Micro-Cathode Arc Thrusters for CubeSat Propulsion

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Vacuum Arc

- Arc attaches to micron-sized spots called cathode spots.
- At low current (up to 100 A for copper) one spot at a time.
- Current density at spot is $10^9 - 10^{12} \text{ A/m}^2$.
- Spot lifetime ranges from nanoseconds to microseconds.


Micro-Cathode Thruster with Extended Lifetime
Outstanding issues with microthrusters

AFRL micro-PPT

Keidar, *JPP*, 2004
Contamination

Weakly ionized plasma
Schematic of the μCT Isolation Material

Core

Magnetic Coil

Spring

Cathode

Isolator

Anode
micro-cathode arc thruster (μCAT)

Schein et al.
Cathode Spot Rotation

The Experiment Result shown that the Rotation Speed is $75\text{m/s}$.

The Rotation As the Direction of $-J \times B$. 

![Graph showing current distribution with probes]
Cathode Spot Rotation

Rotation speed vs. magnetic field

Cathode spot rotation speed (m/s)

Magnetic Field Strength (T)

Uniform erosion
Magnetic field effect

**Graph 1:**
- Title: Mass consumption rate/pulse vs. Magnetic field strength
- Y-axis: Mass Consumption Rate Per Pulse (mg/Pulse)
- X-axis: Magnetic Field Strength (T)
- Data points with error bars

**Graph 2:**
- Title: Impulse bit vs. Magnetic field strength
- Y-axis: Impulse Bit (μNs)
- X-axis: Magnetic Field Strength (T)
- Data points with error bars
Velocity measurements

Time-of-flight

In agreement with measured

\[ \Delta V \approx 10^4 \text{ m/s} \]

\[ Mn \frac{dV}{dt} = j_\theta B_r \]

\[ \Delta V_z = \sqrt{\frac{2e^2 B_z B_r V_e \Delta z}{mM V_{ei}}} \]
PIC simulations

Magnetic field

No magnetic field
Satellite contamination, backflux

Zhuang et al. JPP 2013

Ion current (Arbitrary Unit)

Time (µs)

0 degree

45

90
Thrust vector control

- Holder
- Spring
- Cathode
- Insulator
- Magnetic Coil
- Anode
- Dr
µCAT plume distribution experiment setup
μCAT plume distribution

The ion spatial and temporal distribution with different magnetic coil strength
• $10^7$ pulses are necessary for normal thruster operation in space
• Breakdown becomes very important
Arc Ignition in Micro-CAT

Idealized system

- Cathodic jet
- Cathode
- Anode
- Insulator
- Cathode spot
- Inter-electrode film
- Cathode particles
- Film particles

Graph:
- Lifetime (Number of pulses) vs. Gap (mm)
- Low power regime
- High power regime
Surface of insulator

(a) Before Arcing

(b) After Arcing (500 pulses & 50 us)

Teel et al., J. Appl. Phys., 2017
Cyclic process

Teel et al., J. Appl. Phys., 2017
NASA Ames PhoneSat Experiment


- NASA Ames PhoneSat selected micro-CAT
  
  Android app compatible with PhoneSat Bus will be capable of commanding uCATs
USNA flight experiment
Ballistically Reinforced Communications Satellite (BRICSat-P)

The on-orbit data shows that the propulsion system was able to reduce initial tumbling from an estimated 30 °/s to within 1.5 °/s after 48 hours.

Launch, May 20 2015
New flight experiments

CANYVAL-X  Yonsei U/NASA

Launch, Jan, 12, 2018, ISRO

Thrust: 0.1-0.3 mN
Isp: 1500 s

NASA Goddard pre-flight testing
CUBESATELLITES

- Formation Flying
- Earth observation
- SIMPLEx
(Small, Innovative Missions for Planetary Exploration)
- UNP
(University Nanosat Program)

Vector Space

NASA CubeSat initiative
The μCAT system will be tested to provide 3-axis stabilization to the satellite.

