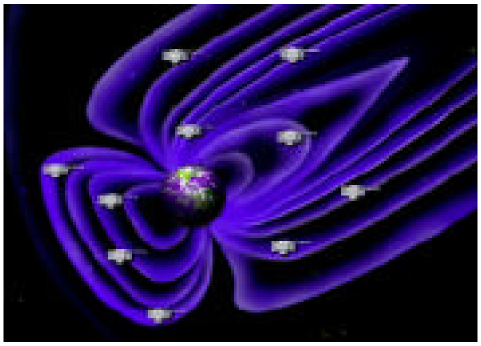


Fig. 2: NASA MagCon Mission Concept based on New Millennium ST-5 20-kg Microspacecraft to study the magnetic field around Earth

*now at Siwave Corp, Glendale, CA

missions. The recently selected New Millennium ST-5 mission will deploy several 20-kg class spacecraft to demonstrate the feasibility of such spacecraft designs[4]. Dispersal of these spacecraft into their different respective orbits will require propulsive capability.

Microspacecraft have been proposed as "micro-inspector" craft, to be detached from the mothercraft to inspect the latter for maintenance purposes, or in case of failures. An example of such a spacecraft is the SNAP-1 craft launched by Surrey Space Centre of England (Fig. 3). This 6.5-kg craft features a 2.4 m/s cold gas (butane) propulsion system to perform the inspection maneuvers[5].

Microspacecraft may also be used in missions beyond earth orbit. For example, detachable microprobes have been contemplated that may be released from a mothercraft to fly through Saturn's rings[6] for an in-situ investigation. Such microspacecraft could collect dust samples, or, if small enough, possibly land on a larger ring object not unlike the recent landing of the NEAR spacecraft on an asteroid. Such a mission would require propulsion.

The aforementioned mission categories (spacecraft constellations, inspector spacecraft, detachable micro-probes), may particularly benefit form use of microspacecraft. Even small mass savings achieved for a single microspacecraft will be compounded into potentially considerable mass savings for the entire spacecraft constellation or cluster, reducing total mission launch cost. Micro-inspector spacecraft or detachable micro-probes may significantly enhance a mission without adding unduly to its mass and cost, presuming that the probe or inspector can be designed small and light-weight enough. This anticipated desire to further shrink microspacecraft sizes for such missions, associated with the need for propulsive capability on these spacecraft, will make propulsion a key element to consider in future miniaturization efforts.

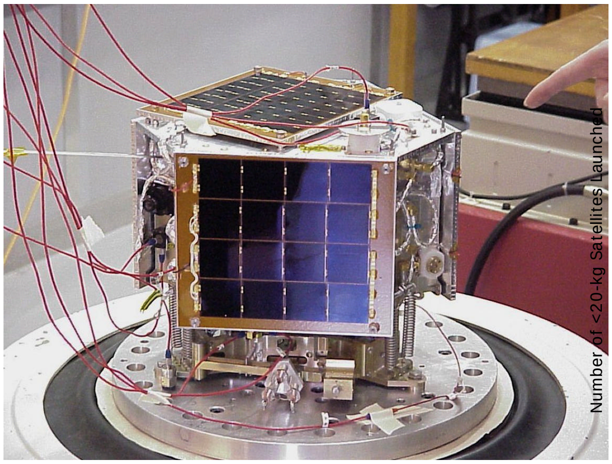


Fig. 3: SNAP-1 Micro-Inspector Spacecraft (6.5 kg total mass, 2.4 m/s cold gas propulsion system).
Note human finger for scale.
(Courtesy of Surrey Space Centre, England)

This increasing trend towards ever smaller microspacecraft can be seen in Table 1, taken from another publication of the author[7]. The table lists several of the more recent small and microspacecraft missions currently in flight, under design, or in planning. The list of spacecraft in Table 1 is by no means complete, but provides a relatively up-to-date cross section of recent activities in this field. Note the large number of microspacecraft in the 10-20 kg class or below. Many of these craft are dedicated to formation flying/constellation demonstration missions, such as those pursued under the University Nanosat program, a joint Air Force Research Laboratory (AFRL), Air Force Office of Scientific Research (AFOSR), Defense Advanced Research Projects Agency (DARPA), and NASA funded project. As mentioned, constellation missions stand to benefit strongly from using microspacecraft architectures due to decreased overall constellation mass and the resulting promise of total launch cost reductions.

This increasing emphasis on very small satellites in the 20-kg class or below appears to be corroborated by a recent study Cáceres[22] published in "*Aerospace America*". In its latest February issue, this publication lists the number of sub-20-kg that has been launched during the past decade. Figure 4 shows a graph, generated from the Cáceres[22] study, plotting the number of such spacecraft launched per year for a given year. Although no clear trends can be discerned yet (notice, for example, several of the years with no microspacecraft launched at all, and the only outstanding peak in launch rate occurring in the last year of the study, 2000), clearly sub-20-kg microspacecraft have made their presence felt.

This interest in ever smaller spacecraft architectures poses unique new challenges in the design of microspacecraft subsystems, including propulsion. Among

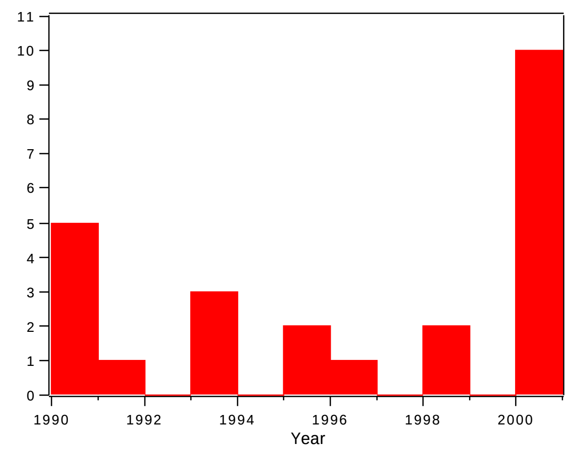


Fig. 4: Number of < 20-kg Microspacecraft Launched Per Year (Cáceres[22])

Table 1: Examples of Some Recent Microspacecraft Designs

Designation	Mission Purpose/Status	Lead	Mass (kg)	Size (cm)	Power (W)	Voltage (V)	Ref
MightySat	Technology Demonstrator, Launched Dec. 1998	USAir Force	64	48x69	≤32	-	8
Micro-Bus 70	Misc. Missions 14 Launches prior to April 1999	Surrey Space Centre, U. of Surrey, England	40-70	35x35x65	21-43	12	9
Orsted	Magnetic Field and Charged Particle Mapping, Launched Feb. 1999	Danish Space Research Inst.	60.7	68x45x34	54 (EOL)	-	10
SNAP-1	Technology Demonstrator, Inspection of other Spacecraft Launched June 28, 2000	Surrey Space Centre, U. of Surrey, England	6.5	34 x 23	4 (avg.) 7 (peak)	7-9	5
New Millennium ST-5	Magnetic Field Mapping Design Phase	NASA Goddard Space Flight Center	20	42x20 (Flat-to-Flat)	7.5-8.5	5/0.25	4
PROBA	Autonomy Demonstrator, In Design Phase	ESA	100	60x60x80	9	28	11
Falconsat	S/C Charging, In Design Phase	US Air Force Academy	50	46x46x43	24	12	12
ASU Sat 1	Awaiting Launch	Arizona State U	5	31x24	8.5-10	13	13
		University Nanosat Program					
3-Corner Sat	3 Spacecraft, Formation Flying Demo, Stereo Imaging, Cell-Phone Comm. In Design Phase	Arizona State U., U. of Colorado, New Mexico State U.	10	45x25	33	3.3-5	13, 14, 15
ION-F	3 Spacecraft, Formation Flying Demo, Ionospheric Studies, micro-PPT Exp. In Design Phase	Utah State U., U. of Washington, Virginia Polytech. Inst.	10/13	45x12/ 45x25	18	28	14, 16, 17
Emerald	2 Spacecraft, Ionospheric Studies, Formation Flying, Micro-Colloid Thruster Experiment. In Design Phase	Stanford U., Santa Clara U.	15	45x30	7	5/12	14, 18, 19
Constellation Pathfinder	3 Spacecraft, Formation Flying Demo, Demo 1-kg S/C Fab. and Flight Operations In Design Phase	Boston U.	1	20x14	1	-	14, 20
Solar Blade Heliogyro	Solar Sail Demo, In Design Phase	Carnegie Mellon	5	-	28	-	21

the more generic system constraints are the obvious mass and volume limitations. These will be of particular importance for attitude control propulsion systems, consisting of multiple thruster units (typically on the order of about one dozen) and the associated feed system hardware.

Equally important, however, is the need to operate subsystems within very limited power levels. Many of the newer microspacecraft designs are expected to offer overall spacecraft power levels of only a few 10s of W (see Table 1). Also notable are the lower bus voltages anticipated for microspacecraft, likely to drop to 3 - 5 V. Providing higher voltages, such as the current standard of 28 V, requires higher-mass power conditioning units which may not be afforded on mass constrained microspacecraft.

