A Novel Cold Gas Propulsion System for Nanosatellites and Picosatellites

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ABSTRACT

A Microelectromechanical System-based (MEMS) PICOSAT Inspector (MEPSI) picosatellite on STS-116, in December 2006, used a five thruster cold gas propulsion system to translate and rotate. The inspector picosatellite measured 4 x 4 x 5 inches in dimension and weighted 1.4 kg. Our propulsion system was produced by a unique (to spacecraft) method of manufacturing that is low cost, tightly integrated, and leak tight. This paper will describe the design, fabrication, testing and limits of this type of unit, and extrapolate to other related uses found at The Aerospace Corporation. This work was funded by The Aerospace Corporation's Independent Research and Development (IR&D) program.

INTRODUCTION

A tethered pair of Microelectromechanical Systembased (MEMS) PICOSAT Inspector (MEPSI) picosatellites was ejected in December 2006 by the United States Space Shuttle Discovery during STS-116. A tether of 15 feet kept the two 4 x 4 x 5 inch picosatellites from drifting apart. One of the picosatellites was configured as a "target" and the other as an "inspector." Both could communicate with an earth-bound ground station. However, only the inspector had a propulsion system developed by The Aerospace Corporation and introduced here.

Picosatellites and nanosatellites are satellites weighing less than 1 kg and 10 kg, respectively. Cubesats are a subset of picosatellite and nanosatellite classes and are specifically designed to fit inside the California Polytechnic State University in San Luis Obispo (Cal Poly) Poly Picosat Orbital Deployer (P-POD) launcher¹. The original cubesats were 10cm cubic picosatellites (called "1U") and the launch and integration cost through Cal Poly was \$40K. Cubesat developers with more money can build a larger cubesat, up to the P-POD limit of 10 x 10 x 30 cm in dimension that will solely occupy a P-POD launcher and cost \$120K to integrate and launch into space. This is called a "3U" cubesat and it provides that additional volume for traditional propulsion and extra surface area for solar power collection. The launch costs are noted here because they establish a reference of how much the finished picosatellite will cost. In this class of satellites, launch costs are typically the largest expenditure for the developer and the entire developed picosatellite is rarely equal and often much less.

Propulsion has been notably absent from cubesats. One reason is that the cubesat concept is relatively new and there have not been that many launch opportunities. Therefore Cubesat participants have been focusing on building other picosatellite subsystems and have not yet focused on attitude control. However another reason is that propulsion units are difficult to build in such a tight package. Two universities have delivered nanosatellites with propulsion systems. The University of Illinois ION nanosatellite (launched 2006) was a "3U" cubesat with four electric thrusters². Electric thrusters are known for their efficiency and would work well for the minor thrust requirements of attitude control. However, our MEPSI mission needs more thrust than electric thrusters can provide. The University of Toronto CANX-2 nanosatellite (launched 2008) is "3U" cubesat with a single sulfur hexafluoride cold gas thruster. The CanX-2 propulsion system³ was constructed using traditional components with numerous joints and a lot of open space for wrenches to tighten fittings. The MEPSI picosatellite was to be approximately the size of a "1U" cubesat and could not accommodate a thrust system of this size. The MEPSI picosatellite also needs five thrusters so the system would be even larger than CANX-2 using that technology.

Two targeted efforts have produced a MEPSI-sized cold gas propulsion unit but neither has flown or been integrated. In 2003, Vacco Industries delivered a Micro Propulsion System (MiPS)⁴ unit to The Aerospace Corporation specifically for the MEPSI project. The Defense Advanced Projects Research Agency (DARPA) paid the development costs. This system is ready to be integrated but is awaiting a version of the MEPSI spacecraft worthy of its quality – in other words, it is a "gold standard" and would be difficult to replace. Another effort to develop a cold gas propulsion unit is internal to The Aerospace Corporation. A laboratory group has been developing an experimental propulsion unit made from photostructurable glass. Lasers and precise X, Y and Z positioning are used to pattern the glass which is then etched out to create 3-dimensional (3-D) channels and other propulsion system features such as converging and diverging nozzles⁵. This system has a similar benefit to the Vacco design in that it packages well. However, this is still in the prototype stage and there is substantial assembly required to create a finished product.

