A MEMS Based Experimental Colloid Thruster Package for Nano satellites

Barry Kent, John Stark, Bob Stevens, Matt Alexander, Adam Baker, Dave Gibbon, Douglas Liddle

Space Science and Technology Department, Rutherford Appleton Laboratory, b.j.kent@rl.ac.uk

Department of Engineering, Queen Mary, University of London, j.p.w.stark@qmul.ac.uk

Central Microstructures Facility, Rutherford Appleton Laboratory, r.stevens@rl.ac.uk

Surrey Satellite Technology Ltd, University of Surrey, a.baker@sstl.co.uk
Properties of Colloid Thrusters

Micro fabricated thrusters

A Mission concept

Micro propulsion System outline
Comparison Parameters

**Thruster**

- ** Thrust **: 
  \[ T = \dot{M} V_e \]

- ** Specific Impulse **: 
  \[ I_s = \frac{T}{\dot{M} g} = \frac{V_e}{g} \]

**Mission**

- ** Delta V **: 
  \[ \Delta V = V_e \ln \left( \frac{M_o}{M_o - M_f} \right) \]
Basic Relationships for Electric Propulsion

Exhaust velocity

\[ V_e = \left( \frac{2qV}{m} \right)^{1/2} \]

Mass Flow rate

\[ \dot{M} = \frac{I_b m}{q} \]

Thrust

\[ T = \dot{M} \left( \frac{2qV}{m} \right)^{1/2} \]

- \( V_e \): Exhaust velocity
- \( m \): Droplet mass
- \( q \): Droplet charge
- \( V \): Acceleration voltage
- \( M \): Mass flow rate
- \( I_b \): Beam current
Power relationships

Thrust = \frac{2 \cdot m}{q \cdot V} \frac{1}{2} \text{ Power}

Thrust = \left\{ \frac{2 \cdot \dot{M}}{\text{Power}} \right\} \frac{1}{2}

Thrust = 2 \cdot \frac{\text{Power}}{V_e}

Higher \( \frac{m}{q} \) \( \Rightarrow \) more thrust per unit power
Lower \( V_e \) \( \Rightarrow \) more thrust per unit power
Higher mass flow rate per unit power \( \Rightarrow \) more fuel required for same \( \Delta V \)

Compared to ion engines and FEEPS Colloids have lower \( V_e \), higher \( \frac{m}{q} \), but higher \( M \)

*If power is limited and fuel mass has small system impact*  
colloids thrusters have advantage
## Scaling Review  (Electric Propulsion Thrusters with $I_{sp} > 300$)

<table>
<thead>
<tr>
<th>Type</th>
<th>Gridded</th>
<th>HET</th>
<th>FEEP</th>
<th>PPT</th>
<th>MPD</th>
<th>ArcJet</th>
<th>Colloid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thrust (mN)</td>
<td>1-50</td>
<td>1-70</td>
<td>µN - few</td>
<td>5 µN - mN</td>
<td>1N+</td>
<td>1-few</td>
<td>µN – few</td>
</tr>
<tr>
<td>Isp</td>
<td>2500</td>
<td>1000</td>
<td>5000</td>
<td>600</td>
<td>1000</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>5000</td>
<td>1800</td>
<td>7000</td>
<td>1400</td>
<td>5000</td>
<td>600</td>
<td>1000</td>
</tr>
<tr>
<td>Rel System Mass</td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td>High</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td>Rel System Vol</td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td>Rel Power</td>
<td>High</td>
<td>Medium</td>
<td>Medium</td>
<td>Low</td>
<td>High</td>
<td>High</td>
<td>Low</td>
</tr>
</tbody>
</table>

Reference – Quinetiq Miniaturised EP Study
## Summary of System Requirements for various missions

<table>
<thead>
<tr>
<th>Property</th>
<th>Science (LISA Darwin)</th>
<th>Small Satellite (SSTL-DMC)</th>
<th>Formation Flying (Proba 2.25)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thrust range (μN)</td>
<td>0.5 – 500</td>
<td>2,000 – 4,000</td>
<td>&lt; 2000</td>
</tr>
<tr>
<td>Thrust Stability (μN)</td>
<td>0.1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Specific Impulse (sec)</td>
<td>~ 500</td>
<td>&gt;300</td>
<td>&gt;500</td>
</tr>
</tbody>
</table>
Electrospray Components