In addition, propulsion has its own unique set of microspacecraft related requirements with respect to its to-be-exhibited performance characteristics. It has previously been estimated that for microspacecraft in the 1-20-kg class, attitude control requirements may range between sub-μNs and up and 10^{-4} Ns impulse bits, depending on required pointing accuracy and time interval between thruster firings needed to maintain a certain spacecraft pointing attitude[7]. These impulse bit values may be coupled with thrust requirements for spacecraft slew, which may still reach into the mN-range[7]. These impulse bit values represent a severe deviation from the norm typically found for contemporary larger-scale spacecraft, and can only be met by very few existing propulsion technologies available or under development today. Some of these options will be reviewed in the next chapter.

II. PROPULSION OPTIONS FOR MICRO-SPACECRAFT AND THE CASE FOR MEMS PROPULSION

Existing Propulsion Options

Among the thruster options available or under significant development today that could potentially meet some of those microspacecraft requirements discussed above, are cold gas systems, some low-thrust field emission electric propulsion (FEEP) devices, and micro pulsed plasma thrusters (PPTs), as well as colloid systems. The latter two are still under development.

Cold gas systems are probably the widest used to date on the limited number of small and microspacecraft launched[7]. A 30-psi butane cold gas system, having twice the propellant storage density than nitrogen, with a 2.4 m/s delta-v capability has been used on the aforementioned SNAP-1 micro-inspector spacecraft[5,7], and cold gas systems are standard attitude control hardware on many other small Surrey Centre satellites. However, cold gas systems may require heavy tankage unless delta-v and propellant requirements are small, and may be prone to leakage.

Small FEEP thrusters easily reach the impulse bit requirements mentioned in the previous chapter, and low-thrust versions are physically small[7]. However, high-voltage power processing units (PPUs) add to the system weight and volume considerably due to very high voltage requirements up into the 10-kV range, and specific power values for these thrusters are high, typically around 60W/mN[7]. As a result, any significant thrust requirement in the mN-range for slew may result in power demands well exceeding the microspacecraft capability.

Pulsed plasma thrusters also are well suited to meet impulse bit requirements such as those discussed in the previous section. However, existing thruster hardware is far too heavy and large to be used as attitude control thrusters on microspacecraft, and also suffer from relatively high specific power values, limiting achievable thrust values on a microspacecraft[7]. However, smaller units are currently under development by General Dynamics (former Primex Aerospace) under the aforementioned University Nanosat program for use on the ION-F constellation (see Table 1), and even smaller units are being developed at AFRL/ Edwards Air Force Base[7,23].

Despite some of these limitations, these thruster units will undoubtedly be used on future microspacecraft. As already mentioned, cold gas systems have seen applications in this regard already, and PPTs are being developed for one of the university nanosat missions. For example, cold gas systems will be suitable for missions of short duration, where leakage concerns may be of less intense and propellant demands are low so that smaller propellant tanks can be used, alleviating weight concerns due to heavy high-pressure propellant storage requirements. FEEP or PPT thrusters may be used on such microspacecraft where slew rate requirements are low or do not exist at all, presuming PPU masses can be obtained fitting the microspacecraft envelope even if multiple units are required (as is the case for attitude control).

However, just as easily one might imagine microspacecraft missions where the existing thruster options may no longer suffice. These may include longer duration microspacecraft missions, microspacecraft missions requiring higher delta-v and higher thrust, as well as missions that have both requirements for fine pointing and significant slews. In addition, the aforementioned tendency to design ever smaller microspacecraft will place further pressure on the continued miniaturization of propulsion hardware, in particular for microspacecraft attitude control[7]. The existing electric propulsion hardware appears to not yet meet this requirement[7].

One relatively novel area of propulsion currently gaining increased attention in the aerospace community is microfabricated, or Microelectromechanical Systems (MEMS), propulsion, and will be the subject of the remainder of this paper.

MEMS-Propulsion

Microfabrication, or MEMS, has advanced significantly in the last two decades[24] and has demonstrated the ability to machine extremely small structures on silicon chips. It therefore seems logical to investigate the applicability of this technology to the fabrication of microspacecraft subsystems, including propulsion. Adapting MEMS technology in the fabrication of micropropulsion components and systems offers many advantages, but is not free of significant new challenges as well, not previously encountered in the propulsion field. Among the advantages are:

Small Size and Mass: This is one of the most obvious benefits. Using MEMS, structures may be machined which may easily fit on 1 cm^2 chips, weighing but a few grams, and may even be machined significantly smaller still.

High Potential Level of Integration: Using chip-based, microfabricated propulsion components, very tightly integrated propulsion modules may be envisioned, featuring integrated PPU or control electronics, and assembled into compact modules consisting of thrusters, valves, and other feed system components through chip-to-chip bonding or by means of other system-on-a-chip (SOAC) integration schemes. Such highly integrated modules would represent a significant leap in integration over state-of-the-art propulsion systems and allow volume and mass savings to be realized that may otherwise not be achievable. Figure 5 illustrates this vision. The picture in the upper right corner shows a conventionally integrated feed system. Note the large components, welded tube joints, and wires stringing across the propulsion assembly plate.

Available off-the-shelf already today, however, are much smaller propulsion components. Figure 5 (center) shows a cold gas valve by Moog as an example. This unit is still conventionally machined, demonstrating an astounding achievement given that individually packaged, commercially available MEMS valves are not much smaller. However, units such as these still would have to be integrated conventionally, which will increase system volume significantly over the sum of the volume of its individual parts due to space required to perform tube welding, for example. Performing this type of integration may also lead to concerns about reliability (given the multiple connections needed to be made, employing potentially very thin tubes), as well as complexity and cost.

A vision of a highly integrated MEMS propulsion system is shown in the lower left corner of Fig. 5, based on examples of MEMS propulsion hardware components currently being developed at the Jet Propulsion Laboratory (JPL). Chip-to-chip bonding or other SOAC technologies may allow to pack thrusters, valves, and support electronics into a volume not much bigger than that occupied by the miniature valve components available commercially today (as shown in the center of Fig. 5). Note that at present this is merely a vision. Many hurdles in the development of such integrated systems will have to be overcome, including the development of suitable integration schemes, bonding technologies, and thermal control issues, among others.

Performance: Listing performance as a potential advantage for MEMS propulsion systems may seem counter-intuitive at first, given that nozzle efficiencies and specific impulses typically will drop as thruster systems get smaller. However, for attitude propulsion applications in particular, specific impulse and efficiency are typically not too important, whereas minimum impulse bit performance and thrust are. Microfabricated thrusters may feature nozzle throat areas many times smaller than can be reliably machined using more conventional fabrication approaches. Smaller throat areas will directly translate into smaller thrust values and, assuming fast valve actuation can be made available on a chip level as well (see next section), smaller minimum

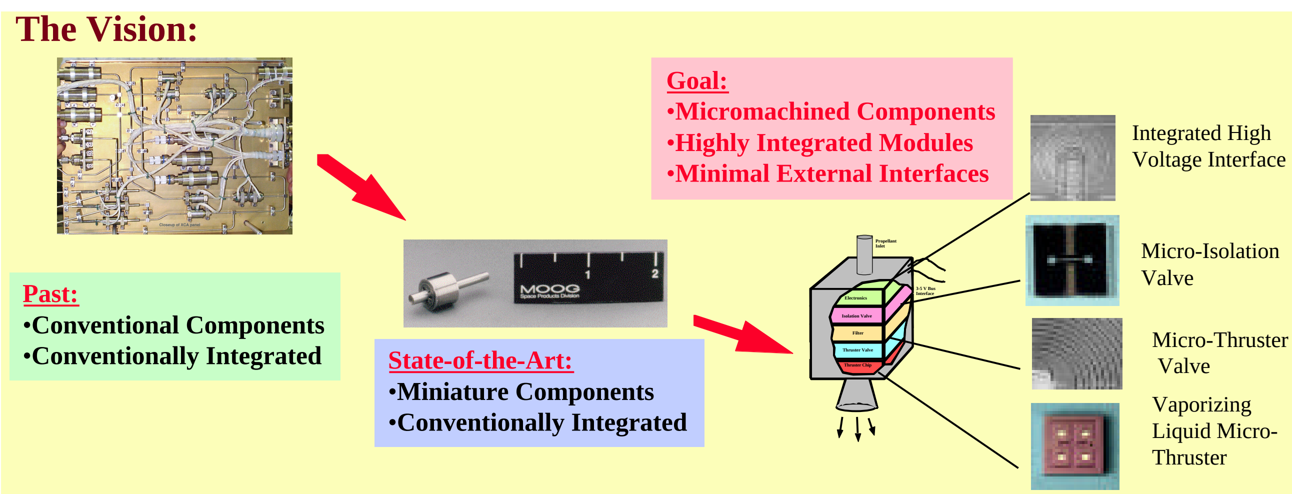


Fig. 5: A Vision of Highly Integrated Future MEMS Micropropulsion Systems

impulse bit values. The latter two are of particular importance for microspacecraft attitude control.