The MEPSI program at The Aerospace Corporation fulfilled its need for a picosatellite propulsion unit for the STS-116 mission by developing a propulsion system that is manufactured differently from the aforementioned cold gas propulsion options. This new method has a quick lead time, is very low in cost and it packages with a minimum of wasted space. It does not have the quality and reliability of the Vacco unit but it is more suited for research into propulsion configurations for picosatellites. This new propulsion system was flown on STS-116 and limited flight results are presented here.



Figure 1. Artist rendering of the MEPSI co-orbiting daughtership.

A PICOSATELLITE PROPULSION MISSION

The MEPSI spacecraft, in its final incarnation, is a miniature daughtership that is resident on a host spacecraft. Ideally it will have as little volume and

mass as possible. The MEPSI will be ejected either by the host spacecraft or by ground command and will establish a co-orbit around the host at a desired range, interrogating it (Figure 1). When the interrogation is complete, the MEPSI spacecraft either moves to a disposal position in front or behind the host, depending on the relative ballistic coefficient, or docks back with the host to be saved for a future inspection mission.

The Aerospace Corporation has been developing MEPSI spacecraft since 2000 under DARPA sponsorship, Air Force Research Labs Information Directorate (Rome, N.Y.) leadership and using Aerospace Corporation Independent Research and Development funds. The MEPSI program was configured as a spiral improvement program and three MEPSI missions have been launched (Table 1).

Table 1. Propulsion system specifications.

Name	Host	Size (inches)	Delivery date
MEPSI 1	MSII.1	1 x 3 x 4	2000
MEPSI 2	STS-113	4 x 4 x 5	2002
Undeliv.	STPsat-1		2005
MEPSI 3	STS-116	4 x 4 x 5	2006

The MEPSI 1 mission was a small 1 x 3 x 4 inch version installed as a daughtership on the Air Force Research Labs (AFRL) MightySat II.1 (MSII.1) spacecraft, demonstrating the host / daughtership This MEPSI picosatellite had no relationship. propulsion capability but flushed out the integration and operational issues of installing a daughtership onto a host. The MEPSI 2 mission was a larger 4 x 4 x 5 inch version installed on the space shuttle mission STS-113⁶. It ejected from the shuttle bay becoming a free-flyer and demonstrated the inertial measurement unit required for future co-orbiting missions. The MEPSI-3 mission on STS-116 was also ejected from the shuttle bay as a free-flyer but was much more advanced and included propulsion capability that will be described below. The "undelivered" mission on STPsat-1 was intended to be the final finished MEPSI spacecraft that would perform the co-orbiting mission around that host. However, development did not keep on schedule and STPsat-1 departed with the MEPSI launcher integrated but with a MEPSI mass model installed in place of a finished daughtership.

The performance requirements for the propulsion system of a MEPSI spacecraft are not too extreme. As quantified in Janson *et al*⁵, the largest thrust is the braking maneuver that counteracts the ejection velocity

from the host. The MEPSI launcher installed on STPsat-1 would eject the picosatellite at 2 meters per second (m/s). This would require a constant thrust of 20 milli-Newtons (mN) for approximately 100 seconds in order to stop the MEPSI at a range of 100 meters at the start of the mission. The second largest propellant cost is the daily station keeping caused by the difference in ballistic coefficient between the host and the MEPSI picosatellite. The delta-V needed to counteract drag in a low-earth orbit (LEO) with a very large ballistic difference between the host and MEPSI would be less than 2 m/s per day. Therefore, the delta-V for a 7-day mission is on the order of 16 m/s. Practically, this amount requires margin to account for any inefficiency in the MEPSI control system.

The physical requirements for the MEPSI propulsion system are extreme. The $4 \times 4 \times 5$ MEPSI has allocated only $3.6 \times 3.6 \times 1$ inches of volume for the propulsion unit and an allocated mass of less than 500 grams. This exceedingly small volume and the large thrust requirement led us to consider a cold gas propulsion unit with a saturated liquid as the propellant.

