MINIATURE ION ELECTROSPRAY THRUSTERS AND PERFORMANCE TESTS ON CUBESATS

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ABSTRACT

Miniature ion electrospray thrusters under development at MIT are opening a new range of possibilities for applications requiring precision thrusting, or for nano-satellite mission design. With a specific impulse (Isp) in excess of 2500 seconds, no moving parts and unpressurized tanks containing zero-vapor pressure liquid propellant, they can be integrated into cubesat compatible multi-thruster assemblies. The technology and the thruster performances are described in this paper in addition to the current development of cubesat compatible prototype assemblies for performance tests in space. The assembly under development in this research effort fits within 1/3 of one 1U cubesat and is designed to provide fine three-axis attitude control and precision thrusting, to deliver a total Delta-V in excess of 200 m/sec to 3U cubesats (3 kg). The overarching goal is to assess in flight the performances of the thrusters as precision actuators. Potential nanosat applications include attitude control and precision pointing, orbital adjustments, constellation control and maintenance, formation flight, re-entry, debris removal and other maneuvers.
INTRODUCTION

Nano and pico-satellites are becoming increasingly popular in a number of applications due to their small size, reduced costs, quick development times and relative ease to deploy. Despite this popularity, their capabilities are often curtailed due to the difficulty in scaling down efficiently a number of subsystems. Propulsion is one of these subsystems. An ideal propulsion system for nano and pico-satellites would feature a small footprint on the small satellite while providing maneuverability with performance metrics comparable, or better, than existing systems for larger space platforms. In this paper we describe current efforts towards the development of a propulsion system aimed at CubeSats. Advancements in micro-electro-mechanical systems (MEMS) make it possible to design and build an electric propulsion system that would fit in the reduced volume of a CubeSat while still leaving enough room for the rest of the spacecraft subsystems and operating with constrained power resources [1]. The goal for the propulsion system is to work at significantly higher $I_{sp}$ (> 2500 sec) compared to state-of-the-art chemical thrusters. Such high $I_{sp}$ is accessible through the use of an ion-electrospray propulsion system. The advantages of this concept are their high efficiency and unsurpassed compactness. A significant part of the effort deals with the development of the power processing unit (PPU) electronics to drive the thruster during operation. The PPU in many instances, particularly for CubeSats will drive the overall system efficiency and volume/mass budgets.

ELECTROSPRAY PROPULSION

Electrospray propulsion is based on the electrostatic extraction and acceleration of ions from ionic liquids, substances with exceptionally low vapor pressure and relatively high electrical conductivity [2,3]. Ionic liquids can be exposed to vacuum conditions with practically no thermal evaporation and can be electrically stressed to form conical tips (known as Taylor cones) where very strong electric fields develop, inducing ion emission when a potential difference of about $V_e = 1-2$ kV is applied between a relatively sharp emitter coated with an ionic liquid and a downstream aperture electrode [4,5]. The thrust produced by each Taylor cone is about 1/10 of a micro-Newton, which is too small except for very specific precision applications. This means that a practical implementation of this technology would require building densely packed arrays of individual emitters. Porous metal substrates are ideal materials for this application due to their ability to transport liquids via capillary forces. Since 2010, MIT’s Space Propulsion Laboratory has been working in the development of the ion Electrospray Propulsion System (iEPS) [6,7]. The basic elements of the propulsion system are small modules 12 x 12 mm and 2.5 mm thick, featuring emitter arrays manufactured using electrochemical microfabrication techniques with emitter-to-emitter spacing of 450 microns.

Fig. 1. iEPS modules fabricated in silicon (SPL).

Fig. 1 shows a picture of iEPS modules and Fig. 2 an electron microscope image of a porous metal emitter array.

Fig. 2 Electron microscope images of ion emitting structures micro-fabricated in porous metals [6]

These modules are able to deliver a thrust density of about 0.25 - 0.5 N/m², which is not that different from plasma-based ion engines, with the important benefit that electrospray thrusters are very compact since no gas-phase ionization is required and the propellant is passively fed from a nearby porous tank directly into the substrate containing the emitter tips (see Fig. 3). These thruster modules are able to produce positive or
negative ions depending on the voltage polarity. In practice, both positive and negative ions need to be produced at identical levels to avoid spacecraft charging. Additionally, chemical neutrality of the propellant is required to avoid liquid/metal corrosion. This is accomplished by alternating the voltage periodically at frequencies of about 1 Hz to keep the electrochemical potential produced at the interface between the metal electrode and the liquid from increasing beyond the limit in which electrochemical reactions are triggered \[5\]. Both the electrical and chemical neutrality requirements dictate the architecture of the (PPU) and its complexity.