Cost: Microfabrication allows batch fabrication and wafer-scale integration of propulsion components, thus offering the potential for significant cost reductions over time. In fact, cost of fabrication and assembly of later production units is a key motivating factor in the development of the microvalve explored jointly between Moog Space Products Division and JPL, to be reviewed below.

However, as is the case in any nascent field of technology, MEMS propulsion still faces many challenges that need to be overcome. For example, the use of silicon as a structure material, as is typical in the field of MEMS, is by no means a matter of choice for propulsion applications. The use of silicon opens up anew many questions of material compatibility between it and various propellants. However, appropriate coating of silicon with various inert materials, such as silicon nitride or metals (even gold) may easily be performed, and is common in the field of microfabrication, thus possibly avoiding materials compatibility issues with silicon.

Silicon also is a very good heat conductor with a thermal conductivity of about 150 W/mK[25]. This high conductivity has been exploited in the design of micro-electronic circuits, the fabrication of which represents one of the roots of the field of MEMS. Here, the silicon base material conducts waste heat away from the electronic circuit. Unfortunately, in the case of thrusters, heat needs to be contained in the propellant to be turned into kinetic energy of the exhaust. Appropriate chip geometries or packaging techniques will need to be explored to reduce heat losses.

Silicon, although very hard, is also a brittle material. Propulsion components may be required to potentially withstand many cycles of internal pressurization. The behavior of silicon under such conditions will need to be studied in much greater detail, and sufficient factors of safety will need to be designed into MEMS propulsion components.

Finally, propulsion components made from silicon will have to be joined to metal. Even the smallest of the microspacecraft designed and built today (see Fig. 3) will require propellant tanks that will need to be conventionally machined (metal or metal-lined composites). Visions of tanks machined directly into silicon wafers will hardly allow for enough propellant volume even for such micro-spacecraft. Joining of silicon chips, possibly via modules such as those shown in Fig. 5, to metal tubes connected to the tank will require leak-tight bonding. Epoxies may lead to propellant compatibility issues. At JPL, we are studying Kovar-Pyrex-silicon bonds, not requiring any glue at all.

The use of MEMS materials different from silicon would therefore be highly desirable in the development of MEMS propulsion. Such an approach, however, might result in significant research and development expenditures since existing cleanroom infrastructure is almost exclusively focused on the processing of silicon material. This existing cleanroom infrastructure represents a significant capital investment. Transferring to non-silicon microfabrication would require substantial fundamental research, the development of new fabrication processes, and an infrastructure adapted to these novel fabrication processes. Costs associated with such a transition might burden the typical micropropulsion research budget considerably, and likely extend well beyond its boundaries. Nonetheless, initial steps in this direction are being taken. For example, Aerospace Corporation has been studying novel glass micromachining techniques[26] and electroplating/LIGA (Lithographie, Galvanization, und Abformung) or silicon carbide micromachining may represent other options.

Techniques such as these may over time be integrated into MEMS propulsion development. Existing, silicon-based MEMS propulsion efforts therefore only represent the first steps into this new field of propulsion, and a significant amount of research and development remains to be undertaken. The technical pay-off of this development, however, could be significant and have a potentially very pronounced impact on future microspacecraft designs, allowing highly maneuverable, very small microspacecraft (< ~10 kg) to be realized. Such microspacecraft may be used in mission designs discussed earlier, such as ultra light-weight spacecraft constellations, or micro-inspectors and detachable micro-probes, and therefore be at the center of many highly visible and exciting future space activities. Micropropulsion, in turn, will be a key component of these spacecraft.

In the next section, MEMS propulsion development efforts at JPL will be reviewed, serving as examples for others. Note that MEMS propulsion development today is being pursued by many other institutions in the US and Europe as well. Reference 7 provides a relatively current survey of those activities.

III. THE JPL MEMS MICROPROPULSION PROGRAM

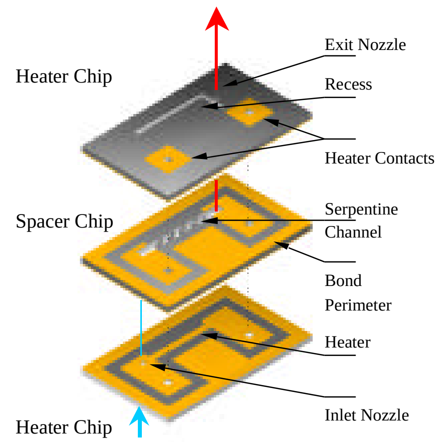
The JPL MEMS micropropulsion program is conducted by the Advanced Propulsion Technology Group in collaboration with the Microdevices Laboratory and the System-on-a-Chip program of the Center for Integrated Space Microsystems (CISM) at JPL. The goal is to study the feasibility of MEMS propulsion components and systems. The program consists of several activities, including both attitude control and primary propulsion, as well as valve development projects and supporting PPU electronics development. The ultimate goal is to incorporate these (and potentially similar technologies developed elsewhere) into highly-integrated propulsion modules as shown in Fig. 5. Such modules would feature minimal external interfaces, easing microspacecraft integration and further miniaturization. The use of such propulsion components and system modules may not be limited to microspacecraft, however, and is envisioned to also be applied to large-scale conventional spacecraft requiring ultra-fine attitude control by means of ultra-low impulse bit propulsion technology (see below). The different JPL MEMS propulsion activities are reviewed in the following.

Note that micropropulsion research at JPL is not limited to these MEMS activities outlined below. Separate non-MEMS development efforts exist as well. They include the development of a milli-Newton hydrazine thruster[27], ultra-light weight tanks, and light-weight flow components. These activities complement the MEMS development efforts by addressing different performance ranges and supporting more conventional system integration schemes suitable also for larger spacecraft.

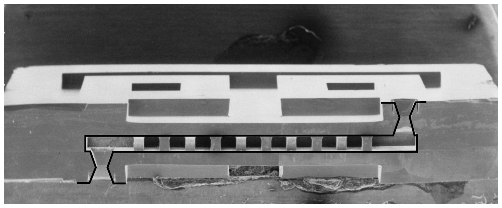
The Vaporizing Liquid Micro-Thruster (VLM)

The Vaporizing Liquid Micro-Thruster (VLM) is targeted for attitude control functions on microspacecraft[28-30]. Figure 6 (a) shows an exploded view of the thruster concept. The VLM operates by vaporizing a suitable liquid propellant inside a micro-machined, thin-film deposited heater assembly. Water, ammonia, and hydrazine are currently under consideration as propellants, although in principle any propellant that can be vaporized, and does not exhibit compatibility issues with the materials of construction, may be used. The thruster chip is of a three-laminate construction. Propellant enters the thruster chip assembly through an opening (currently 50 x 50 μm^2 throat) machined into the bottom wafer. It then flows along a channel machined into the center ("spacer") wafer. Heaters deposited onto the top and bottom wafer form two of the channel walls and heat the fluid to vaporization. The propellant vapor exits the chip assembly through a nozzle machined into the top wafer. In the design iteration shown in Fig. 6, the nozzle is anisotropically etched and has a pyramidic square-shaped contour. A newer design features a conical 2D-nozzle contour, machined by means of deep reactive ion etching (DRIE), allowing for a greater variety of more optimized nozzle contours (Fig. 7). In this design, the propellant exits out of the side of the chip. The separate chip components are bonded via thin gold layers by means of thermal compression bonding. Gold is also the material from which the thin film heaters are made. Gold has a low resistance and therefore allows low-voltage operation, a concern in future microspacecraft designs.

A key aspect in the VLM thruster approach is the ability to use liquid propellants. Liquid propellants can be more compactly stored, can use much lighter-weight tanks than gaseous propellants, and are much less prone to leakage. All these issues are of critical importance to future, weight and volume constraint microspacecraft. On the



(a) VLM Concept



(b) Cross Section of VLM showing Flow Path (Chip Size is 1 x 1 cm^2)

Fig. 6: Vaporizing Liquid Microthruster (VLM) Concept

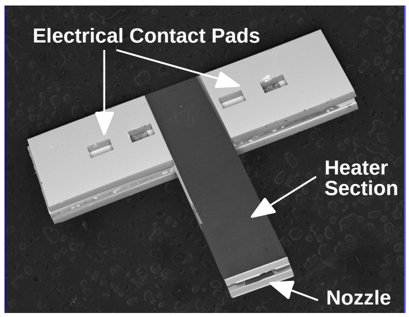


Fig. 7: VLM "T" Thruster

other hand, this thruster concept requires heating of the propellant, representing a power penalty. Increasing heat transfer to the propellant, and reducing heat losses through the high-thermal-conductivity silicon structure material is a central design concern. Heat transfer into the liquid propellant is further hampered by the fact that in very low-Reynolds number microchannel flows (about Re < 10) flow separation and turbulent mixing is not likely to be achieved.

