The University Micro/Nanosatellite as a Micropropulsion Testbed

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Abstract

Using reconfigurable and adaptable networks of micro/nanosatellites to support cost-effective space missions is a popular new direction in the space community. Since the overall resources of micro/nanosatellites are more restricted than those of a single large satellite, the micropropulsion system needs to be lightweight, low-cost, and practical. This paper describes the collaboration between the Arizona State University Student Satellite Lab and the Air Force Research Laboratory Propulsion Directorate to flight test a micropropulsion system on a nanosatellite, ASUSat2. The motivation behind this conjuncture is to employ university satellites as an inexpensive testbed for unconventional new technologies. This paper first provides background on the needs of a micropropulsion system on a micro/nanosatellite cluster, and outlines the issues concerning its development. Then it addresses the experience of the ASU group in designing and building nanosatellites, and describes the design and mission of ASUSat2, which is part of a three-satellite constellation. Next, it examines two micropropulsion systems, the free molecule micro-resistojet and the cold-gas micronozzle, for the ASUSat2 mission. The preliminary study shows that the free molecule micro-resistojet would be an attractive micropropulsion system for ASUSat2.

Introduction

There is strong interest in the use of networks and clusters of reconfigurable and adaptable micro- and nanosatellites to support cost-effective space missions. By definition, a microsatellite is 10-100 kg mass, and a nanosatellite 1-10 kg mass. One concept to address this technology involves satellites flying in formation that operate cooperatively to perform a surveillance mission: the Air Force Research Laboratory's (AFRL) TechSat 21 concept. The TechSat 21 mission was motivated by the need to reduce the weight and cost of space systems. Previous studies have suggested that, by partitioning the functions of a single large satellite into a number of smaller satellites that orbit together in close proximity and operate cooperatively, one could achieve cost and weight reductions[1]. Such ideas involve a cluster of several to many satellites that fly in formations from 10 to 1000 meters in size. The satellites are in communication with each other, and each could perform a unique dedicated task, or the cluster could operate like a parallel computer: each nearly identical satellite contributing a small part to the whole. The cluster operates cooperatively to perform a function like a "virtual" satellite. These ideas have been applied to the radar mission, and preliminary estimates have indicated that there is merit to this approach.[1]

To succeed, technology must be developed to enable each micro/nanosatellite to be lightweight, low-cost, safe, and very capable. As the Department of Defense Program Plan seeks seamless transition from technology development to on-orbit demonstration, a university satellite program with its industry and government partners can provide an inexpensive testbed and innovative rethinking of technology, while at the same time effectively educating the next generation of scientists and engineers.[2] This paper will describe the partnership of Arizona State University (ASU) and AFRL personnel to flight test a micropropulsion system on a university nanosatellite.

A key element for microspacecraft operations is a feasible micropropulsion system. Micropropulsion can

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offer a wide variety of mission options, all relevant to formation flying: attitude control, orbital-drag makeup (low Earth orbit, LEO), altitude raising, plane changes (costly), and de-orbit. Consider altitude raising: a spiral transfer requires a low-thrust, constant burn. Yet rather large Δv is still required of the propulsion system as shown in Fig. 1. As individual satellites become useless, there is a strong interest in de-orbiting them to eliminate the growing problem of space debris. Because the propulsion system operates only at end-of-life (EOL) for a de-orbit maneuver, system failures are more tolerable. The propulsion system is also simplified since one-time valves can be used, pressure regulation is not required, power usage is not critical, and lifetime testing will be reduced. Fig. 2 shows the Δv required for de-orbit to 0 km altitude.