Finally there are some practical requirements on the MEPSI propulsion system. First, the cost for the propulsion unit must not be so large that it could not be replaced if there was a testing mishap or failure, or so expensive that it would cause budget pressure. Second, the lead-time should be as short as possible so that we can recover if there was a design or fabrication error or if a unit was damaged in testing or handling.

MEPSI was not a large program. It existed for years at the 2-man year level. It therefore did not have the planning and acquisition resources typically found in larger programs. This forced us into low cost and rapid turnaround solutions. However, this was not entirely bad since rapid response is an interest of the United States Air Force⁷. Additionally quickly producing spacecraft can be a "simulation" tool for larger space systems, for instance evolving quality and program management strategies on an accelerated time-scale. Finally, rapidly producing spacecraft provides practical experience for persons participating and that experience can be carried on to more expensive and critical national security programs.

A NOVEL FLUIDIC MODULE IDEA

A basic propulsion system will consist of a propellant storage tank, a valve and a nozzle (Figure 2). Each of these is a distinct component and is typically joined to the others by tubes. If the tubes follow 3-dimensional paths to go from one component to the next, then bending them, if they are metal, is a precise exercise. A joint occurs where each tube interfaces with a component and it is the most likely point for leaks. If a joint is sealed using a wrenching fitting, then room must be allowed to apply the wrench. If welding is used, then room must be allowed to apply the heat to the joint, plus the materials used must be compatible. If adhesive is used, then it must be applied carefully so as not to creep into the tube inner diameter, it must be strong enough to secure the tube during vibration loads and the joint has to be accessible to apply the glue. The aforementioned methods which use tubing to join distinct components into a cold gas propulsion system are all time consuming and quite artistic. They are appropriate for larger satellites where the distance between propulsion system components is many inches and high quality components are required. For Cubesats, where the components are close together and are usually industrial grade rather than spaceflight grade, the process of joining them is inordinately difficult. For miniature satellites, a better way to join tanks, valves, nozzles and other propulsion unit components is needed.



Figure 2. A basic cold-gas propulsion system.

The Aerospace Corporation MEPSI team has created a leak tight manifold for a picosatellite cold gas propulsion unit using the stereolithography apparatus (SLA) additive rapid manufacturing method. The manifold has everything necessary, such as a tank to hold the gas or liquid, plumbing to the valves and nozzles and converging / diverging nozzles themselves built into it in a monolithic fashion. All of the connections between these elements are leak tight because they are manufactured from the same material, at the same time and there are no distinct joints with the exception of the connection to the valves. All of this is possible because rapid manufacturing plastics and methods exist that are impermeable to gas, have a reasonable tensile strength and are precisely controlled to produce minimum features sizes on the order of 0.005 inches.

The benefits of using additive rapid manufacturing to create a manifold go far beyond the leak tight construction. It is also a simple, quick and inexpensive manufacturing technique that is perfectly aligned with the current capabilities of 3-dimensional computeraided-design (CAD) software. Rapid Manufacturing machines take the 3-dimensionsal part output from your CAD software and use it to create a physical part in a matter of hours. There are no drawings for the designer to annotate or the fabricator to interpret. Plus, all of the un-manufacturable aspects of your CAD software (shelled parts, complicated curves, internal tubing) are relevant and manufacturable with additive rapid manufacturing. In practice, the designer can upload the part file to any of several vendors and receive an instant quote with price and lead time. The lead time for the MEPSI picosatellite propulsion manifold was always less than one week and cost approximately \$250 per copy. One final benefit is that the intricacy of the part has almost no effect on its cost or lead time.

There are a number of additive rapid manufacturing methods⁸. These are listed in Table 2 and described below in the context of our application. The SLA and SLS methods use a vat of photosensitive resin or of powdered material, respectively, and have a build platform that moves downward in 0.005 to 0.010 inch increments. As shown in Figure 3, a laser is used to either cure the liquid resin or heat the powder to melt to form a solid. As each layer is written, the platform moves down for the next layer. Parts with enclosed volumes inside must provide a way for uncured resin or powder to be drained out. This is a limiting factor that made the liquid resin in the SLA process preferable to the powder used in the SLS process: the liquid was easier to drain and therefore allowed for smaller inner internal plumbing features. The SLA method was thought to provide the highest likelihood of creating a leak free and homogeneous part for the purpose of a propulsion manifold.

