Thruster Subsystem for the United States Naval Academy’s (USNA) Ballistically Reinforced Communication Satellite (BRICSat-P)

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With over 272 attempted launches since 2000, CubeSat technology has exponentially increased as industries and universities have realized their potential. While this growth looks promising for space research possibilities, there are still a number of issues, with the largest being CubeSat maneuverability. The majority of CubeSats cannot orient or propel themselves, meaning mission functionality is limited and collision probability will increase as time goes on. CubeSat technology has been improving, and the mission of this technology has become increasingly more important in the development and advancement of new technologies. The Micro-propulsion and Nanotechnology Laboratory at The George Washington University has constructed a four-channel Micro-Cathode Arc Thruster (μCAT) micro-propulsion subsystem that allows these satellites to perform missions without reliance on their launch vehicles. The propulsion system has a volume of approximately 541 cm³ that can produce specific impulse values up to 3000 s. Each μCAT onboard is used for the CubeSat’s attitude control, orbit change, de-orbiting, and movement. The μCAT system was integrated into the USNA’s 1.5U CubeSat (BRICSat-P) to be used to perform three maneuvers while at an orbit of 500 km: de-tumbling, spin, and a delta-V that will attempt to change the orbit of the CubeSat relative to the orientation of Earth’s magnetic field. The objective of this paper is to provide an overview of the thruster subsystem’s development and application for the BRICSat-P mission parameters. In addition, the μCAT subsystem’s circuitry, thruster head design, and development will be reviewed to provide the information used to reach CubeSat flight standards.

Key Words: Electrothermal, Electromagnetic or Electrostatic Thruster Concepts, Flight Programs and In-flight Experience

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>( \phi )</td>
<td>pulse frequency</td>
</tr>
<tr>
<td>DC</td>
<td>duty cycle</td>
</tr>
<tr>
<td>Er</td>
<td>erosion rate of the cathode</td>
</tr>
<tr>
<td>I</td>
<td>current</td>
</tr>
<tr>
<td>Isp</td>
<td>total impulse</td>
</tr>
<tr>
<td>L</td>
<td>inductance</td>
</tr>
<tr>
<td>( \Delta m )</td>
<td>change in mass</td>
</tr>
<tr>
<td>P</td>
<td>cathode impulse</td>
</tr>
<tr>
<td>( \Delta t )</td>
<td>change in time</td>
</tr>
<tr>
<td>t</td>
<td>firing time</td>
</tr>
<tr>
<td>tp</td>
<td>time of pulse</td>
</tr>
<tr>
<td>T</td>
<td>thrust</td>
</tr>
<tr>
<td>U</td>
<td>units</td>
</tr>
<tr>
<td>V (or VDC)</td>
<td>voltage (Direct Current Voltage)</td>
</tr>
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</table>

1. Introduction

Small satellites were first used in the 1960s, but were overtaken by the promise of larger satellites. In recent years mini-, micro-, nano-, pico-, and femto-satellites have gained a significant amount of popularity in the scientific community. The CubeSat boom started in the late 1990s and early 2000s due to their versatility. CubeSats cost less to make and have a general development period of two years. This makes them ideal for universities and private companies to perform small-scale experiments on orbit, without incurring the costs and burden of launching a full-size satellite. CubeSats are typically 10 cm x 10 cm x 10 cm, and are named as such because they measure one cubic liter in volume. In addition, they can be stacked in 1, 2, 3, and 6U (1 kg = 1U) formations in the vertical plane.

Today’s industry is realizing the potential of the CubeSat, but is facing a great challenge with respect to the propulsion systems for these satellites. There are many near-future space missions involving science, military, and commercial payloads utilizing micro- and nano-satellite platforms. These platforms require very small levels of thrust for very fine attitude control, for high resolution Earth imaging and astronomy, very fine positioning requirements, for spacecraft formation flying, and interferometry missions. Nowadays, many basic components of a spacecraft are being miniaturized allowing micro-satellites
and nano-satellites to be designed and built. To satisfy the needs of both the low-thrust missions and the small-scale spacecraft, miniaturized propulsion systems are required.