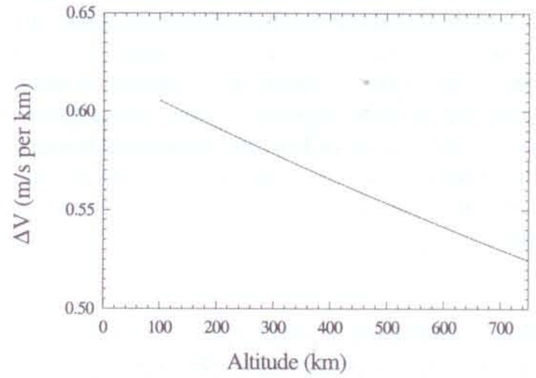


Figure 1. Δv required for orbit raising

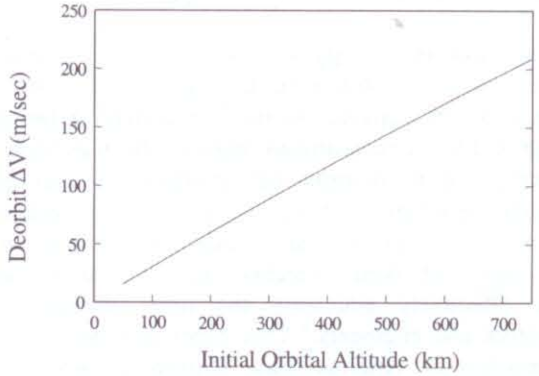


Figure 2. Δv required for De-orbit

The field of micropropulsion is still in its infancy, and further development of current concepts is very much needed. Nevertheless, there is a wide range of new concepts presently being investigated within government agencies, industry and universities.[1,3] For example, the ASU Student Satellite Lab (ASUSat Lab) developed a system of instruments and sensors that integrate solar power and ionospheric plasma for low-thrust propulsion, attitude control, and electrical power generation.[4,5,6] This idea will be further developed in a separate effort in an attempt to fly it on a future mission. Several micropropulsion concepts have also been conceived and are currently under development at the AFRL's Propulsion Directorate.[1,3]

The issues encountered for micropropulsion systems on a micro/nanosatellite include:

- the use of hazardous propellants (safety)
- propellant/system materials incompatibility (propellant reacts with surface)
- contamination problems from propellant ablation and vaporization
- valve leakage
- system reliability and durability
- manufacturing complexity
- flow passage clogging in micromachined devices (single-point failures)

In order to be useful in micro/nanosatellite operations, micropropulsion systems must be designed with these challenges and attributes in mind while working to keep the unit compact and low-cost.

As can be imagined, overall system considerations enter the selection of a thruster in addition to performance (specific impulse, Isp) of the propellant. The resources of mass, volume, and power available on micro/nanosatellites are no longer "unlimited" as with larger satellites. No longer is a micro/nanosatellite just a bus with systems added inside; every part must be justified, minimized, optimized, and ideally multifunctional. When considering the design of nanosatellites, this is particularly important due to the severe constraints associated with these very small systems.

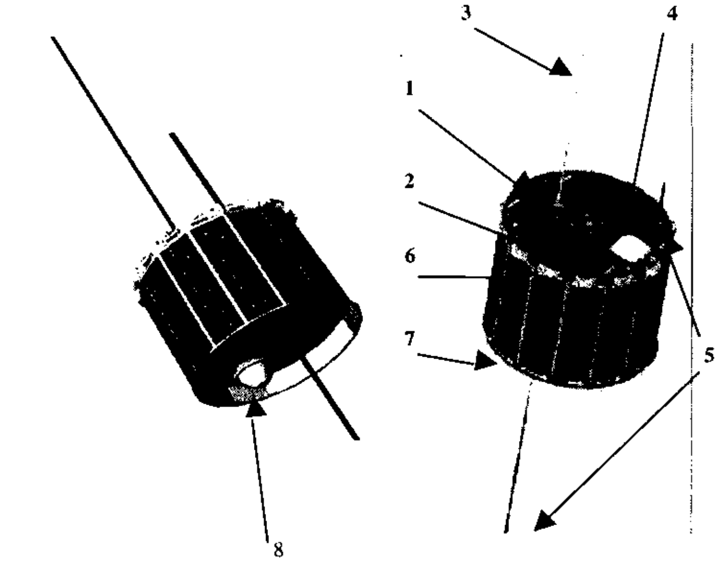
ASU Student Satellite Program - ASUSat Lab

To demonstrate our team's heritage in nanosatellite design, a description of ASU's first program, ASUSat1, is in order. This will be followed by the details of our collaborative effort with AFRL in flight testing a micropropulsion system on ASUSat2.

ASUSat1

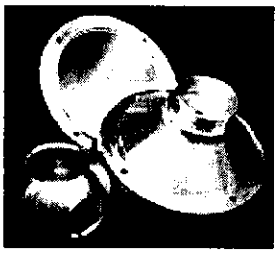
In October of 1993, Orbital Sciences Corporation (OSC) agreed to launch a small payload on a Pegasus vehicle if the satellite would perform meaningful science, weigh under 6 kg (including the release mechanism), and fit within an envelope of 33 cm in diameter and 27 cm in height. With the given constraints from OSC, ASUSat1 would be designed to be one of the lightest satellites ever to do valuable science. The size and weight restrictions eliminated many commonly used techniques, and thus added another dimension of technology demonstration to the project. Due to weight constraints, active control, radiation shielding, large battery packs, aluminum structures, and many complex mechanisms were eliminated from the design. Also with the minimal power that could be generated from the small surface areas, only the lowest-power-consuming devices could be used onboard.