The FDM, ZCorp and PJET methods were not tried for the purpose of creating a manifold for the MEPSI spacecraft. These methods are printers that add material sparingly in the traditional sense that someone would see an inkjet printer produce an image on paper. Only PJET could have produced the fine detail and smooth surface finish, comparable to SLA that is essential for the propulsion manifold⁸.

Table 2	Common	ranid	manufacturing	methods
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Name	Acronym
Stereolithography Apparatus	SLA
Selective Laser Sintering	SLS
Fused Deposition Modeling	FDM
Z-Corp Three-Dimensional Printing	ZCorp
Polyjet	PJET



Figure 3. Stereolithography Apparatus rapid manufacturing machine (courtesy Spectrum3D).

THE MEPSI PROPULSION UNIT

The MEPSI picosatellite propulsion system had to fit within a 1 x 3.6 x 3.6 inch volume and provide five independently controlled thrust axes that, when combined, could translate the picosatellite along one axis (forward and backwards) as well as control the three attitude angles, roll, pitch and yaw both positive and negative directions. The picosatellite would weigh approximately 1 kg when it was finished, without the propulsion system weight. If a saturated liquid was used as a propellant, then the necessary storage tank volume was 20 cc. As mentioned earlier, the Vacco Industries MiPS unit was slated for this mission and met all of the aforementioned requirements. However, it's cost warranted a much more mature MEPSI picosatellite avionics package than was ready for the STS-116 mission. It therefore was put in storage for a later date.

The Aerospace Corporation MEPSI engineers, under schedule pressure, needed an alternative propulsion system for STS-116 and they came up with the idea of using additive rapid manufacturing to create a finished part to be used in space. Table 3 lists the three iterations that occurred over 2 months before a final, workable design was reached. Each design was about \$250 in cost and delivered in 1 week. Rapid turnaround and low cost facilitated a mature design. The following paragraphs describe the evolution of the final design.

Table 3. Development of the MEPSI propulsion unit.

Unit	Mfg date	Material	Results
STL #1	8/3/05	Somos 11120 (SLA), 3-D Systems Duraform GF (SLS)	Poor geometry for strength
STL #2	8/18/05	Somos 11120 (SLA), Somos Prototool (SLA)	Floating structures are weak
STL #3	9/30/05	Somos 11120 (SLA)	Solid, more than 1,000 psi burst strength

The first unit, STL #1 (Figure 4) was a study into the limits of additive rapid manufacturing for this purpose. In Figure 4, the main tank is shown in olive green, Plenum #1 in tan and Plenum #2 in blue. The only tube to the only nozzle is shown in brown and is floating inside the tank. The first isolation valve would move gas or liquid from the main tank to Plenum #1. A second isolation valve, would allow it to exhaust down a tube to a nozzle on the exterior wall of the structure. This unit had a huge volume for propellant storage but its square shape with relative thin walls was not predicted to be very strong. Under pressure it would bow despite the supports that were designed in to strengthen it.

NASA wanted information about the fracture nature of the STL propulsion unit. STL #1 was therefore burst tested using a pressurized gas. The compressibility of gas caused the unit to explode when it reached 400 psi (Figure 5). The violence of the explosion exposed the brittleness of the Somos 11120 plastic. Developers of this type of unit should be careful as the shards are very sharp. (Future burst tests used a hydraulic hand pump and water as the working fluid. This was much safer since the fluid is effectively incompressible. It also was much more convenient because the propulsion unit could be tested anywhere since explosion was no longer a danger.)

The STL #1 unit was made using Somos 11120 SLA resin and also 3-D systems Duraform GS SLS material. The former was an unfilled liquid resin and the later is a glass filled polyamide (nylon) powder. The 11120 unit was burst tested in Figure 5. The SLS material was not useable as a propulsion system manifold. The powder was too difficult to remove from the long tubes that lead from the last plenum to the nozzles. Also the surface roughness was so great that, even with polishing, a smooth surface could not be realized such that an o-ring sealed valve could be mated to the manifold without leaks.