Different designs have emerged to increase heat transfer into the liquid propellant. Figure 6 (b) shows a cross section of one VLM design iteration showing the flow channel featuring internal "fins", increasing the hot surface area exposed to the liquid flow. A similar design has been studied recently by others[31]. At Aerospace Corporation, micro-resistojet thrusters concepts using suspended heater surfaces are being explored, allowing flow to pass over and under the heater surface[32]. In the VLM chip shown in Fig. 7, the heater element is located in the darker colored beam structure forming one leg of the "T"-shaped thruster design. This will allow the thruster to be mounted in such a way that the heater section does not make contact with underlying (packaging material) surfaces, reducing heat losses (bonding will be limited to the electrical contact area only).

Performance goals for the VLM include impulse bits in the range of maybe 10^{-5} - 10^{-6} Ns, provided suitable microvalve technology can be made available (see below), to be applicable to microspacecraft attitude control, or ultra-fine attitude control on larger spacecraft. Thrust values in the range of 0.1 - 0.5 mN at power levels of about 1-2 W or less are being aimed for. Expected specific impulse values are likely low (<100 sec), however, are not of particular importance for most attitude control applications.

Actual performance measurements so far have been paced by the lack of suitable diagnostics. In particular measurement of the low liquid flow rates required the development of new mass flow sensors. Using a recently developed flow sensor that determines flow rates by measuring pressure drops in very small ID tubing, yielded a flow rate of 0.2 mg/hr through a VLM chip of the design shown in Fig. 7. Required power to vaporize the propellant (water) was about 0.7 W. Performance is still poor due to the fact that these tests were performed in a laboratory environment (resulting in convective heat losses into the air).

Tests will be repeated in vacuum. Exposure to vacuum may also lead to the onset of vaporization of the liquid inside the microchannel at lower temperatures and power values. A thrust stand with micro-Newton resolution (see Fig. 8), and a novel thrust stand design with a resolution of about 100 nN currently under development at JPL, will be used to determine thrust values later this spring.

Fig. 8: JPL Micro-Thrust Stand Facility (Design by Princeton University)

The Moog Micro-Valve (MMV)

A microvalve is a keystone in the realization of micro-thruster modules such as those shown in Fig. 5. A recent survey has shown that although many commercial, chip-based micro-valve designs exist, none appear suited for space propulsion applications due to reasons of leakage and slow valve response, among others[33]. Fast valve actuation is a key requirement for thruster valves in order to allow for small impulse bit operation of the thruster. Leakage is a major concern for all propulsion systems, but particularly for microspacecraft systems due to the severely limited propellant supply. Even very small leaks could potentially lead to the depletion of a very significant fraction of the loaded propellant, in particular for gaseous propellants.

A joint development activity between Moog Space Products Division and JPL is addressing the need for a fast-acting, leak-tight microvalve. This valve, also termed the Moog Micro-Valve (MMV), is a solenoid-type of hybrid metal/MEMS construction and approximately 1 cm^3 in size (see Fig. 9). The valve body is machined using low cost metal batch fabrication methods while the coil is MEMS-fabricated. The valve is designed to be interfaced directly through low temperature Kovar-to-Pyrex bonding with other MEMS devices, such as the above described VLM thruster, or other MEMS propulsion components[34]. Compared with more conventional valve technology this valve, through the use of batch-fabrication processes in the metal body as well as coil fabrication, can be produced more cost-effectively and is potentially scalable to much smaller sizes. The MMV concept will also be characterized by faster actuation times, higher sealing forces, and a larger thermal operating range than previous silicon MEMS-based microvalves.

Work on this valve is currently on hold, awaiting future funding. An internal Moog and JPL discretionary development activity, however, pioneered MEMS coil fabrication and led to the assembly and test of a preliminary valve prototype. The MEMS coil will consist of a stack of spiral coil wafers, produced through copper electroplating onto a silicon substrate using a thick photoresist (SU-8) mold. One such wafer is shown in Fig. 10. Stacking several of such wafers on top of each other and bonding them on a wafer-level will allow coils to be manufactured cheaply.

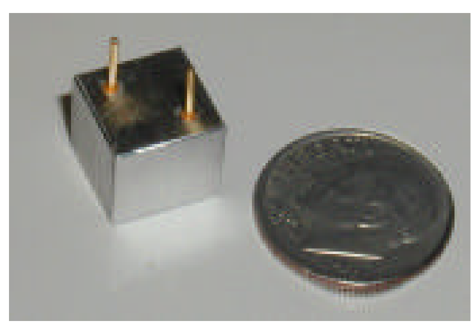


Fig. 9: Moog Micro Valve Prototype

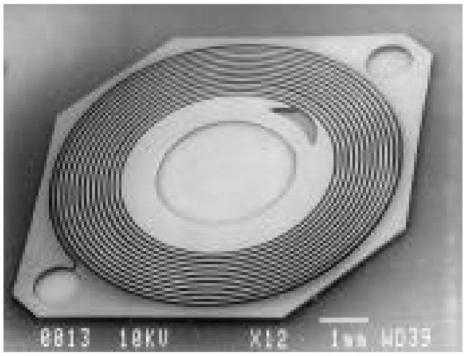


Fig. 10: Single Spiral Coil Chip

Copper electroplating the coil into the SU-8 mold still requires further process refinement and is subject to ongoing study.

Using a conventional wire-wound coil as a place holder, a set of preliminary valve prototypes was tested at Moog in order to study general operation, performance and leak tightness of the design. Performance parameters obtained during these tests are summarized in Table 2. Note that no leakage was detectable (i.e. $< 10^{-4}$ sccs GN_2) even after performing 1 million opening and closing cycles. This demonstrates that reliable, leak-tight microvalves can be obtained, the result of using a soft seat design in the case of the MMV. Continuous (holding) power levels are very low (0.7 W), requiring a voltage of only 5 Vdc. These values are very compatible with anticipated microspacecraft design constraints. The valve volume is 1 cm^3, corresponding to about 2/3 of the linear dimensions of a sugar-cube, and weighs about 7 gram.

Note that the MMV may be used in any number of applications, extending well beyond the field of micropropulsion. It may, for example, be used in low-flow macroscopic feed systems, such as electric propulsion. There also exists a substantial commercial, non-space market for such a valve, covering such varied areas as micro-instruments, micro-fluidics, bio-chemical applications, and micro-robotics.

Table 2: Performance Parameters of the MMV Prototype

Parameter	MMV Performance
Mass (gram)	7
Size (cm^3)	1 (approx. 1 x 1 x 1 cm)
Power (W)	0.7 (continuous)
Voltages (Vdc)	5
Response (ms)	1.5 (open), 0.5 (close)
Pressure (psi)	300 (nom), 1000 (max)
Operating Temp(^{o}C)	0-70
Life	1,000,000 cycles*
Leakage	$< 10^{-4}$ sccs GN_2 (after 1M cycles)

*Test terminated voluntarily

Micro-Piezo Valve

A micro-piezoelectrically actuated valve is being developed by Yang at JPL and previously by Chakraborty et al.[35] Initially developed for cryo-cooler applications, it also holds promise for micropropulsion applications and is continued to be funded with such applications in mind. As with any other valve, many other applications exist as well (see above). Figure 11 shows the principle of operation of the valve. A piezoelectric laminate actuator is attached to a movable membrane (see Fig. 12). Applying a voltage to the piezo actuator causes it to contract and lifts the membrane off the valve seat, opening the valve outlet. The piezoelectric laminate allows for a higher force density and hence better valve sealing than offered by a single crystal piezoelectric actuator, yet requires less voltage to actuate. All valve parts are bonded together via thermal gold compression bonds. The piezoelectric stack is forced into a slightly contracted position during the bonding process to apply a large sealing force on the two openings. Similar designs are also being explored at the University of Uppsala in Sweden in support of cold gas thruster development[36].

Key advantages of this valve concept are fast actuation, like the MMV and unlike thermally actuated (thermopneumatic or bi-morph MEMS valves) available today[33], and the potential to allow for flow control. Depending on how much voltage is applied to the piezoelectric laminate, the valve can be opened to varying degrees, regulating propellant flow. There is a need for miniature flow control systems not only in the newly emerging micropropulsion field, but also in existing propulsion fields such as low-flow electric propulsion.