From the conception of the project to the present, the launch opportunity has changed four times (not unusual for an industry environment). As a consequence, the ASUSat1 team has developed a number of science experiments for each launch opportunity. For example, for the initial design for a 450-km altitude, 6am-6pm, sun-synchronous orbit, the science of the mission consisted of the Micro-particle Recognition Experiment (MRE).[7] For a later launch opportunity to a 325-km altitude, 6am-6pm, sun-synchronous orbit, the Ionospheric Plasma Research Experiment (IPRE) was planned, which integrated solar power and ionospheric plasma for low-thrust propulsion (Hall accelerators), attitude control, and electrical power generation. The current mission to a near-polar 750-km altitude orbit includes low-cost coarse-resolution spectral imaging, global positioning system (GPS), innovative passive stabilization and damping, 10-degree attitude determination at low cost ($1000 per satellite), autonomous operations, and provision of an audio transponder for amateur radio (AMSAT) operators.[2,4-6,8]

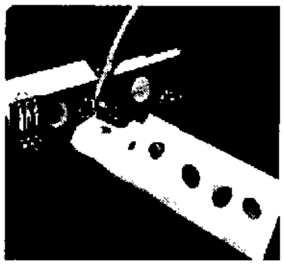


Exterior Components:
1. Composite Bus
2. GaAs Solar Array
3. Gravity Gradient Boom
4. GPS Patch Antenna
5. TX & RX Antennae
6. Sun-Earth Sensor Array
7. Marmon ring
8. Gravity Gradient Fluid Damper

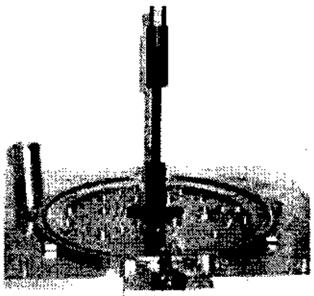
Interior Components:
Student Electronics: Computer, Modem, Sensor Interface board, Sensors
GPS Receiver
Two Receivers and Transmitter
Batteries
Power control board
GG Boom Deployer
Two Dycam Cameras



Fluid damper to reduce oscillations of satellite in orbit



Sun- and earth-sensor array to determine satellite orientation



Marmon-clamp deployment mechanism

Figure 3. ASUSat1 Satellite and Various Components

The current ASUSat1 mass (satellite only) is approximately 5 kg. The satellite body, shown in Fig. 3, is constructed of a low-cost, light-weight M55J carbon fiber in a 954-2A epoxy resin. The 1.1 kilogram structure is a 14-sided cylinder inscribed within a 31 cm diameter circle with a length of 24 cm and a thickness of 0.8 mm. GaAs solar arrays are mounted on all 14 sides of the spacecraft and on one of the bulkheads. Each panel consists of thirty 2 cm x 2 cm space-rated cells which provide approximately 13 volts from the 14 panels connected in parallel. The remainder of the power system consists of commercial-grade NiCd batteries capable of providing an average of 8.5 to 10 Watts to the spacecraft subsystems. Other components include dynamics and thermal sensors, a spherical fluid damper, a torque coil, and a gravity-gradient boom, in addition to the cameras, voice repeater and a number of house-keeping electronics components. An innovative passive approach using a gravity-gradient fluid damper coupled with a gravity-gradient boom will provide spacecraft stabilization.[6,9] A low-cost array of student-designed light-sensing diodes is used for attitude determination. A block of 3 diodes is mounted on seven of the 14 sides of the satellite. Two diodes are sensitive to visible light from the sun and one is sensitive to infrared radiation from Earth. All sensors are read every 5 minutes to determine the orientation of the satellite. Attitude determination is possible within a $\pm 10^\circ$ band. Position and velocity information is obtained from an on-board global positioning system.