Science mission:
Partner: TEC University of Costa Rica
TEC will place ground station in a wetland in a remote area of Costa Rica. Water temperature, acidity, oxygen levels will be transmitted to GWSat.
# Summary of micro-CAT performance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>System mass (g)</td>
<td>200</td>
</tr>
<tr>
<td>System volume (cm$^3$)</td>
<td>200</td>
</tr>
<tr>
<td>Propellant</td>
<td>Metal</td>
</tr>
<tr>
<td>$I_{sp}$ (s)</td>
<td>3000</td>
</tr>
<tr>
<td>Propellant mass (g)</td>
<td>40</td>
</tr>
<tr>
<td>Delta-V (for 4 kg satellite) (m s$^{-1}$)</td>
<td>300</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>15</td>
</tr>
<tr>
<td>Thrust-to-mass ratio (μN g$^{-1}$)</td>
<td>0.63</td>
</tr>
<tr>
<td>Ionization degree</td>
<td>High</td>
</tr>
<tr>
<td>Cost</td>
<td>Low</td>
</tr>
<tr>
<td>Technical readiness level (TRL)</td>
<td>6</td>
</tr>
<tr>
<td>Current:</td>
<td>7/8</td>
</tr>
</tbody>
</table>

High-thrust to power micro-CATs

Table 1. Expected performance data for the different μCAT propulsion system family. The values are expected.

<table>
<thead>
<tr>
<th>Figure of Merit</th>
<th>μCAT Current Status</th>
<th>μCAT-MPS (gridded) (Estimated Data)</th>
<th>μCAT-MPS (TAL) (Estimated Data)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRL</td>
<td>TRL-6</td>
<td>TRL-3</td>
<td>TRL-4/5</td>
</tr>
<tr>
<td>$I_{sp}$</td>
<td>~ 2000 s</td>
<td>3000 s – 4000 s</td>
<td>2000 s – 34000 s</td>
</tr>
<tr>
<td>Power</td>
<td>&lt; 10 W</td>
<td>Up to 60 W</td>
<td>Up to 60 W</td>
</tr>
<tr>
<td>Efficiency</td>
<td>~10-15%</td>
<td>&gt; 50%</td>
<td>&gt; 50%</td>
</tr>
<tr>
<td>Thrust to Power ratio</td>
<td>10 μN/W @ 10 Hz</td>
<td>&gt; 100 μN/W @ 10 Hz</td>
<td>&gt; 100 μN/W @ 10 Hz</td>
</tr>
<tr>
<td>Size / Volume</td>
<td>2-4 thruster heads + PPU per PC104 PCB</td>
<td>Approximately 1-1.5 U including PPUs and thruster</td>
<td>Approximately 1-1.5 U including PPUs and thruster</td>
</tr>
<tr>
<td>Voltage</td>
<td>1 – 2 kV</td>
<td>~1 kV</td>
<td></td>
</tr>
<tr>
<td>Relative cost to comparable technologies</td>
<td>Very low</td>
<td>low</td>
<td>low</td>
</tr>
</tbody>
</table>

Lukas et al, AIP Advances, 2016
Kolbeck & Keidar, IEPC-2017
Summary

• High TRL microthrusters are developed & flight experience
• Solid propellant, electrically triggered, impulse bit throttle, fully ionized plasma
• New high-thrust to power for 6U Cube Sats are under development
Workshop

**International Workshop on Micropropulsion for CubeSatellites (IWMC)**

- July 31- Aug 1, 2018
- Lehman Auditorium, Science & Engineering Hall [https://seascf.seas.gwu.edu/lehman-auditorium]
- (The George Washington University)
- 800 22st St NW, Washington, DC 20052
- Click here to register for the Conference [https://secure.touchnet.com/C20789_ustores/web/store_main.jsp?STOREID=21&SINGLESTORE=true]
- Early birds registration (before June 1, 2018) : $250
  Regular (after June 1): $350
- This workshop is the followup meeting (MPCS-III [https://www.micropropulsion.org/mpcs-3]) of Micropropulsion and CubeSatellites (MPCS) after two successful meetings in Italy and Singapore.

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WASHINGTON, DC
Thank you!