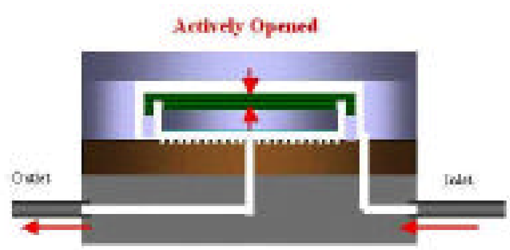


Fig. 11: Micro-Piezovalve Concept

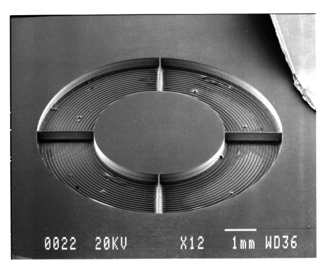


Fig. 12: Piezovalve Membrane

At present this valve is in fabrication and has undergone preliminary flow and leak tests.

Micro-Isolation Valve (MIV)

Isolation valves, such as the commonly used pyro-valves used in conventional feed systems, are one-time opening valves (normally closed type) or one-time closing valves (normally open type). Thus, they cannot replace the function of a valve allowing for repeated actuation, but serve critical functions in a propulsion system nonetheless. Isolation valves serve to seal the propulsion system during launch, for example, where valves designed for repeated actuation may shutter, leading to leakage, or seal a propulsion system during long, inactive interplanetary cruises, providing zero leak rates.

This latter point is of particular importance for microspacecraft applications. Unlike conventional spacecraft, microspacecraft may initially be used in such roles as micro-inspectors or detachable micro-probes as discussed in the Introduction. This role may leave these microspacecraft dormant for large portions of the mission, during which the limited microspacecraft propellant supply will need to be conserved. All valves designed for repeated actuation will leak to some degree across valve seats. In the case of microspacecraft, the limited propellant supply, combined with possibly long dormant spacecraft periods, may cause even the smallest leak rates to have a potentially disastrous impact on the mission, leading to the loss of all or a significant portion of the propellant supply. Zero-leak rate isolation valves may therefore play a much greater role in microspacecraft than in conventional spacecraft.

A MEMS version of such an isolation valve is currently being developed at JPL[37-39]. This valve is silicon-based and fits on a chip 1x1x0.05 cm^3 in size. A photograph of a valve prototype is shown in Fig. 13 and the valve concept is shown in Fig. 14. In this valve concept, flow is prevented from exiting the valve prior to actuation by a doped silicon barrier blocking the flow. This barrier ("plug" - see Fig. 15) is an integral part of the valve structure, machined by etching it into place and does not feature any seals that may be compromised through contamination or vibrations experienced by the valve. To actuate the valve, an electric current is passed through the narrow barrier (15 - 50 μm thick). As a result of the heat dissipation by the current passing through the barrier, causing it to melt, and the upstream propellant pressure, the barrier is blown away, opening the valve. In its current design, the silicon flow passages are sealed via an anodically bonded Pyrex cover, allowing for viewing of the flow passages in this early stage of the experimental program.

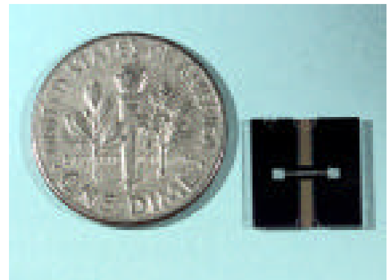


Fig. 13: Micro-Isolation Valve Prototype

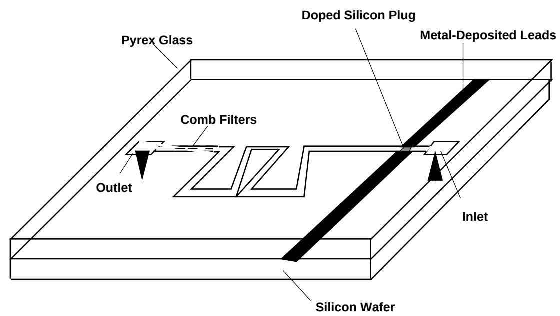


Fig. 14: Schematic of the Micro-Isolation Valve

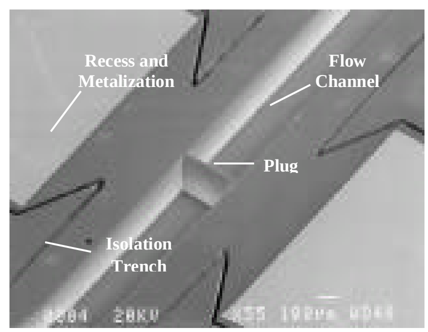


Fig. 15: Close-Up of MIV Barrier and Flow Channel

Three key design issues need to be addressed in the development of this valve. They include (a) structural energy levels compatible with microspacecraft design constraints; and (c) the ability to trap barrier debris within the isolation valve body to avoid the contamination of downstream flow components.

Isolation valves will experience the full tank pressure of the propulsion system in their closed position and will be required to withstand it. For some applications requiring cold gas (i.e. xenon ion engines, or nitrogen cold gas thruster systems selected for the inertness of their propellant) these pressures may be significant, ranging as high as many thousand psi. Recent MIV chips have been pressure tested successfully to burst pressures as high as 3000 psi. Figure 16 shows the test results obtained for valves with different barrier thicknesses. Note that while for

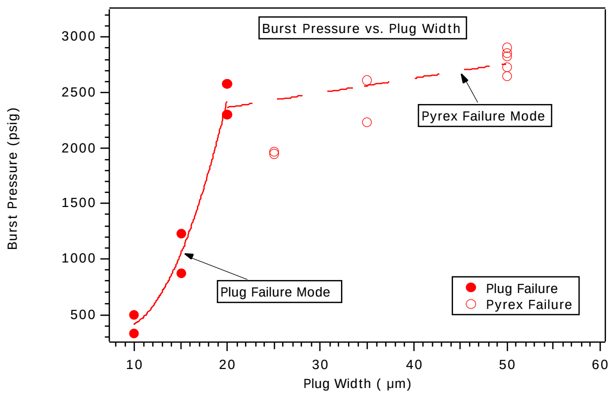


Fig. 16: Results of MIV Burst Pressure Tests

barrier thicknesses below 20 micron, barrier breakage was the cause of failure, for barrier thicknesses greater than 20 micron the barrier remained intact even at the burst pressure, the valve failure now being caused by Pyrex cover breakage[37,38]. This may allow one to assume that by replacing the Pyrex cover (now 0.5 mm) with a thicker Pyrex, or a stronger material, such as silicon (since viewing of the flow channels would no longer be required in operational devices), even higher burst pressures may be obtained.

Figure 17 shows the energies required to melt the barrier. Depending on barrier thickness (25 - 30 micron) the minimum required energies to open the barrier range between 1 - 30 mJ and are therefore very compatible with microspacecraft constraints[39]. Valves typically open very fast, within 0.1 - 0.3 ms[39].

The remaining issue to be resolved is debris trapping within the isolation valve body. Experiments have shown that barrier removal is due to both melting and cracking of the silicon material making up the barrier[39]. The top of the barrier melts, indicating temperatures above 1400 C, being the melting temperature of silicon. Due to the rapid actuation of the valve, the barrier goes into thermal shock and fractures due to difference in thermal expansion along

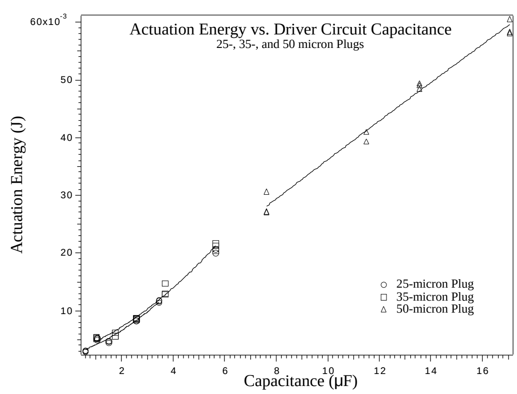


Fig. 17: Energy Requirements to open MIV Barrier

its height. Figure 18 shows an opened barrier. Evidence of molten silicon material can be seen deposited on the downstream flow channel walls. This molten debris may be most easily trapped by optimizing the downstream flow path to condense molten material in dedicated regions of the chip (compare with Fig. 14).

Large fracture material, such as that shown in Fig. 19, may also be trapped quite easily in comb filters located downstream of the barrier. However, associated with the fracture of the barrier and the generation of large shards, such as the ones shown in Fig. 19, are also many very small particles. Initial investigations indicate that the smallest particle sizes generated are less than 1 micron across. Sub-micron filtering is possible via porous metal plugs, and such filters are commercially available. Future MIV designs will need to feature porous filters, either attached to, or, in more advanced design versions, integrated into the chip.