Figure 4. MEPSI STL #1: (top) plan view of 3-D CAD model; (bottom) actual unit ready for burst testing.

The second design, STL #2 changed the main tank from a large prismatic structure to a modest tubular tank floating inside the outer walls. In Figure 6, the tank is shown in olive green, the fill tube is bright green, the tube to the first Plenum is pink, Plenum #1 is tan, Plenum #2 is blue, the tube to Nozzle #1 is brown and the nozzle itself is red. There are five nozzles in this design. Each tube is a floating structure inside the 1 x 3.6 x 3.6 inch outer case wall. The picture in Figure 6, bottom, is a cutaway of the outer case wall exposing the cylindrical tank and one of the floating tubes. The idea of the cylindrical tank was to gain strength by geometry and then, when failure occurred, contain the fractured pieces of the cylindrical tank within the outer case walls.



Figure #5. Burst test of STL #1.





Figure 6. MEPSI STL #2: (top) plan view of 3-D CAD model; (bottom) cutaway of unit exposing free-floating main tank and one tube.

The second design, STL #2 was manufactured in two different SLA materials: Somos 11120 and Somos Prototool. The Prototool material, while stronger and more temperature tolerant, was dropped from consideration because it was a filled resin and left a powder residue behind. So while the surface finish was sufficiently smooth to seal to a valve gasket, the Prototool powder residue clogged internal passages, although not as badly as the SLS powders.

The second design, STL #2 was an attempt at the final MEPSI picosatellite propulsion system. It had the five independently controlled thrusters and adequate fluid storage. In the illustration of STL #2 (Figure 6, top), the walls of the free floating tank and tubes can be distinguished. However, the internal tank was not as strong as one would predict, due to warpage of material, and also there is a lot of unused and therefore wasted volume. The next design iteration was a large improvement for both of these problems.

The third and final design, STL#3, started with a solid block of material into which we created voids for the fluid storage tank, tubing channels and plenums. The result, shown in Figure 7, was a simpler but much stronger unit that would be tested to 1000 psi without breaking. This was well beyond 2.5X the maximum design pressure of 115 psig required by NASA. The only concern for leaks was at the valve interface - the concern of internal leaks was eliminated. The unit was made using the SLA process and Somos 11120 material. One giant benefit of the 11120 material is that it is transparent. When a solid piece of material is used, the exterior of the solid part can be polished and one can clearly see through it to verify the absence of bubbles, cracks or other flaws and visually inspect the internal plumbing elements including the quality of the converging / diverging nozzle (Figure 8). One can also see inside the main tank to visually verify the presence of the liquid propellant. The finished STL #3 plastic manifold is light and the system weighs only 188 grams with the valves attached.

The MEPSI picosatellite is also a research spacecraft. We did not know if reaction wheels would be a better way to finely control the attitude so they were added to the picosatellite. The third design of the propulsion manifold, STL #3 had ample unused volume. Therefore, tubing and the main tank were moved around such that voids to hold three orthogonal reaction wheels could be created. These are visible in Figure 9 which is a photograph of the final MEPSI propulsion unit assembly. The ability to so easily move around the plumbing is specific to rapid manufacturing techniques - traditional manufacturing would have taken too long and the idea of adding the reaction wheels, if indeed even possible, would have been abandoned. There was still free volume even after the reaction wheels were added so a VGA camera was also included (Figure 7).





Figure 9. Fully assembled MEPSI propulsion unit.



Figure 7. MEPSI STL #3: (top) plan view of 3-D CAD model; (bottom) partially assembled unit.



Figure 8. Close-up of an STL #3 tube and nozzle.