- Nano emitter
- Taylor Cone
- Fluid jet
- Spray

560 µm
Micro fabricated Colloid thruster concept

- Powder blasted high density graphite accelerator grid
- DRIE Micromachined Silicon layer
  - Front surface: Micro nozzle array
  - Back surface: Microfluidics manifold & micro-filtration system.
- Charged electrospray droplets
- Molybdenum coated silicon DRIE grid
- Powder blasted glass layer with via holes for fluid inlet and outlet
- Satellite chassis with fluid interface
- To fluid reservoir
Integrated Micro Fabricated thrust head

- Acceleration electrode
- Polyimide Alignment spacers
- Extraction electrode
- Emitter plane
- Micro fluids layer

single emitter

seven emitters
Standard Micro Fabrication Process enable large arrays

20,000 emitters on 75mm diameter

Each emitter 178 µm OD
## Thrust scales with number of emitters

<table>
<thead>
<tr>
<th>Application</th>
<th>Thrust (N)</th>
<th>Number of nozzles</th>
<th>Area (cm²)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch augmentation</td>
<td>0.1 – 1</td>
<td>40,000 – 400,000</td>
<td>100 – 1000</td>
<td>~ 6 - 20 cm</td>
</tr>
<tr>
<td>(Primary Propulsion)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Orbit Maintenance</td>
<td>0.01 – 0.1</td>
<td>4000 – 40,000</td>
<td>10 – 100</td>
<td>~ 2 - 6 cm</td>
</tr>
<tr>
<td>(Station Keeping)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Attitude</td>
<td>10⁻³ – 0.1</td>
<td>400 – 40,000</td>
<td>1 – 100</td>
<td>~ 0.6 - 6 cm</td>
</tr>
<tr>
<td>(i.e. Orientation) control</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Disturbance compensation</td>
<td>10⁻⁴ – 10⁻²</td>
<td>40 – 4000</td>
<td>0.1 – 10</td>
<td>~ 0.2 - 2 cm</td>
</tr>
<tr>
<td>Precision Formation flying</td>
<td>10⁻⁶ – 10⁻⁵</td>
<td>1 – 4</td>
<td>0.001 – 0.01</td>
<td>~ 0.02 - 0.06 cm</td>
</tr>
</tbody>
</table>
Reference Mission

• Concept: formation flying/station-keeping using variable low thrust, with low thrust noise.

• Target mission is to track the motion of a nano satellite relative to a micro satellite

• Assumed baseline orbit is 700 km

• Launch near solar minimum conditions ~ 2006

• Micro satellite has mass 100kg, projected area 600mmx 800mm
  Drag at 700km (low solar activity) ~5x10^-7 N

• Nano satellite has mass 10kg, projected area 465mmx 210mm
  Drag at 700km (low solar activity) ~9x10^-8 N
• Mission analysis is based upon a linearized simulation

• Assumption that the major perturbation is due to atmospheric drag

• Require the orbit to remain near circular

• Adopt the approach of Cornelisse:

\[ h = 2 \times \frac{\mu}{r_0^2} \times \frac{T}{m} \left( \frac{V_{co} t}{r_0} - \sin \left( \frac{V_{co} t}{r_0} \right) \right) \]

\( h \): change in height at altitude \( r_0 \); \( T \) is thrust applied over time \( t \)
\( V_{co} \) local circular velocity; \( \mu \) Earth’s gravitational parameter

• *Neglect effects due to J2 etc*
Thrust for Drag compensation

- Evaluate length of thrust arc to offset drag.
- Assume 1 thruster firing per day

Burn time as a function of thrust (s/day)

<table>
<thead>
<tr>
<th>Altitude (km)</th>
<th>Nano Satellite Maintenance</th>
<th>Match Nano Satellite to Micro Maintenance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thruster</td>
<td>Thruster</td>
</tr>
<tr>
<td>700</td>
<td>100,\mu N</td>
<td>100,\mu N</td>
</tr>
<tr>
<td></td>
<td>300,\mu N</td>
<td>300,\mu N</td>
</tr>
<tr>
<td>755</td>
<td>503</td>
<td>598</td>
</tr>
<tr>
<td>598</td>
<td>399</td>
<td>399</td>
</tr>
<tr>
<td>Relative Fuel mass</td>
<td>1.0</td>
<td>2.2</td>
</tr>
</tbody>
</table>
Surrey Satellite Technology Ltd