Micro-Ion Engine

The micro-ion engine under development at JPL[40] is a MEMS-hybrid device in the sense that the bulk of the engine is fabricated using miniature, yet conventional metal machining, while several critical engine components are machined using MEMS technologies, thus enabling these small engine designs. The engine prototype shown in Fig. 20 has a discharge chamber diameter of 3 cm. Smaller

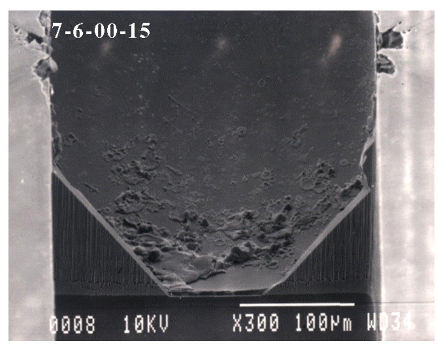


Fig. 18: Opened MIV Barrier

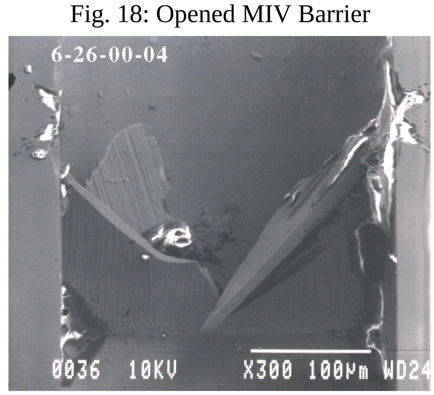


Fig. 19: Opened MIV Barrier showing Barrier Debris

Fig. 20: JPL Micro-Ion Engine Prototype (3-cm Dia.)

engines (1-2 cm) may be explored in the future if they can be realized.

In an ion engine, a neutral gas propellant (typically xenon) is ionized by electron bombardment in a discharge chamber. An internal electron source (cathode) provides and injects these electrons into the discharge chamber. Ions are then extracted from the discharge chamber via electrostatic forces generated between two ion engine grids (see Fig. 20).

Several critical design areas need to be addressed in micro-ion engine development. First, in a micro-ion engine a plasma discharge has to be maintained within a potentially very small discharge volume. As discharge volume decreases, surface-to-volume ratio increases, in turn increasing electron wall losses. These electrons, which now may recombine at the discharge chamber walls, are no longer available for propellant ionization. Therefore higher discharge currents (the electron current emitted by the engine cathode) are required to offset wall losses, decreasing the efficiency of the engine. Below a certain engine size, ion engines may no longer be feasible because they either become wholly inefficient, or can no longer maintain a plasma within given power limits. Studies performed at MIT, for example, indicated that for these reasons entirely MEMS-based ion engine designs may not be feasible[40,41]. In the current program, 3-cm engines, and possibly 1-2 cm engines will be studied.

A second major challenge in the design of an ion engine is the development of appropriate cathode and neutralizer technology. As discussed, the cathode is required to inject electrons into the plasma to generate ions. The neutralizer acts as an externally mounted electron source and injects electrons into the ion beam to neutralize it, avoiding spacecraft charging which otherwise would prevent an ion beam from being extracted. In conventional ion engine designs, hollow cathodes are being used to generate a DC plasma, from which electrons can be extracted. These devices, however, are far too heavy, large, complex, and power consuming to be used in micro-ion engine designs. On the other hand, field emitter cathodes, consisting of microfabricated tips with integrated gate electrodes, may function as micro-ion engine cathodes and neutralizers[42-46]. These devices, originally developed for flat panel displays, are obviously small and light-weight, and emit cold electrons high electric fields between the gate and the sharp emitter tip (see Fig. 21). FEA cathodes have demonstrated 100 mA with less than 1 mW consumed by the gate electrode. Packing densities of these tips have exceeded 10^8 tips/cm^2. However, in a plasma environment, unlike in the flat panel display environment, the fine negative emitter tips may be subject to positive ion bombardment and erosion. Therefore, operation of field emitter cathodes within a plasma environment needs to be studied carefully, and field emitter cathode designs need to be optimized for this environment.

At JPL, in collaboration with other institutions, a thorough feasibility study of various field emitter array (FEA) structures is underway[42-46]. This activity not only supports the micro-ion engine development, but also other activities, such as field emitter array cathodes for conventional, yet small, ion or Hall thrusters, other electric micropropulsion devices (FEEPs and colloid thrusters), or space contacting of tethers[46]. Different cathode materials and configurations are being studied to determine which is most resistive to the rigors of a plasma environment. Currently, molybdenum and silicon emitter tips, and flat carbon-film cathodes have been tested[42]. Thin film coatings on Mo and Si FEAs, like ZrC, HfC, and C, are also studied to lower the cathode work function and increase the energy threshold for sputtering[42]. Finally, integrated electrostatic grid structures, designed to prevent positive ions emanating from the plasma from reaching the cathode tips, are also being explored. Fabrication of such "Cathode Lens and Ion Repeller" (CLAIR) structures is currently in progress.

The ion engine shown in Fig. 20 features micromachined grids required to extract ions from the discharge chamber. These grids are machined by Vacco Industries of South El Monte, CA using a fabrication

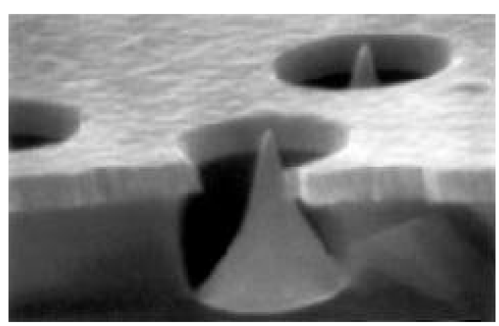


Fig. 21: A single element of a Mo FEA cathode fabricated at SRI International

technique called ChEMS™ [47]. This fabrication technology relies on precision etching of either metals or plastics. Machining tolerances are typically better than those obtained with more traditional machining techniques (i.e. Electric Discharge Machining, laser machining, etc., typically yielding 50 micron (0.002”) tolerances) but less than are obtainable with state-of-the-art silicon-based MEMS technologies, achieving tolerances of 1 micron or less in special cases. ChEMS™ offers similar benefits to MEMS technology, such as cost-effective batch fabrication[47]. ChEMS™ offers an advantage over MEMS by being able to use metals and plastics as base materials, rather than silicon[47]. Although silicon is a stronger material, metals are less brittle. In this particular case, sputter resistant molybdenum was used in the grid fabrication. Grid apertures in the positive screen grid and the negative accelerator grid were 300 micron and 200 micron, respectively.

The engine shown in Fig. 20 was recently tested and shown to be able to generate and maintain a plasma. Currently, research is focused on optimizing the magnetic field configuration of the engine, required to increase the mean free path of the ionizing electrons in the plasma, and performance characterization of the engine. Tests are ongoing at this stage. Operation of the engine with field emitter cathodes is one of the next crucial steps. At present the engine operates with hot filament tungsten electron emitters. These emitters are too power consuming to be considered for an operational micro-ion engine and are merely acting as placeholders for future FEA cathodes[40].

IV. MICROPROPULSION BEYOND MICRO-SPACECRAFT

Although micropropulsion systems, such as those listed in this paper, so far have been discussed mostly in light of potential microspacecraft uses, applications may extend well beyond this area. For example, as alluded to in the Introduction, certain classes of missions not necessarily employing microspacecraft architectures may also have a need for very low impulse bit attitude control thrusters in order to allow for ultra-fine attitude control. These include interferometry missions, either aiming to detect gravity waves such as LISA (Laser Interferometer Space Antenna - see Fig. 22), or other future missions, focusing on the detection of planets around other stars, for example, requiring very high resolution optical interferometry (Fig. 23). Impulse bit requirements may range well into the micro-Newton-second range for all these missions, with thrust control accuracies reaching levels as fine as 0.1 μN[48]. Interferometry missions will likely require higher specific impulse (> 500 sec) thruster technology.