The present launch is scheduled for September 15, 1999 on the first Air Force Orbital/Suborbital Program Space Launch Vehicle. The final flight hardware was delivered to Weber State University on May 13, 1999, for final integration with the other payloads on the JAWSAT structure. Once launched and inserted, the lifetime of the satellite is estimated to be two years with scientific data transmitted to an ASU-based ground station.

Since October 1993, the program has consisted of approximately 25 students each semester, with most being undergraduate. The students come from various disciplines of engineering, liberal arts and sciences, business, art, and journalism. They serve on the satellite subsystems: commands, communications, dynamics and control, ground support equipment, mechanisms and deployment, power, propulsion, science and instruments, software and data analysis, structures and materials, thermal, and systems. The students participate in all leadership, management, and teaming aspects of an industrial space program. There are weekly meetings at all levels for the entire team, and a weekly report is required of each student to ensure timely progress toward team and individual goals. Design reviews (Conceptual Design, Preliminary Design, Critical Design, etc.) are performed by the students with significant industry participation to ensure the project's success. Support to date, in the form of mentoring and assessment, hardware donations, student support, and use of fabrication and testing facilities has been secured from some forty companies and the NASA Space Grant Program.

Student projects such as ASUSat1 provide a unique opportunity to combine the educational and research missions of a university in a single program.[2] The students are presented with a multidisciplinary work environment, where teamwork is absolutely essential. This experience, while it represents the real working environment of most engineers today, is still unusual in a university setting. Moreover, the limited resources and rigid constraints placed on this particular satellite require the development of innovative technical solutions. These new solutions range from the design of new low-cost components to the development of manufacturing techniques that can be easily performed by students with little manufacturing experience.

ASUSat2

Concurrent with the research and development of the candidate micropropulsion system will be the design of ASU's second nanosatellite. This project, started in January 1999 as part of the AFOSR/DARPA University Nanosatellite Program, is a joint effort among ASU, University of Colorado at Boulder (CU, Elaine Hansen and Dan Rodier), and New Mexico State University (NMSU, Steve Horan). Aptly named Three Corner Sat (3$\wedge$Sat), our proposed constellation of three identical nanosatellites will demonstrate stereo imaging, formation flying, cellular-phone communications, and innovative command and data handling.[10] In addition, each University in the 3$\wedge$Sat constellation has the opportunity to fly an individual unique payload should it desire. ASU's nanosatellite, designated ASUSat2, will demonstrate orbit raising and de-orbiting with an innovative micropropulsion system as described in a later Section. The 3$\wedge$Sat constellation is scheduled to be launched in late 2001 by the Air Force.

The projected constraints include a minimum total mass of 10 kg and volume of 0.03 m^3. The exterior envelope of the spacecraft bus is a six-sided disk structure based on maximum illuminated surface area versus structural complexity. The design will be modular, allowing for on-the-spot modifications without extra machining or irreversible processes. The design incorporates a common electrical bus that is easily accessible and durable. All components will mount to aluminum honeycomb plates, which fasten to the main frame via slide-in interface brackets. For attitude control, the ASU students have developed an innovative, passive, gravity-gradient fluid damper which, coupled with a parallel-gravity-gradient-boom configuration, can yield a reasonable (+/- 5 degrees) pointing accuracy. In addition, we are also highly interested in pursuing small, lightweight, low-power control moment gyros, torquerods, or other form of attitude control devices. Each satellite will consist of body-mounted solar arrays that should provide a maximum average illuminated area of 0.22 m^2 with an estimated in-Sun average of about 0.16 m^2. This translates to 33 watts of power based on 18%-efficiency solar cells.

To effectively select, design, and integrate an appropriate micropropulsion system, the author serves as Propulsion Subsystem Leader for 3ASat/ASUSat2 and works directly with AFRL personnel, and will visit the Lab when appropriate for reviews and testing. She also participates in the weekly general-team and systems meetings for 3ASat and prepares weekly reports on her research to be distributed with the other subsystem reports. This collaboration facilitates seamless communication between ASU and AFRL.

ASUSat2 Mission Profile

The AFOSR/DARPA requirement for 3ASat is only for a four-month on-orbit demonstration. Further validation of technologies, data collection and student education would favor an extended mission up to two years. The antiscipated launch vehicle for the University Nanosatellite Program is the NASA Space Shuttle, which could leave the microspacecraft at a rather low altitude of approximately 250 – 400 km. As a result, a propulsion system will be required to extend the orbital lifetime of ASUSat2. In addition, a propulsion system would be desirable for spacecraft attitude control and to demonstrate formation flying. The final objective of the ASUSat2 mission will be to perform a de-orbit maneuver to remove the satellite from LEO.

