Quad-Thruster FEMTA Micropropulsion System for CubeSat 1-Axis Control

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Film Evaporating MEMS Tunable Array (FEMTA)

Technology Overview

• Microelectromechanical systems (MEMS) thruster using ultra-pure deionized liquid water as propellant

• Utilizes thermally controlled microcapillaries with low-power platinum microheaters to generate micronewton thrust

• FEMTA Gen4 nozzles used for this demo

• FEMTA Gen3 demonstrated $I_{sp} > 80$ s, thrust-to-power ratios of 230 μN/W, and thrust was measured from 6-68 μN$^2$
<table>
<thead>
<tr>
<th>Propulsion Technology</th>
<th>$I_{sp}$ [sec]</th>
<th>Thrust [mN]</th>
<th>Power [W]</th>
<th>Mass [g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold Gas</td>
<td>32 - 80</td>
<td>0.01 - 40.0</td>
<td>1 - 5</td>
<td>10 - 500</td>
</tr>
<tr>
<td>Electrospray</td>
<td>800 - 2,300</td>
<td>0.06 - 0.7</td>
<td>1.5 - 15</td>
<td>95 - 500</td>
</tr>
<tr>
<td>Ion Engine</td>
<td>300 - 3,500</td>
<td>0.05 - 1.4</td>
<td>10 - 60</td>
<td>~ 400</td>
</tr>
<tr>
<td>Pulsed Plasma Thruster (PPT) and Vacuum Arc</td>
<td>540 - 3,000</td>
<td>0.001 - 0.09</td>
<td>2 - 14</td>
<td>200 - 500</td>
</tr>
<tr>
<td>FEMTA</td>
<td>50 - 95</td>
<td>≤ 0.5</td>
<td>&lt; 1</td>
<td>~ 45</td>
</tr>
</tbody>
</table>

FEMTA is a low mass, low power alternative for small spacecraft attitude control.
FEMTA nozzle is etched into a 300-micron thick, 100 mm diameter, \langle1 0 0\rangle oriented silicon wafer.

**Fabrication Methods**
- Standard Photolithography
- Oxide Growth
- Wet Etching
- Plasma Etching
Research Intent

Quad - Thruster FEMTA Micropropulsion Experiment

- Demonstrate the ability to cause rotation about the satellite’s vertical axis
  - Fabricate 1U cubesat to standard specifications – 10 cm cube, 1.33 kg
  - Design and fabricate duplex FEMTA thrust cell with shared, gravity fed propellant tank and electrical connections
  - Design and build harness for testing inside Purdue’s large vacuum chamber
  - Include an on-board angular position sensor
  - Battery must provide at least 5V and 2 A h
  - Minimize weight of system

- Characterize the thrust and spin of the satellite
- Demonstrate repeatable control of the satellite with a FEMTA micropropulsion system
1U-Quad-Thruster FEMTA CubeSat

Design Overview

1U-Quad-Thruster Model components

- Inertial Measurement Sensor
- FEMTA Duplex Thrust Cell
- Power Conditioning Board
- Microcontroller Raspberry Pi 3B
- Power Supply 2,500 mAh battery

Communication Diagram
1U-Quad-Thruster FEMTA CubeSat

FEMTA Duplex

- Houses 2 opposing FEMTA thrusters
- Contains 3.5 g of ultra-pure deionized water as propellant
  - Approximately 12 hours of single FEMTA use
- Total mass of approximately 33 g
- 3D printed with a stereolithography resin printer
1U-Quad-Thruster FEMTA CubeSat

Experiment Setup

- Testing conducted in 4.2 m³ vacuum chamber at 30 - 40 microTorr.
- Satellite suspended using a harness system designed to dampen external vibrations.
## Results