In order to provide maneuvering capability to CubeSats, the Micro-propulsion and Nanotechnology Laboratory (MpNL) has developed a Micro-Cathode Arc Thruster (μCAT) subsystem, consisting of four thruster heads, one controller Printed Circuit Board (PCB), and two thruster channel PCBs. The PCBs can produce specific impulse values up to 3000 s, impulse-bits of approximately 1 μNs or better, with a very low probability of spacecraft contamination. These thrusters are integrated into the USNA’s 1.5U BRICSat-P, to perform three maneuvers and prove their ability to propel a CubeSat.

2. Background of the Micro-Cathode Arc Thruster

The MpNL developed the μCAT in 2007. The technology used to create the μCAT was derived from the Vacuum Arc Thruster (VAT), which was identified as a valid form of spacecraft propulsion in the 1960s. Vacuum arc based thrusters are an ideal propulsion system for this application to control the movement of the satellites. Vacuum arc thrusters are a type of plasma-based electric propulsion that utilizes two metallic electrodes, separated by a dielectric insulator, that ionizes propellant to release a plasma acceleration. This type of system is ideal because it is a compact way to propel a CubeSat without the use of heavy propellant tanks or risk of explosion, while also being triggerless, which reduces the overall volume of the propulsion system. In addition, they also have low energy consumption and require less fuel to stay functional for a longer duration.

The United States Naval Academy (USNA)’s Small Satellites Program (NASSP), in conjunction with The George Washington University MpNL, has created a 1.5U CubeSat that integrates the MpNL micro-propulsion system for on-orbit testing and verification.

3. Thruster Design

3.1. Thruster heads

The thruster heads consist of a coaxial anode and cathode with a ceramic insulator in between to prevent contact between the elements; an aluminum housing has been designed to encase the thruster components. The thruster creates an arc between an anode and cathode, similar to a spark plug. The cathode acts as the propellant and is pushed forward as it ablates by a helical spring for uniform erosion. According to experiments done by the MpNL, the use of titanium increases the ion current by 3.25%, as opposed to nickel which only increases the ion current by 3%, rendering the cathode a titanium cylinder with a brass screw anode. Each of the four thrust heads integrated into BRICSat-P has this set-up, also known as a Bi-Modal Micro-Cathode Arc Thruster. A CAD model of the system is portrayed in Fig. 1.

By sending an impulse and arcing across the cathode and anode, plasma is created. However, due to the vacuum of space there is no medium present for the arc to travel through, therefore a thin conducting layer is added to the insulator that separates the anode and cathode, which produces a vapor when heated, allowing for the arc to form. This forms a localized region of high temperature plasma, from a cathode spot formed at the cathode surface. The cathode spot follows a circular path along the circumference of the cathode, which ablates a small portion of cathode material and generates high velocity quasi-neutral plasma. The electron flux that exits is greater than the ion flux, creating a positively charged layer, also known as a plasma sheath. The plasma sheath begins to form on the cathode surface, producing a dense plasma that provides enough energy to the electrons to ionize neutral particles and generate thrust; this aids in accelerating the electrons to ionize the neutral particles. A schematic of the acceleration mechanism in a cathode spot is shown in Fig. 2. The cathode spot has a self-magnetic field which should allow for spot rotation and uniform erosion. However, this is not always the case because, at times, spot localization can occur. To help prevent this, each thruster contains a magnetic coil, which creates a magnetic field that helps direct the spark of plasma outward, creating uniform erosion, and aids in controlling the direction of the plasma plume. In this way, the magnetic coil increases the efficiency of the thruster. Using FEMM software the magnetic field analysis yielded that the thrusters require 0.042-0.049 Tesla to create a large enough field for the cathode spot rotation. This information has been used to calculate the requirements of the copper wire to create the magnetic coil, determining that a 24 gauge magnetic-wire will be wrapped around the spool 20 times to achieve the desired configuration.
USNA desires an ISP of 3000 s; this restriction has been used to calculate the design parameters of the system. These design parameters include the dimensions of each piece of the thruster. The total impulse is used to calculate the firing time required using the following set of equations:

\[ T = \phi \cdot P \]  
\[ t = \text{Isp} \cdot T \]  
\[ DC = t_p \cdot \phi \]  
\[ \Delta t = DC \cdot t \]  
\[ \Delta m = E_r \cdot I \cdot \Delta t \]