One additional concern with the plastic propulsion unit was outgassing. Early into the rapid manufacturing development of the propulsion manifold, samples of two candidate SLA materials, Somos Prototool and Somos 11120 were sent to NuSil Technology LLC for outgassing tests. Table 4 lists the results. The Somos 11120 material had a large total mass loss (TML) but a very small collected volatile condensable mass (CVCM). To prepare for the NuSil tests, the materials were heated to 60°C for 12 hrs at ambient pressure to drive off volatile elements. After the NuSil test, we amended the procedure to heat the units to 60°C in a vacuum because heating them in oxygen gives them a yellow color (Figures 7 and 8) and perhaps a lower TML can be achieved.

Table 4. NUSIL test results for TML and CVCM.

Material	TML*	CVCM
Somos Prototool	0.01	0.01
Somos 11120	2.85	0.01

* TML >1% is allowable if it has no adverse effect on part function (JSC 27301D)

MEPSI STEREOLITHOGRAPHY PROPULSION UNIT PERFORMANCE

The MEPSI mission on STS-116 was ejected in December 2006. Two MEPSI picosatellites were tethered together by a 15 foot tether to keep them in proximity of each other. The photograph shown in Figure 10 was taken by an astronaut on that mission just after ejection. The two picosatellites were almost identical except that one, called the "target", did not have any propulsion or attitude control and the other, called the "inspector", did. The mission was to have the inspector try to maneuver with respect to the target using its reaction wheels and propulsion unit. Both picosatellites had suites of VGA cameras that could capture pictures of the other picosatellite. And both picosatellites had radios for direct communication to an earth ground station.



Figure 10. Tethered MEPSI pair ejected from STS-116 (Photo courtesy of NASA).

MEPSI on STS-116 featured a propulsion unit made from Somos 11120 photopolymer plastic built using an additive rapid manufacturing method that was described earlier. Its main tank was 20cc in volume and was designed to hold DuPont SUVA HFC-236fa refrigerant as a propellant so that the estimated delta-V would be 20 m/s – the estimated delta-V needed for a MEPSI mission. However, NASA would have required more testing than we were prepared to do to certify that the propulsion system would not turn-on inadvertently and cause the MEPSI inspector picosatellite to come back and strike the Orbiter. To solve this problem, the MEPSI propulsion unit used 100 psig of Xenon gas as the propellant and the expected delta-V dropped to a NASA acceptable 0.4 m/s.

The propulsion unit was positioned on one end of the MEPSI inspector picosatellite with the thrust axes as shown in Figure 11. The thrusters A, B, C and D were canted 60 degrees to provide a component of force to oppose the direction of the E thruster, thereby allowing the picosatellite to "zoom in" towards and object and "zoom out" without having to change attitude. Combinations of thrusters would be used to realize a pure yaw, roll or pitch angle change. For example, thrusters A, C and E, used appropriately, would cause a pure roll about the Z axis. Each thruster is controlled by a valve. Two additional valves move the Xenon from the storage tank to plenum #1 and then from plenum #1 to plenum #2, respectively.



Figure 11. Thrusters on MEPSI "inspector" picosatellite.

On orbit, the MEPSI propulsion unit was commanded to perform a burst of gas from nozzle A. The onboard triaxial rate sensors recorded the picosatellite rotation rates during the experiment. Figure 12 is the resulting data downloaded from the MEPSI inspector. The picosatellite was commanded to open and then close the first isolation valve, thereby filling plenum #1 with gas to 115 psia. Next the gas in plenum #1 was transferred to plenum #2 by opening and then closing the second isolation valve. Finally nozzle valve A was opened and the Xenon gas expelled. The picosatellite rotated about both the X and Z axes because of the nozzle location and orientation relative to the picosatellite center of gravity. In Figure 12, it is unclear if the rotation rate spikes are due to the valves opening and then closing or whether it is electrical noise on the rotation rate sensor.



Figure 12. MEPSI Inspector thruster experiment December 22, 2006.