### High-Vacuum Testing History

<table>
<thead>
<tr>
<th>Test</th>
<th>Failure Description</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Test 1</strong></td>
<td>Failure - Water leaked into chamber</td>
<td>May 2, 2017</td>
</tr>
<tr>
<td><strong>Test 2</strong></td>
<td>Failure - Nozzles clogged</td>
<td>May 9, 2017</td>
</tr>
<tr>
<td><strong>Test 3</strong></td>
<td>One thruster operational</td>
<td>June 6, 2017</td>
</tr>
<tr>
<td><strong>Test 4</strong></td>
<td>Three thrusters operational, partial IMU failure</td>
<td>June 8, 2017</td>
</tr>
<tr>
<td><strong>Test 5</strong></td>
<td>Failure – Battery</td>
<td>June 9, 2017</td>
</tr>
<tr>
<td><strong>Test 6</strong></td>
<td>Failure - Pi disconnected, CPU overheating</td>
<td>June 28, 2017</td>
</tr>
<tr>
<td><strong>Test 7</strong></td>
<td>4 thrusters operational, one constantly firing</td>
<td>July 7, 2017</td>
</tr>
<tr>
<td><strong>Test 8</strong></td>
<td>Very low speed rotations achieved</td>
<td>July 13, 2017</td>
</tr>
</tbody>
</table>
Results

Test 4 - Video From

Indications of performance

- Observe the rotation through a window in the vacuum chamber.

- Watch the background vacuum chamber pressure spike (~35 microTorr to ~80 microTorr).

- LED lights indicate that power is supplied to the FEMTA.
Results

Test 4 - IMU Data

Bosch BNO055 9-axis IMU

Averaged Position Data

Averaged Velocity Data

Beginning of Rotation
Conclusions

- The quad-FEMTA thrusters integrated into a 1U CubeSat prototype and yielded quantitative verification of single-axis rotation under high vacuum conditions.

  - An average **slew rate of 7 degrees per second** and **average angular acceleration of 0.3 degrees per second squared** was measured.

  - Single-axis rotation was successfully provided by the propulsion system at a **power input of 250 mW**.

- Gyroscopes on COTS IMUs fail in high-vacuum, likely due to packaging in low-vacuum. Magnetometer yields reliable rotation data.

- Copper plate heat sink (< 50g) provides adequate heat transfer from Raspberry Pi CPU allowing operation under < 40 °C for several hours in high vacuum.
Future Work

1U - Quad - Thruster FEMTA CubeSat

➔ Incorporate new and more advanced sensors
  More advanced and durable angular position sensor
  Propellant tank temperature sensor
  Barometric sensor to measure local pressure changes due to FEMTA operation

➔ Improvements to the FEMTA duplex design
  Controlled pressure relief valves
  Using non-acrylic material
  Changing from Gaskets to O-rings for easier installation

FEMTA advancement for flight demo

➔ GSFC electrothermal shutters to mitigate quiescent evaporation in vacuum (20 mg/hr=20 g for 6 wks)
➔ Closed-loop control of heaters
➔ Gravity-free propellant feed for flight demo
Acknowledgements

• Purdue University’s School of Aeronautics and Astronautics for providing the support for the undergraduate course

• Khary Parker and Carl Kotecki at GSFC for their help and advice on this project

• Engineering staff at the Birck Nanotechnology Center and the Artisan Fabrication Laboratory at Purdue University for their assistance

• Professors Dan Dumbacher and David Spencer at Purdue University for their criticism and feedback during the project design reviews
References


Questions?

Undergraduate Research Team
Fabrication Techniques

- Standard Photolithography
  - AZ 9260 (negative photoresist) for the larger and thicker features
  - AZ 1518 (negative photoresist) for smaller more delicate features
  - Method for laying: Spinning
  - Soft and hard bake before and after exposing to photoresist
- Plasma Etching
  - Sulphur Hexafluoride to etch throat and oxide layer
- Wet Etching
  - Nozzle Inlet
Control System

- Proportional - Integral - Derivative (PID) controller designed to minimize the difference between actual spin angle and reference spin angle

\[ e = \phi_{\text{ref}} - \phi_{\text{act}} \]

\[ \frac{de}{dt} = \frac{e_{\text{curr}} - e_{\text{last}}}{\Delta t} \]

\[ \int e \, dt = \sum e_i \]

- Controller output is in the form of percentage of maximum thrust
  - Output is converted to a voltage for each FEMTA
Avionics

- On-board microcontroller communicates with a second Raspberry Pi inside the chamber via wifi
- Custom software allows user to issue commands to the satellite as well as run diagnostics
- Printed circuit board designed with a 4 channel DAC provides analog signals for thruster control
- Circuitry has been designed to incorporate propellant temperature sensors in future iterations