Another class of future missions potentially in need of micropropulsion systems are large inflatable spacecraft. These spacecraft, as shown in Fig. 24, may be subject to constant low solar pressure disturbance torques acting on the large inflatable structure, attempting to turn the spacecraft around its center of mass, still located within the main spacecraft bus. The effect of integrating thrusters with the inflatable structure, thus taking advantage of the long moment arm provided by this structure, to offset these disturbance torques was recently investigated in an unpublished JPL mission study called ARISE. This potential future mission aims to detect radio-wave emissions from black holes by deploying a large inflatable antenna from a spacecraft, to be used via Very Long Baseline (VLB) techniques in conjunction with earth-based radiotelescopes for higher resolution imaging. It was found that integrating a micro-ion engine of a type similar to the prototype shown in Fig. 20, with the inflatable antenna would reduce propellant requirements by one order of magnitude over an

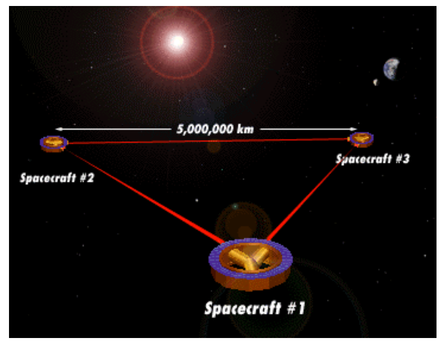


Fig. 22: LISA Mission Concept

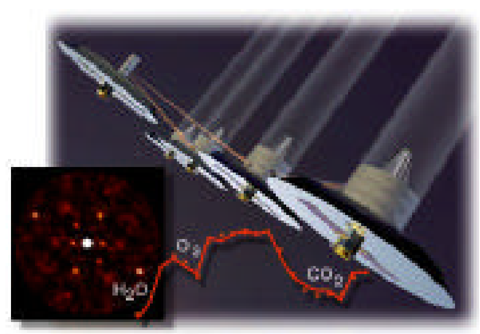


Fig. 23: NASA Terrestial Planet Finder Mission Concept

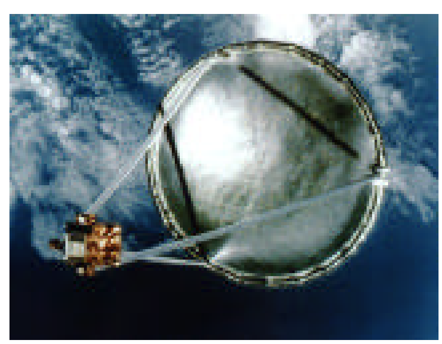


Fig. 24: Space Inflatable Demonstrator Mission (STS-77)

ion engine system integrated with the spacecraft bus. The reduction in propellant is due to the lower required thrust levels (about 1-3 mN) in the case of the antenna-integrated micro-ion engine system, due in turn to the long moment arm provided by the inflatable structure.

V. CONCLUSIONS

Decreasing spacecraft sizes and new spacecraft missions currently being studied, such as interferometry or inflatable spacecraft, require the development of novel propulsion technologies adapted to a new set of requirements that these missions present. Besides requirements to be physically small in size and light-weight for microspacecraft applications, such propulsion systems will also need to operate within very stringent power budgets of a few 10s of W or less of total spacecraft power, and be required to use bus voltages of possibly only 3-5 V. The small size of microspacecraft, as well as ultra-fine pointing requirements of some novel larger spacecraft missions (interferometry), requires thruster technologies capable of delivering impulse bits in the micro-Newton-second range.

One new class of micropropulsion systems that has emerged only recently is MEMS propulsion, employing novel microfabrication techniques to realize extremely small propulsion components. Besides small size and weight, such components may be envisioned to be integrated via on-chip fabrication or chip-to-chip bonding into extremely compact propulsion modules, including the required PPU electronics, thus enabling potentially very small microspacecraft designs (<< ~10 kg) to be obtained. Using such spacecraft may benefit spacecraft constellations, where mass reductions for the individual spacecraft multiply into potentially very significant mass savings for the entire constellation, or detachable micro-probes and micro-inspectors. In the latter cases, mission return may be significantly enhanced but may represent no great weight penalty for the mission.

A very active MEMS propulsion research program is currently underway at JPL, studying the feasibility of a variety of MEMS thrusters and valves, in addition to other, more conventional micropropulsion architectures as well. These include a vaporizing liquid micro-thruster for attitude control applications, a micro-ion engine for primary propulsion and/or attitude control on larger spacecraft, and several valve types, including fast-acting solenoid and piezolelectric valves, representing significant advances in regards to space applications over state-of-the-art commercial MEMS valves, and a micro-isolation valve, required to seal microspacecraft propulsion systems during potentially long dormant periods, as may be the case for micro-probe or inspector missions.

VI. ACKNOWLEDGMENTS

The work described in this paper was conducted at the Jet Propulsion Laboratory, California Institute of Technology under contract with the National Aeronautics and Space Administration. Portions of this work have been funded through the Moog IRAD program and the JPL Director's Research and Development Fund (DRDF), and support is gratefully acknowledged.

VII. REFERENCES

1. Fleeter, R., "Microspacecraft", The Edge City Press, Reston, VA, 1995.
2. Schilling, J.H., Spores, R.A., and Spanjers, G.G., "Micropropulsion Options for the TechSat 21 Space-Based Radar Flight", Micropropulsion for Small Spacecraft, Progress in Astronautics and Aeronautics, Vol. 187, edited by Micci, M. and Ketsdever, A., AIAA , Reston, VA, 2000, Chap. 1, pp. 3-23.
3. Martin, M and Stallard, M.J., "Distributed Satellite Missions and Technologies – The TechSat 21 Program", AIAA Paper 99-4479, AIAA Space Technology Conference, Albuquerque, NM, Sept. 28-30, 1999.
4. Ticker, R.L. and McLennan, D., "NASA's New Millennium Space Technology 5 (ST5) Project", Proceedings, IEEE Aerospace Conference, Big Sky, MN, March 18-25, 2000.
5. Gibbon, D., Surrey Space Centre, England, Pers. Communication, May 2000.
6. West, J., JPL, Pers. Comm., Fall 1995.
7. Mueller, J., "Thruster Options for Microspacecraft: A Review and Evaluation of State-of-the-Art and Emerging Technologies", Micropropulsion for Small Spacecraft, Progress in Astronautics and Aeronautics, Vol. 187, edited by Micci, M. and Ketsdever, A., AIAA , Reston, VA, 2000, Chap. 3, pp. 45-137.
8. Braun, B., Davis, R., Itchkawich, T., and Goforth, T., "MightySat 1: In Space", Paper SSC99-I-3, 13th Annual AIAA/USU Conference on Small Satellites, Utah State University, Logan, UT, Aug. 23-26, 1999.
9. Zheng, Y., "The Gander Microsatellite Radar Altimeter Constellation for Global Sea State Monitoring", Paper SSC99-V-4, 13th Annual AIAA/USU Conference on Small Satellites, Utah State University, Logan, UT, Aug. 23-26, 1999.
10. Thomson, P.L. and Hansen, F., "Danish Orsted Mission In-Orbit Experiences and Status of the Danish Small Satellite Programme", Paper SSC99-I-8, 13th Annual AIAA/USU Conference on Small Satellites, Utah State University, Logan, UT, Aug. 23-26, 1999.
11. Teston, F., Creasey, R., Bermyn, J., Bernaerts, D., and Mellab, K., "PROBA: ESA's Autonomy and Technology Demonstration Mission", Paper SSC99-V-8, 13th Annual AIAA/USU Conference on Small Satellites, Utah State University, Logan, UT, Aug. 23-26, 1999.
12. Chari, R., "Pre-Flight Characteristics of the US Air Force Academy's FalconSat-1", Paper SSC99-VII-8, 13th Annual AIAA/USU Conference on Small Satellites, Utah State University, Logan, UT, Aug. 23-26, 1999.
13. Wong, J., "The University Micro/Nanosatellite as a Micropropulsion Testbed", Paper SSc99-VIII-5, 13th Annual AIAA/USU Conference on Small Satellites, Utah State University, Logan, UT, Aug. 23-26, 1999.
14. Weidow, D. and Bristow, J., "NASA/DoD University Nano-Satellites for Distributed Spacecraft Control", Paper SSC99-V-5, 13th Annual AIAA/USU Conference on Small Satellites, Utah State University, Logan, UT, Aug. 23-26, 1999.
15. Underhill, F., Friedman, A., Wong, J., Reed, H., Hansen, E., Colaprete, A., Rodier, D., Horan, S., and Anderson, B., "Three-Corner Sat Constellation – Arizona State University: Management; Electrical Power System; Structures, Mechanisms, Thermal, and Radiation; Attitude/Orbit Determination and Control; ASU Micropropulsion Experiment; and Integration", Paper SSC99-III-1, 13th Annual AIAA/USU Conference on Small Satellites, Utah State University, Logan, UT, Aug. 23-26, 1999.