Obviously, the proposed launch mass requirements would determine the amount of on-orbit maneuvering. The following sections will investigate the propellant requirement and size the micropropulsion system for the ASUSat2 mission profile. The analyses that lead to the results presented were conducted by Dr. Andrew Ketsdever and his associates.

Estimated Δv Required for Drag Make-up

Since a launch aboard the Shuttle is expected in 2001, maximum solar conditions will be used throughout the analysis. [11] A critical design requirement is that the thrust produced by the micropropulsion system must exceed the atmospheric drag imposed by the LEO. In order to calculate the drag force on a spacecraft and subsequently the propellant requirement, several parameters are required. Since ASUSat2 has not yet been fully designed, a range of values is given in Table 1 and will be used in the following calculations to estimate the propellant budget.

Table 1. Spacecraft Parameters for ASUSat2 Mission.

Minimum Total Mass (kg)	10
Minimum Cross Sectional Area (m^2)	0.125
Minimum Drag Coefficient[12]	2.0
Maximum Total Mass (kg)	17
Maximum Cross Sectional Area (m^2)	0.131
Maximum Drag Coefficient[12]	4.0
Minimum Ballistic Coefficient (kg/m^2)	19.1
Maximum Ballistic Coefficient (kg/m^2)	68.0

The minimum and maximum drag coefficients are calculated using various gas/surface-interaction processes.[12] A typical value of the drag coefficient for most spacecraft is approximately 2.2.[11] The ballistic coefficient is defined as

$$B = m / (C_D A) \qquad (1)$$

where m is the total spacecraft mass, C_D is the coefficient of drag, and A is the total frontal area of the spacecraft (i.e. in the direction of the velocity).[11] The force due to drag on a spacecraft is given by

$$F_D = 0.5\, m\, \rho\, v^2 B^{-1} \qquad (2)$$

where ρ is the atmospheric density and v is the spacecraft orbital speed at a given altitude. The maximum drag force extends from 0.53 to 3.2 mN for the range of ballistic coefficients at the lowest orbital altitude (250 km). Consequently, the minimum thrust from the micropropulsion system should be approximately 10 mN to adequately overcome the expected drag force.

The effects of drag on ASUSat2 can be counteracted in two manners. First, a micropropulsion system can be used periodically to maintain the original orbit. Second, a micropropulsion system can be used to raise the spacecraft to a specific altitude that can support the desired mission lifetime. A combination of these two methods can allow the spacecraft to be raised to an intermediate altitude that can then be maintained with reduced propulsive requirements.

Table 2 shows the estimated values of ASUSat2 lifetime and propulsive requirements. Under the assumed maximum solar conditions, the shortest lifetime would result from the worst-case Shuttle altitude of 250 km. Maintaining the orbit at 250 km for two-years would require a prohibitive Δv. Therefore, the preferred technique would be to raise the orbit of the microsatellite to one which can support a nominal two-year mission. For the B=19.1 k/m^2 case, the optimum orbit raising maneuver would be to raise the orbit to 650 km initially. Since an altitude of 650 km will provide a two-year mission lifetime for the B=19.1 k/m^2 case, additional propulsive maneuvers to maintain this altitude would be optional. For the B=68.0 k/m^2 case, the optimum orbit raising technique would be to raise the orbit to 550 km initially with the option of additional propulsive maneuvers to maintain the altitude. Therefore, maintaining the orbit at a given altitude would be preferable, and the following calculations will include these altitude maintenance maneuvers.

Table 2. Estimated Propulsive Requirements for Drag Make up and Altitude Maintenance

Final Altitude (km)	Lifetime [11] (years)		Δv to raise orbit from 250 km (m/sec)	Δv to maintain final orbit for two years (m/sec)		Total Δv required for drag makeup (orbit raise/maintain) (m/sec)	
	B=19.1 kg/m^2	B=68 kg/m^2		B=19.1 kg/m^2	B=68 kg/m^2	B=19.1 kg/m^2	B=68 kg/m^2
250	0.005	0.01	0	11940	3350	11940	3350
300	0.015	0.05	29	4774	1342	4803	1371
400	0.065	0.2	86	1022	288	1108	374
450	0.15	0.5	115	516	146	631	261
500	0.3	1	142	270	76	412	218
550	0.6	**2.5**	170	146	42	316	**212**
600	1	15	197	80	22	277	219
650	**2.5**	30	224	44	12	**268**	236
700	20	60	251	26	8	277	259