Fig. 3. CAD drawing illustrating a iEPS module mounted on top of a 1.5 cc propellant tank. This small volume would provide about 50 m/s delta-V to a 1U CubeSat

iEPS devices have been characterized \[7\], demonstrating current emission levels on the order of 100’s of \(\mu A\) (Fig. 4), which as expected is significantly higher than standard currents observed in traditional electrosprays used in mass spectrometry (a few nA). The corresponding thrust is about 0.1 \(\mu N/\mu A\).

THRUSTER ASSEMBLIES FOR CUBESATS AND OTHER APPLICATIONS

The electro-spray micro-thrusters demonstrate very high \(I_{sp}\), require no pressurized tank, have small size and weight and good thrust levels relative to their mass/volume. They are particularly suitable for CubeSat applications for which mass, volume, and power are by definition very limited. Their characteristics also make them excellent actuators for very fine control, with applications in high performance space applications, if properly configured and provided with well controlled high voltage power supplies. The electrospray thrusters with power supplies providing high resolution voltage/current/pulse-length controls can achieve high precision thrust pulses for very accurate control of space systems.

Fig. 4 Typical current vs. voltage characteristics of iEPS modules. Notice the current does not saturate in the range of voltages indicated. Absolute value of current is shown for clarity

Under NASA SBIR funding our team is developing a Precision Electrospray Thruster Assembly (PETA) to explore, characterize, and take advantage of these microthruster characteristics. The PETA assemblies are designed in a CubeSat compatible form factor to facilitate rapid flight tests of assemblies and thrusters. These assemblies are conceived to provide pitch, yaw and roll control as well as primary propulsion for the CubeSats, and thus open a new range of capabilities for CubeSat/nanosat missions.

PETA ASSEMBLIES MAIN CHARACTERISTICS

The baseline prototype PETA assembly design occupies a volume of 1/3 U (measured from actual electronics boards and components). It includes 16 microthrusters assembled into eight pairs controlled through 6 independent channels. This allows three-axis control, and propulsion, with a total equivalent of 200 m/sec delta-V for a 3kg/3U CubeSat. The thruster configurations and orientations can be adjusted for different specific applications within the same volume envelope.

The prototype assembly is divided into three electronics boards: HV providing interfaces and high voltage control; SW including the primary switching circuitry; and ET integrating thrusters and connecting circuitry. The electronics provides alternating positive and negative voltage outputs to the thrusters pairs in the range 0 to 1600 volts (3200 V differential) with 16 bit resolution and voltage and current feedback. Maximum output current is about 1 ma (3.2 W applied to the thrusters) providing thrusts in the 100 micro-N range.

Thrust pulse duration is controlled in the millisecond range (limited by supply/thruster/tank on-off response
times). The assembly is controlled through RS232 (test) or SPI (flight) interfaces, managed by an FPGA. Commands select voltage, channels (1 to 6 on or off), polarity reversal cycles, and thrust timing. Housekeeping data includes state, voltage, current, temperatures. The FPGA code can be configured for a variety of platform protocols and batch commands, and includes internal oversight including watch-dog timers.

As laid out this precision assembly with 8 pair of thrusters has the capacity (about 20 gram of propellant) to provide 200 m/sec overall delta-V to a 3U cubesat, which is sufficient for thorough testing of the precision thrust performances, and many other applications. If needed, additional capacity within the same envelope can be added with larger thruster tanks on the thruster board. More radically, if the need arises, another configuration with an additional board (bringing the overall assembly to a thickness of 38 mm) will allow for more propellant and larger delta-V capabilities, applicable for example to de-orbiting maneuvers or insertions in higher orbits or escape trajectories. For example from a geosynchronous orbit (GO) a total of 150 grams of propellant would be sufficient for getting a 3U platform to escape to interplanetary space. Fig. 5, 6 shows dimension drawings of the three-board-assembly and photographs of initial (rev. 1) PETA prototype boards.

The system is by design very modular, and the thrusters can be arranged in different ways on the ET board; the “roll” thruster might be eliminated depending on the application, or faced “up” to provide a 16 thruster propulsion array with 2 axis attitude control; or conversely all thrusters can be oriented to point out of the sides of the ET board, if that configuration is advantageous in particular for attitude control (Fig. 7).