The rate changes measured at the picosatellite and plotted in Figure 12 can be calculated using the picosatellite properties listed in Table 5. The total gas expended was the volume stored in plenum #1 at 115 psia. Therefore, the impulse created by 0.2cc of Xenon gas at 115 psia is calculated to be 2.6×10^{-3} N-s using 30s specific impulse. The torsional impulse imparted

by thruster A on the MEPSI inspector results in a rotation rate change about the X and Z axes of

$$\begin{split} \omega_{\rm X} &= 2.6 \ {\rm x} \ 10^{-3} \ {\rm N}\text{-s} \cdot [\sin (60) \cdot (0.057 \ {\rm m}) + \cos (60) \cdot (0.043 \ {\rm m})] \ / \ 3.0 \ {\rm x} \ 10^{-3} \ {\rm kg}\text{-m}^2 \\ &= 0.062 \ {\rm rad/s} \\ &= 3.5 \ {\rm deg/s} \end{split}$$

$$\begin{split} \omega_{Z} &= 2.6 \text{ x } 10^{-3} \text{ N-s} \cdot \sin (60) \cdot (0.033 \text{ m}) / 2.3 \text{ x } 10^{-3} \\ & \text{kg-m}^{2} \\ &= 0.032 \text{ rad/s} \\ &= 1.8 \text{ deg/s}. \end{split}$$

These match well with the measured response in Figure 12 of 3.2 and 1.6 deg/s, respectively.

mass	1.36 kg
Ixx	$3.0 \text{ x } 10^{-3} \text{ kg-m}^2$
Іуу	$3.0 \times 10^{-3} \text{ kg-m}^2$
Izz	$2.3 \times 10^{-3} \text{ kg-m}^2$
plenum #1 volume	0.2 cc

Table 5. MEPSI "inspector" physical parameters

The MEPSI picosatellites were put to sleep over the Christmas holiday in 2006 and instructed to awake ten days later. They never awoke. The problem was traced to a memory overflow condition. Our desire to record satellite state-of-health information every 16 seconds meant that over ten days the memory overflowed and the flight computer went into an infinite loop. Therefore, no further propulsion experiments were carried out. The MEPSI picosatellites were primary battery satellites and should have had a lifetime of approximately two weeks.

BEYOND PROPULSION UNITS

The leak-free manifold introduced in this paper can be used to for other purposes. The Aerospace Corporation also builds Cubesats as part of the University Cubesat program. One of its Cubesats, AeroCube-2 was designed with a small pressure system containing SUVA HFC-236fa refrigerant (Figure 13). The pressurized container was made with the SLA process and Somos 11120 material. A single valve releases the refrigerant into a balloon to inflate it. The balloon would serve as a de-orbit device⁹ as required by the Federal Communications Commission due to the projected lifetime of the cubesat.

CONCLUSION

The Aerospace Corporation has produced a low cost cold gas propulsion system that was used on the MEPSI picosatellite mission on STS-116 in December 2006. The propulsion system centered around a leak free manifold consisting of a propellant storage tank, tubing and converging / diverging nozzles that was manufactured using the Stereolithography Apparatus (SLA) additive rapid manufacturing method and Somos 11120 resin. Only the valves were external and sealed with a face gasket. The entire unit weighed 188 grams and could have provided 20 m/s of delta-V for a 1 kg picosatellite had DuPont SUVA HFC-236fa refrigerant been used a propellant. The MEPSI mission was short lived, however, the propulsion system was exercised and its performance matched our calculations. The AeroCube-2 cubesat launched in April 2007 also featured an SLA manifold but its purpose was to inflate a de-orbit balloon.



Figure 13: AeroCube-2 de-orbit balloon inflation gas module.

Additive rapid manufacturing is an ideal way to make a leak proof pressure vessel. Combined with face mounted sealing valves, an inexpensive propulsion unit for picosatellites and cubesats can be realized. This same technology can be used for holding gas or fluid for inflating structures in space. The lead time for manufacturing is less than 1 week and, in the case of the MEPSI propulsion manifold, cost \$250 per copy which is ideally priced for the cubesat and picosatellite community. Furthermore, the entire process from design to finished part is digital and no drawings are necessary to have the part fabricated. The complete functionality of the computer aided design software can be utilized since the constraints of traditional manufacturing do not apply. Such manifolds can be optimized so that very little volume in the picosatellite is wasted. Other satellite structures, other than pressure vessels, can be constructed using additive rapid manufacturing anywhere part complexity is extreme and the plastic material will supply sufficient strength.

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