Estimated Δv Required for Attitude-Control Errors

Orbit-raising maneuvers performed with a low-thrust propulsion system will require a constant-thrust spiral transfer, which is subjected to pointing errors of the microspacecraft. The utilization of a gravity-gradient boom and a fluid damper is expected to minimize the microsatellite pointing error to within 10°. This will increase the total propellant budget by 3% for the worst-case pointing configuration throughout the altitude-raising maneuver.

Estimated Δv Required to De-orbit

The propulsive requirements for de-orbit range from a Δv of 0 m/sec to 110 m/sec. No propulsive de-orbit is required if the final orbit is not maintained during the mission once the initial orbit-raising maneuver is complete. If the orbit is maintained at either 550 km (B=68 kg/m^2) or 650 km (B=19.1 kg/m^2), it would be desirable to lower the altitude to the point where a lifetime close to two months is achieved. This would allow further data collection on the drag force experienced by the spacecraft. The final altitude after the de-orbit spiral transfer would be approximately 350 km (B=68 kg/m^2) or 450 km (B=19.1 kg/m^2), resulting in a Δv near 110 m/sec for either case.

Table 3. Total estimated Mission-Required Δv for ASUSat2

Ballistic Coefficient (kg/m^2)	19.1	68.0
Δv – Drag Makeup (m/sec)	268	212
Δv – De-Orbit (m/sec)	109	112
Δv – Other Maneuvers (m/sec)	20	20
Δv – Pointing Errors (m/sec)	11.9	10.3
Total Δv Required for Mission (m/sec)	**408.9**	**354.3**

The total propulsive budget is given in Table 3 for all potential maneuvers and compensation for losses. Additional maneuvers are desired to assess the micropropulsion system's ability to perform attitude control and demonstrate formation flying. However, they are expected to require minimal propellant.

Potential Micropropulsion Systems for ASUSat2

Two micropropulsion systems are being developed to demonstrate unique technology on ASUSat2 within the pre-launch time frame. They are the free molecule micro-resistojet (FMMR), which is described in detail elsewhere, and a cold-gas micronozzle thruster (CG), which incorporates a laser-machined, 3-dimensional conical nozzle with a throat diameter of 90 μm.[13] Compared to other micropropulsion systems being developed in the industry, such as variations of the ion thruster, the FMMR and CG system are better candidates for ASUSat2. Although these two systems do not produce very high Δv as opposed to some systems (Hall thruster), their mass and power requirements are a better match for the ASUSat2 constraints. In addition, the maturity of the technology sets these two systems ahead of the others for the two-year pre-launch time frame.

System Requirements for Free Molecule Micro-Resistojet (FMMR)

The predicted performance characteristics of the FMMR are shown in Fig. 5 for a water propellant and a heated-wall temperature of 600 K. These results were derived from numerical simulations using the Direct Simulation Monte Carlo (DSMC) technique.[12,13] The FMMR will operate most effectively for the ASUSat2 mission by utilizing a water propellant stored as ice on orbit. For typical spacecraft temperatures in LEO (260 K), the vapor pressure of ice is approximately 195 Pa which is an ideal stagnation pressure for the FMMR with a 100 μm slot width. This operating pressure gives a thrust per unit slot length of approximately 10 mN/m (Fig. 5), which implies that 100 slots with an individual length of 1 cm are required to produce a 10 mN thrust. Although higher values of thrust can be obtained with higher stagnation pressures, there is a distinct advantage to operating the FMMR at low pressures.[13] The FMMR specific impulse at this stagnation pressure is approximately 70.25 sec. As can be seen in Fig. 5, smaller thrust required for attitude control can be obtained by reducing the FMMR stagnation pressure (or propellant storage temperature) without significantly compromising the overall efficiency.