**PROTOTYPE TEST MISSION**

An example of a prototype 3U CubeSat mission defined for thorough flight testing of the thrusters (in that case 12 pairs) is sketched in Fig. 8. The system includes two PETA assemblies equipped with side thrusters. The extremities of the 3U structure are reserved for the two S-band patch antennas providing 4 Pi steradian coverage for the platform communication system. A star sensor baffled by the solar panel (and slanted for a clear field of view) provides the final high resolution measurements to fully assess the thruster assembly fine control (and stabilization) capabilities.
APPLICATIONS

Separated space platforms flying in formation can carry different elements of optics and sensor systems kept in controlled relative locations for interferometric measurements from space. There are many proposed applications in astrophysics from RF through infrared to visible light, UV and X-ray. The Precision Electrospray Thruster Assemblies are capable of very fine thrusting performances and have advantages in terms of mass, volume and simplicity of operation/ruggedness which makes them promising candidates as precision actuators for these applications.

The same characteristics could be useful for systems relying on interferometric laser measurements between platforms in space, such as planned for long baseline gravitational waves detection.

Gravitational waves, General Relativity, and geodetic space experiments are often based on maintaining the spacecraft around a reference mass in “free fall.” The platforms keep thrusting at very low levels to compensate for the effects of atmospheric drag, photon pressure and other disturbances. The very low thrust levels and thrust resolution achievable by the ion electrospray micro-thruster can facilitate such experiments.

Outside of interferometric observatories, large space based telescopes designs are considered using fractionated architectures to support very large apertures (fractionated mirrors) and long focal lengths (separated mirror or coded masks and focal plane instrumentation). Such observatories have applications in the X-ray, optical, and infrared ranges. They require very accurate alignments of the mirror elements and the focal plane instruments, through low level thrusting. These systems are an application for the PETA-type high precision thrust control.

For example, a large grazing incidence mirror for an X-ray telescope can be decoupled from the focal plane instruments on another platform, with their relative positions and attitude measured through laser interferometry, and controlled through PETA type units.

Fine thrusting also has applications to close formation flights and rendezvous, and, in particular, to coalesce a larger structure from small units. Precision thrusting will be an enabling tool for the assembly and self-assembly of space structures. In support of these applications the PETA type assemblies can be miniaturized further to control a single pair of thrusters.

Because of their small sizes and high Isp electrospray thrusters are ideal for CubeSat constellation control, even with a coarse power supply. With a PETA thruster assembly used for either or both propulsion and attitude control, the CubeSat can obtain very fine maneuvering, pointing and stabilization performances, opening new range of possible applications for the small platforms, to create synthetic antennas or multi-sensor systems based on sparse arrays.

An example of the type of possible application is a 3U CubeSat astronomical platform using precise electrospray thrusting to achieve the required pointing stabilization.

Another application for nanosats is the combination of a minisatellite platform with good ground communication capabilities at the L1 Lagrange surrounded by a swarm of more than a dozen small platforms forming an RF sparse array antenna to observe the sun at low frequencies (30 kHz to 10 MHz). Such a system, a new version of the proposed SIRA mission, would provide RF imaging of the sun, and radically new data for imaging RF solar activities and tracking CMEs. PETA thrusting can maintain the constellation in tight formation for very long mission operations and control its elements geometry to optimize measurements.

For applications where magnetic torquing is not possible or desirable the small thrusters can be used for general attitude control and momentum dumping.

Another obvious and important application of the iEPS assemblies is as a thrusting mechanism for controlled re-entry of CubeSats or other nanosats when their missions are over.

The MIT laboratory is now equipped for the rapid production of the thruster micro-fabricated emitter arrays, and has developed specific custom-designed manufacturing equipment for the processing and characterization of micro-machined porous arrays. These tools will permit the fabrication of multi-thruster arrays scaled to support the whole range applications from small probes to large space platforms.
CONCLUSIONS

The ion Electrospray Propulsion System and its integration into Precision Electrospray Thruster Assemblies have the potential to provide flexible, high-performance propulsion to nano and pico-satellites, including popular CubeSats. The working principle of iEPS thrusters make them ideal for scalable propulsion with practically no penalty for miniaturization. Positive and negative ions are emitted from small 1 cm² modules at high Isp. It is important to keep both electric and chemical neutrality during thruster operation, thus the power processing unit requires simultaneous firing of pairs of thrusters (one positive and one negative) while also providing voltage alternation at relatively low frequency (~1 Hz). Applications for PETA range from attitude control, down to ultra-high precision (10's of nano-N thrusts) to main propulsion to provide high delta-V capabilities. These capabilities will enable CubeSats to perform a number of missions that are currently not possible in the small vehicles. Very importantly, this small and efficient propulsion technology can also be used to force a CubeSat reentry when mission is ended, to mitigate the important problem of growing space debris.

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REFERENCES

1. P. Lozano and D. Courtney, On the development of high specific impulse electric propulsion thrusters for small satellites, 1915685, Proceedings 4S Conference, Madeira Portugal (2010)