16. Hall, C.D., Davis, N.J., DeLaRee, J., Scales, W.A., and Stutzman, W.L., "Virginia Tech Ionospheric Scintillation Measurement Mission", Paper SSC99-III-2, 13th Annual AIAA/USU Conference on Small Satellites, Utah State University, Logan, UT, Aug. 23-26, 1999.
17. Campbell, M., "UW Dawgstar: One Third of ION-F", Paper SSC99-III-4, 13th Annual AIAA/USU Conference on Small Satellites, Utah State University, Logan, UT, Aug. 23-26, 1999.
18. Kitts, C., Pranajaya, F., Townsend, J., and Twiggs, R., "Emerald: An Experimental Mission in Robust Distributed Space Systems", Paper SSC99-VI-5, 13th Annual AIAA/USU Conference on Small Satellites, Utah State University, Logan, UT, Aug. 23-26, 1999.
19. Bloomquist, R., Campbell, M., Das, A., Hall, C., Hansen, E., Horan, S., Kitts, C., Luu, K., Martin, M, Mistola, J., Pfeffer, A., Redd, F., Reed, H., Schlossberg, H., Twiggs, B., and Weidow, D., "Microsatellites and Formation Flying Technologies on University Nanosatellites", AIAA Paper 99-4535, AIAA Space Technology Conference, Albuquerque, NM, Sept. 28-30, 1999.
20. Rayburn, C.D., Spence, H.E., Petschek, H.E., Bellino, M., Vickers, J., and Murphy, M., "Constellation Pathfinder: A University Nanosatellite", Paper SSC99-V-1, 13th Annual AIAA/USU Conference on Small Satellites, Utah State University, Logan, UT, Aug. 23-26, 1999.
21. Luu, K., Martin, M., Stallard, M., Schlossberg, H.,Weidow, D., Blomquist, R., Campbell, M., Hall, C., Horan, S., Kitts, C., Redd, F., Reed, H., Spence, H., and Twiggs, B., "University Nanosatellite Distributed Satellite Capabilities to Support TechSat 21", Paper SSC99-III-3, 13th Annual AIAA/USU Conference on Small Satellites, Utah State University, Logan, UT, Aug. 23-26, 1999.
22. Cáceres, M., "The Emerging Nanosatellite Market", *Aerospace America*, Feb. 2001, pp. 16-18.
23. Spanjers, G., "Micro-Propulsion Research at the Air Force Research Laboratory", Proceedings, Air Force Research Laboratory Formation Flying and Micro-Propulsion Workshop, Oct. 20-21, 1998, Lancaster, CA.
24. Wolf, S. and Tauber, R.N., "Silicon Processing for the VLSI Era", Vol. 1, Lattice Press, Sunset Beach, CA, 1986.
25. Ketsdever, A., "System Considerations and Design Options for Microspacecraft Propulsion Systems", Micropropulsion for Small Spacecraft, Progress in Astronautics and Aeronautics, Vol. 187, edited by Micci, M. and Ketsdever, A., AIAA , Reston, VA, 2000, Chap. 4, pp. 139-163.
26. Fuqua, P., Janson, S.W., Hansen, W.W. and Helvajian, H., "Fabrication of True 3D Microstructures in Glass/Ceramic Materials by Pulsed UV Laser Volumetric Exposure Techniques", SPIE Conference Proc. on Laser Applications in Microelectronic and Optoelectronic Manufacturing IV, San Jose, CA. SPIE Vol. 3618, p. 213.
27. Parker, M., Thunnissen, D., Blandino, J., and Ganapathi, G., "The Preliminary Design and Status of a Hydrazine MilliNewton Thruster Development", AIAA Paper 99-2596, , 35th Joint Propulsion Conference, Los Angeles, CA, June 20-24, 1999.
28. Mueller, J., Tang, W., Wallace, A., Li, W., Bame, D., Chakraborty, I., and Lawton, R., "Design, Analysis, and Fabrication of a Vaporizing Liquid Micro-Thruster", AIAA Paper 97-3054, 33rd Joint Propulsion Conference, Seattle, WA, July 6-9, 1997.
29. Mueller, J., Chakraborty, I., Bame, D., Tang, W., and Wallace, A., "Proof-of-Concept Demonstration of a Vaporizing Liquid Micro-Thruster", AIAA Paper 98-3924, 34th Joint Propulsion Conference, Cleveland, OH, July 13-15, 1998.
30. Mueller, J., Chakraborty, I., Bame, D., and Tang, W., "The Vaporizing Liquid Micro-Thruster Concept: Preliminary Results of Initial Feasibility Studies", *Micropropulsion for Small Spacecraft*, Progress in Astronautics and Aeronautics, Vol. 187, edited by Micci, M. and Ketsdever, A., AIAA , Reston, VA, 2000, Chap. 8, pp. 215 - 230.
31. Bayt, R. and Breuer, K., "Systems Design and Performance of Hot and Cold Supersonic Microjets", AIAA Paper 2001-0721, 39th AIAA Aerospace Sciences Meeting, Reno, NV, Jan. 8-11, 2001.
32. Janson, S., "Batch-Fabricated Resistojets: Initial Results", IEPC Paper 97-070, 25th International Electric Propulsion Conference, Aug. 24-28, 1997, Cleveland, OH.
33. Mueller, J., "A Review and Applicability Assessment of MEMS-Based Microvalve Technologies for Microspacecraft Propulsion", Micropropulsion for Small Spacecraft, Progress in Astronautics and Aeronautics, Vol. 187, edited by Micci, M. and Ketsdever, A., AIAA , Reston, VA, 2000, Chap. 19, pp 449- 476.
34. Vargo, S., Green, A., Mueller, J., Bame, D., and Reinicke, R., "Characterization of Kovar-Pyrex anodically bonded samples – a new packaging approach for MEMS devices", SPIE 2000 Symposium on Micromachining and Microfabrication, Santa Clara, CA, Sept. 18-19, 2000.
35. Chakraborty, I., Tang, W., Bame, D., and Tang, T., "MEMS Micro-Valve For Space Applications", Technical Digest, Transducers'99, Sendai, Japan, June 7-11, 1999, pp. 1820-1823.
36. Stenmark, L., Lang, M., Köhler, J., and Simu, U., "Micromachined Propulsion Components", Proceedings, 2nd Round Table on Micro/Nano Technologies for Space, ESTEC, Noordwijk, The Netherlands, ESA WPP-132, pp. 69-76, Oct. 15-17, 1997.
37. Mueller, J., Vargo, S., Bame, D., Chakraborty, I., and Tang, W., "The Micro-Isolation Valve Concept: Initial Results of a Feasibility Study", Micropropulsion for Small Spacecraft, Progress in Astronautics and Aeronautics, Vol. 187, edited by Micci, M. and Ketsdever, A., AIAA , Reston, VA, 2000, Chap. 17, pp. 399 - 422.
38. Mueller, J., Vargo, S., Bame, D., Tang, W., " Proof-of-Concept Demonstration of a Micro-Isolation Valve", AIAA Paper 99-2726, 35th Joint Propulsion Conference, Los Angeles, CA, June 21-23, 1999.
39. Mueller, J., Vargo, S., Green, A., Bame, D., Orens, R., and Roe, L., "Development of a Micro-Isolation Valve: Minimum Energy Requirements, Repeatability of Valve Actuation, and Preliminary Studies of Debris Generation", AIAA Paper 2000-3675, 36th Joint Propulsion Conference, Huntsville, AL, July 16-19, 2000.
40. Mueller, J., Marrese, C., Wang, J., and Polk, J., "Design and Fabrication of a Micro-Ion Engine", AIAA Paper 2000-3264, 36th Joint Propulsion Conference, Huntsville, AL, July 16-19, 2000
41. Yashko, G., Giffin, G., and Hastings, D., "Design Considerations for Ion Microthrusters", IEPC Paper 97-072, 25th International Electric Propulsion Conference, August 24-28, 1997, Cleveland, OH.
42. Marrese, C. M., Polk, J. E., Jensen, K. L., Gallimore, A. D. , Spindt, C., Fink, R. L., Tolt, Z. L., Palmer, W. D., "An Investigation into the Compatibility of Field Emission Cathode and Electric Thruster Technologies: Theoretical and Experimental Performance Evaluations and Requirements," Micropropulsion for Small Spacecraft, AIAA Progess Series Vol. 187, edited by M. Micci and A. Ketsdever, AIAA , Reston, VA, 2000, Chapter 11, pp. 271 - 302.
43. Marrese, C. M., Wang, C., Goodfellow, K. D., Gallimore, A. D., "Space-Charge Limited Emission from Field Emission Array Cathodes for Electric Propulsion and Tether Applications," Micropropulsion for Small Spacecraft, AIAA Progess Series Vol. 187, edited by M. Micci and A. Ketsdever, AIAA , Reston, VA, 2000, Chapter 18, pp. 423 - 447
44. Marrese, C. M., "Molybdenum Field Emission Array Cathode Performance in Primarily Xenon Environments: Preliminary Experimental Results at Low Operating Voltages," AIAA Paper No. 2000-3266, 36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, July, 2000, Huntsville, AL.
45. Marrese, C. M., "Field Emitter Cathodes and Electric Propulsion Systems," Paper #R4.7, Materials Research Society Conference, April 24-28 2000.
46. Marrese, C.M., Polk, J.E., Hoyt, R.,"Field Emission Array Cathode Development for Electrodynamic Tethers," Space Technology and Applications International Forum, Albuquerque, NM, Feb. 2001.
47. Cardin, J. and Otsap, B., "A Digital Xenon Flow Controller Based on ChEMS™ Technology", AIAA Paper 99-2563, 35th Joint Propulsion Conference, Los Angeles, CA, June 20-24, 1999.
48. Cosmis Journeys, Structure & Evolution of the Universe Roadmap 2003-2023, NASA, NP-1999-11-184-GSFC, 1999.