Propellant Mass Requirements

The propellant mass required to perform Δv maneuvers is given by

$$m_p = m_o \{1 - \exp(-\Delta v / Isp\, g_o)\} \qquad (3)$$

where m_o is the initial dry mass of the spacecraft. For the range of total required Δv given in Table C, the propellant mass required for the FMMR varies between 2.8 and 3.1 kg. The volume required to store the liquid water propellant on the ground would therefore be approximately 0.003 m^3. Since the FMMR propellant is stored as a liquid at room temperature, the propellant tank need only be designed to survive the launch environment. For instance, the largest propellant volume could be contained in a spherical tank with a diameter of 9.05 cm. For a graphite propellant tank, the tank mass would be about 0.4 kg. The composite results are summarized in Table 4 for Δv of 410 m/sec (worst case scenario for ASUSat2) and a dry spacecraft mass of 7 kg.

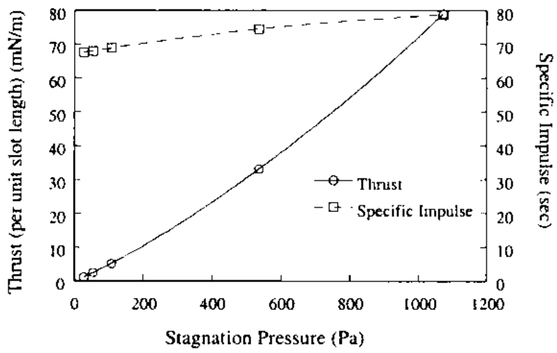


Figure 5. FMMR Performance as Function of Operating Pressure for Water Propellant

Power Requirements

The FMMR uses electrical power to heat the thin-film elements which transfer energy into the propellant gas through surface collisions. For the FMMR geometry and operating conditions described above, approximately 10 Watts is required to heat the propellant gas to obtain the expected performance. Heat loss is the major source of inefficiency in an electrothermal device and has been characterized for the FMMR elsewhere.[14] For the geometry described above, the additional power required due to heat loss in the thruster is approximately 2 W by radiation and 7 W by conduction, although the conduction losses may be significantly reduced with simple MEMS fabrication techniques. Hence, the total power required to operate the FMMR can be maintained under 20 W. Since the FMMR operates at very low pressures, the valve-sealing requirements are minimized, and the additional power required for valve operations should be a minimal 300 mW.[15] Pressure regulation inside the device can be achieved by controlling the propellant storage temperature (propellant vapor pressure) with waste heat from the microspacecraft.

Overall System Structure

The FMMR offers several additional benefits from a systems standpoint. First, the long expansion slots are not prone to catastrophic plugging by contaminants. Second, the propellant feed system mass and valving requirements are minimized. Third, the micromachined structure is lightweight and robust in construction. In addition, the entire slot assembly for the FMMR geometry of 100 slots with a width of 100 μm and an expansion angle of 54.7° can be contained within a 2.5 cm x 2.5 cm area. Plus the added benefit of launching a benign propellant at atmospheric pressure makes the FMMR very attractive, especially in the case of the proposed Shuttle launch. Lastly, the total FMMR system mass will be approximately 4 kg including propellant.

System Requirements for Cold Gas Micronozzle

The cold gas (CG) micronozzle thruster has a throat diameter of 87.6 μm, an exit diameter of 257 μm, and a supersonic expansion angle of 15°. To provide a thrust of 10 mN with a molecular nitrogen propellant, the CG thruster will be required to operate at a stagnation pressure of 10^6 Pa. At these conditions, the anticipated specific impulse for this thruster is 80.3 sec.

Propellant Mass Requirements

Following the same analysis developed for the FMMR, the propellant mass required for the CG micronozzle thruster to perform the required mission ranges from 2.5 to 2.8 kg. The minimum design operating pressure for the CG thruster is approximately 10^5 Pa, which indicates that some propellant will remain in the propellant feed system at the spacecraft's end of life. Based on the assumption that no propellant will be lost due to valve leakage, this implies that 0.7% more propellant mass will need to be stored in order to perform the mission based on the same Δv requirements. However, valve leakage can be a major concern with high-pressure systems.

The use of gaseous propellant on microspacecraft has two serious drawbacks. First, the relatively low density of the propellant requires large storage volumes on extremely space-limited microspacecraft. Second, gaseous propellants must be stored at high pressures which requires relatively massive fortified propellant tanks when compared to propellant mass. For example, a graphite propellant tank containing nitrogen stored at 20 MPa will require a mass approaching 1.3 kg. To reduce the storage volume, the storage pressure can be increased; however, the tank mass may increase to unacceptable levels.[13] The CG system requirements are summarized in Table 4.

