Ion electrospray microthrusters, new propulsion for small satellites

Miniature ion electrospray thrusters and performance tests on CubeSats

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• Microthruster concept and characteristics
• Microthruster fabrication
• Performances and fine control
• Precision thruster assemblies for CubeSat propulsion and attitude control
Microthruster Concept

- Electrostatic extraction and acceleration of ions from liquid passively pumped by capillary forces towards micro emitter tips
Microthruster Characteristics

- Miniaturized, very low mass and small volume
- Effective thrust density (0.1-0.2 N/m²)
- Very high ISp (2500-5000 sec) hence low volume / mass of propellant
- Rugged, no moving parts, no valves, no pressurized tank, non-toxic propellant
- Modular for mass production and assembly in large arrays or miniaturized assemblies
- Efficient and high precision control
Thruster pairs and propellant tanks

- Thrusters are configured in pairs
- The elements in the pair are powered at opposite (and alternating) potentials for an overall neutral beam.
- Size and geometry of the propellant tanks are adjustable to mission requirements and constraints.
- The current tank version is designed for integration on PC boards
High ISp, low propellant mass and large ΔVs

- The high ISp of the ion microthrusters (2500-5000 sec) minimizes the amount of propellant required to achieve large ΔVs.
- For example low propellant requirements and the low-mass thruster assemblies will allow 3U LEO CubeSats to reach escape velocity using a fraction of a U.
- Slew, spin, ”walking” and raising or lowering orbits require from fractions of a milligram to a few grams of propellant

Propellant mass fraction

\[
\frac{M_p}{M_0} = 1 - \exp\left(-\frac{\Delta V}{gIsp}\right)
\]

In a first approximation for:
Isp~ 3000 sec; Mo=3kgm

- \(\Delta V e(600km) \sim 3.12 \text{ km/sec}\)
- \(M_p = 320 \text{ grams}\)

- \(\Delta V e(36000km) \sim 1.27 \text{ km/sec}\)
- \(M_p = 127 \text{ grams}\)
# CubeSat maneuvers, time and propellant estimates

## De-orbit, Orbit raise

\[
t_{\text{orb}} = \frac{v_0}{a_\theta} \left(1 - \sqrt{\frac{r_0}{r}}\right)
\]

\[
\Delta r = 400 \text{ km} \quad t_{\text{orb}} \approx 26 \text{ days} \quad M_p \approx 6.4 \text{ g}
\]

## Slew

\[
t_{\text{slew}} \approx \sqrt{\frac{4 M l \Delta \theta}{3F}}
\]

\[
\Delta \theta = 2\pi \quad t_{\text{slew}} \approx 2 \text{ min} \quad M_p \approx 0.3 \text{ mg}
\]

## Spin

\[
t_{\text{spin}} = \frac{M l \dot{\theta}}{3F}
\]

\[
\dot{\theta} = 1 \text{ Hz} \quad t_{\text{spin}} \approx 1 \text{ hr} \quad M_p \approx 10 \text{ mg}
\]

## Walking

\[
t_{\text{walk}} = \sqrt{\frac{4s}{3F/M}}
\]

\[
s = 10 \text{ km} \quad t_{\text{walk}} \approx 5 \text{ hr} \quad M_p \approx 51 \text{ mg}
\]
Fabrication Process

Frame fabricated in silicon using plasma processing

Porous metal substrate bonded to silicon frame

Porous metal processed to form a 2-D array of ion emitters

Extractor grid is bonded to silicon
Examples of Etched Micro-Tips
Alignment of Extractor Grid

• Precise alignment is essential for thruster performance

Thruster assembly inspection

Details of extractor/emitter assembly
Microthruster Performance and Fine Control

Isp: 2500-5000 sec

Thrust: 0.1 - 0.2 N/m²

Current (and thrust) are strong functions of voltage beyond the extraction potential

Precision actuators with high resolution control of extractor grid potentials and pulse durations
The Precision Electrospray Thruster Assembly (PETA) is a NASA SBIR R&D effort to develop and test an integrated thruster assembly to demonstrate the performance of the miniature ion electrospray thrusters as precision actuators.

The PETA assembly is designed as a functionally capable propulsion and attitude control assembly for CubeSats to facilitate practical and rapid flight tests of the thruster and assembly performances.

The PETA prototype assemblies also provide new capabilities to CubeSat missions with a minimum of 200m/sec ΔV to 3U CubeSat and pitch/yaw/roll control.
Precision Electrospray Thruster Assembly baseline configuration

- 1/3 U configuration (33mm thickness)
- Total of 20 grams propellant (200 m/sec-3U) (+)
- 16 bit voltage resolution; 0 to ±1600 V
- Millisecond level switching
- ~ 70% power conversion efficiency
- Pitch, yaw, roll and propulsion
- RS-232, SPI interfaces (+) with FPGA control
Rev 1 HV board (in test) provides ± 800V to ± 1800 V (3600V) with 16 bit resolution, and current and HV feed-back measurements. Rev 3 (in production) provides 0 to ±1600 V, and 70% conversion efficiency.
PETA Rev 1 Tests

- High Voltage / Control board (Rev. 1) undergoing tests with ion electrospray source at MIT
• High voltage steps applied to a single ion electrospray source

• In that case the estimated equivalent thrust is about 6 nanoNewtons, and is brought through three large 25 Volt steps to about 7.5 nanoNewtons, a total of 1.5 nanoNewton modulated through 75 volts

• PETA prototype assembly can provide at least 1 ma of current, or 100 micro-Newton of thrust
Example of PETA CubeSat test mission

- Two PETA assemblies provide propulsion, pitch, yaw, and roll high resolution control to the three U CubeSat platform for a total of about 400 m/sec $\Delta V$

- In this case the thrusters are all oriented “side-way” to leave the 3U extremities to the S-band antenna patches; fine control performance is verified using a star camera