SNAP-1 satellite
Launched 2000
Mass 6.5 kg
Power available 6W
SNAP-2
A Nano satellite concept
using colloidal
6 dof attitude control

Thrust head
25mm diameter
10mm height
2000 emitters

Fuel tank
Ti tubing
OD 9mm
Wall ~0.5mm
Outline Hardware - Propellant control valve

Example solenoid fluid control valve

Lee Company

Power requirement ~ 0.75W
Outline Hardware - High Voltage supply

**EMCO HIGH VOLTAGE CORPORATION**

**Cube**
22 mm side
28g

---

**CASE C**
Q60, Q80 & Q101

**PHYSICAL CHARACTERISTICS**

- **SIZE:** 0.85 x 0.85 x 0.85 (21.59 x 21.59 x 21.59)
- **WEIGHT:** 1 Ounce (28.3 Grams)
- **PACKAGING:** Fully Encapsulated
- **CASE MATERIAL:** Glass-filled Epoxy

**ELECTRICAL SPECIFICATIONS**

- **INPUT VOLTAGE:** 0 to 5, 12 or 24 VDC
- **TYPICAL TURN-ON VOLTAGE:** 0.7 Volts
- **OUTPUT VOLTAGE TOLERANCE @ FULL LOAD:** +5%, -10% typical
- **ISOLATION:** 500 Volts +V out
- **OPERATING TEMP:** -10° to +60° C
- **STORAGE TEMP:** -20° to +105° C

**NOTE:** Do not allow output voltage to exceed maximum rating.

<table>
<thead>
<tr>
<th>Wire #</th>
<th>Color</th>
<th>Function</th>
<th>Qxx</th>
<th>QxxN</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>Red</td>
<td>Input</td>
<td>(+)</td>
<td>(+)</td>
</tr>
<tr>
<td>W2</td>
<td>Black</td>
<td>Input</td>
<td>(-)</td>
<td>(-)</td>
</tr>
<tr>
<td>W3</td>
<td>Brn</td>
<td>Output</td>
<td>(+)</td>
<td>(-)</td>
</tr>
<tr>
<td>W4</td>
<td>Vio</td>
<td>Output</td>
<td>(-)</td>
<td>(+)</td>
</tr>
</tbody>
</table>

Dimensions are in inches
Dimensional Tolerances: ± .03 (.76mm)
(Metric Equivalents in Parenthesis)
## Hybrid system – part micro fabricated

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Number</th>
<th>Mass (g)</th>
<th>Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thrust head assembly inc. valves</td>
<td>9</td>
<td>217.8</td>
<td>&lt; 4.5 (3 x 2 valves simultaneously.)</td>
</tr>
<tr>
<td>Propellant</td>
<td>N/A</td>
<td>17</td>
<td>0</td>
</tr>
<tr>
<td>Neutraliser</td>
<td>3</td>
<td>&lt; 45.9</td>
<td>&lt; 0.75</td>
</tr>
<tr>
<td>Propellant tanks &amp; mounts</td>
<td>3</td>
<td>105.0</td>
<td>0</td>
</tr>
<tr>
<td>High Voltage supply</td>
<td>2</td>
<td>56.6</td>
<td>2.5</td>
</tr>
<tr>
<td>Interface electronics</td>
<td>1</td>
<td>21.0</td>
<td>0.6</td>
</tr>
<tr>
<td>Power conditioning</td>
<td>1</td>
<td>20.0</td>
<td>2.5</td>
</tr>
<tr>
<td>Fluid feed pipes, misc. attachments</td>
<td>N/A</td>
<td>~20</td>
<td>0</td>
</tr>
<tr>
<td>Electrical isolation</td>
<td>N/A</td>
<td>~20</td>
<td>0</td>
</tr>
<tr>
<td>Estimated TOTAL (upper limit)</td>
<td></td>
<td>523.3</td>
<td>10.85</td>
</tr>
</tbody>
</table>
Conclusions

• Micro fabrication allows the construction arrays of identical emitters

• Outline system design for Colloid micro propulsion for nano satellite

• 6 degree of freedom capability

• Typical performance
  
  • Nine thrust heads each of 100µN
  • Propellant Ionic liquid (BmimBF₄)
  • Specific Impulse ~ 500s
  • Orbit Average power ~ 0.1 W (maintenance at 1 per day)