Power Requirements

Unfortunately, the use of a CG micronozzle thruster does not come at reduced power consumption. Since the propellant storage pressure is roughly 200 atmospheres, a valve is required with an extremely low leak rate. Typically these valves require power to open on the order of 10 to 30 W.[16] However, lower power valves with increasingly lower leak rates are currently being developed even on the MEMS level.[17] In this general survey, it is assumed that the power supply mass for the CG thruster is equivalent to that required for the FMMR.

Overall System Structure

The CG micronozzle thruster has several disadvantages from an overall systems viewpoint; however, the technology has been previously demonstrated. The CG micronozzle system will require high-pressure feed lines, pressure regulation, and strict propellant filtering due to an additional concern of catastrophically plugging the nozzle throat. The total CG propulsion system mass will be approximately 5 kg including propellant.

Table 4. Micropropulsion System Comparison

Thruster	FMMR	CG
Propellant	Water	N_2
Thrust (mN)	10	10
Isp (sec)	70.3	80.3
Propellant Mass (kg)	3.1	2.8
Empty Propellant Tank Mass (kg)	0.4	1.3
Full Propellant Tank Mass (kg)	3.5	4.1
Spherical Tank Diameter (cm)	9.1	14.4
Estimated Power Requirement (W)	20	10-30

Summary

Micropropulsion System

The FMMR and CG system are chosen from among other micropropulsion technologies because their mass and power requirements are a better match for ASUSat2. Moreover, the maturity of the technology also promises a functional system to be completed within the two-year pre-launch time frame. Although both micropropulsion systems can satisfy the same operation requirements, the FMMR has several beneficial systems characteristics which makes it the more attractive system for ASUSat2. For example, the propellant storage volume is greatly reduced over the high-pressure cold-gas system; the geometry of the FMMR is much easier to machine; and it is less liable to catastrophic clogging compared to the CG system. On the other hand, CG thrusters have been flight-proven, and additional propulsion technology (e.g. MEMS valves and components) can be incorporated and flight tested on ASUSat2. Since the FMMR requires some additional development to make it a flight ready system, an innovatively customized CG micronozzle system will be developed in parallel to ensure a micropropulsion system is ready for the launch of ASUSat2.

The mission presented is a worst-case scenario in which ASUSat2 is released at 250 km. With a higher Shuttle insertion of 400 km, smaller micropropulsion-system requirements for mass, volume, and power will be necessary. Moreover, trading on-orbit lifetime for smaller resource usage provides another possibility. For example, ASUSat2 could be on-orbit for one year instead of two, thus requiring it to be raised to a lower orbit. Another possibility to keep resource usage down is to allow the higher orbit to decay over the lifetime of the mission; which eliminates the additional orbit maintenance maneuvers. These are system trades that will be considered over the next six months of design. However, the team feels that the numbers are encouraging and suggest success of the FMMR as a candidate for microspacecraft propulsion.

University Micro/Nanosatellite Program

Besides the utility of ASUSat2 as an inexpensive testbed for the on-orbit demonstration of new micropropulsion technology, another significant benefit of this collaboration is the role this and similar projects have within education. Over 400 students who have been involved in the ASUSat Lab since the beginning in 1993 have all benefited in different ways in this non-traditional program. The main benefit of the program comes in the skills obtained by the students. This project has increased student knowledge and awareness in such areas as teamwork; systems engineering; public relations and politics; various engineering tools; documentation practices; space-hardware design, manufacturing, and testing; and space environmental conditions. The program has also helped enhance classroom knowledge through application of theories and tools presented in the classroom setting.

Another feature of the project that strongly impacts the students' education is interaction with industry and government. This day-to-day operation of a realistic project brings the students closer to the industry environment and helps students establish a long-lasting network and identify future job opportunities. With the large amount of industry interaction associated with such a project, students also gain confidence in their abilities and develop effective public-speaking and human-interaction skills. Students acquiring these skills at the university level become even more valuable to their profession.

Conclusion

The collaboration described in this paper has two significant outcomes:

- Regardless of the type of micropropulsion system flown, this endeavor will significantly contribute to the TechSat21 goal of "seamless transition from technology development to on-orbit demonstration". Here AFRL has teamed with a low-cost university flight experiment to validate the concept.
- In the process, undergraduate and graduate students are providing fresh ideas and gaining invaluable hands-on experience in cutting-edge technologies relevant to National needs while still in school.

The ASUSat team would strongly encourage others to pursue similar collaborations.

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