Where \( I_{sp} \) is the total impulse, \( P \) is the cathode impulse, \( \phi \) is the pulse frequency, \( T \) is thrust, \( t \) is the firing time, \( DC \) is the duty cycle, \( t_p \) is the time of pulse, \( I \) is the current, \( E_r \) is the erosion rate of the cathode, \( \Delta t \) is the change in time, and \( \Delta m \) is the mass for the cathode required to reach the desired impulse. The calculated mass result is 200 g, which is used to develop the volume of the cylindrical cathode. Following this deduction, each corresponding piece’s dimensions are determined.

### 3.2. Power Processing Unit (PPU)

In the design of the \( \mu \)CAT there is an inductive energy system, known as the Power Processing Unit (PPU) as shown in Fig. 3. The PPU is equipped with an inductive energy storage (IES) circuit, which is a one channel thruster subsystem. This system utilizes an Insulated-Gate Bipolar Transistor (IGBT) to act as a semiconductor gate. As a voltage pulse is passed through, the gate closes and the energy accumulates in the inductor. Once fully charged, a voltage spike, as demonstrated in (6), is produced surging between the electrodes.

\[ V = L \cdot \frac{dI}{dt} \]  

The total current that passes through is controlled by the variable length of the trigger signal to regulate the energy stored in the inductor that causes the arc discharge. This is because the voltage spike across the electrodes breaks down the film coating the insulator, separating the anode and cathode, creating a vapor medium for the arc to form in.

### 3.3. Control Unit (CU)

Separate from the PPU is a Control Unit (CU). The CU controls the actions of the thrusters and consists of several PCBs with standalone microcontrollers to create a multichannel subsystem. They are modular in order to incorporate the power system and control system without any restrictive orientation. The CU contains a power distribution section, power connectors, a CubeSat KIt bus connection, and a subsystem interface. Within the subsystem interface there are three groups: the command signal input, the telemetry signal output, and the power supply input. Utilizing 6-36 VDC, the CU outputs impulses to all channels at a maximum firing rate of 55 Hz to regulate the pulses sent to the PPU to produce the thruster discharge. The system in its entirety is shown in Figure 4.

### 4. Mission Parameters and Satellite Integration

The focus of the mission is to integrate the \( \mu \)CAT into the CubeSat system in order to validate its capabilities. The thruster system must be able to detumble the CubeSat to a stable orientation and spin rate for several orbits, demonstrate the ability to spin around two axes, and perform a desired delta-V using a gyroscope and magnetometer. To allow the system to perform these maneuvers, the thrust head configuration must be optimized for peak performance. Prior to sending the CubeSat to orbit, it must be verified that the components can withstand a series of vibrational and thermo-vacuum tests to ensure it is able to survive the launch conditions and the harsh environment.
of space. Once the CubeSat is launched, the thruster subsystem will be assessed based on its performance and ability to execute the desired tasks in orbit without consuming an inordinate amount of fuel or power.

The CubeSat itself must remain within the mass limit of 2 kg (being a 1.5U). Taking into consideration the mass of the satellite bus, the propulsion system was allotted 1 kg. Due to the fact that the thruster system is only 600 g in total, a decision has been made to have four separate power units – rather than two units with a switch interface. Figure 5 depicts a thruster board with two power units integrated together with two thruster heads on one board. Two of these boards, together with a control unit, are integrated into BRICSat-P. The entire satellite assembly, without the external solar panels is also shown in Fig. 6. As can be seen in the figure, the two thruster boards were separated by an interface board, forming a four-thruster-head system. All thruster heads were designed to be facing a single direction, giving the satellite the ability to control rotation in the x and z axes. The y axis, that is not directly controlled, is an intermediate axis (as to major/minor axis), and the rotation about this axis is controlled by letting the rotational momentum decay down to the major axis, then controlling the major axis rotation. Simulation results showed that this method is adequate to control tumbling in all three axes within a reasonable time. Details of this analysis and result are published in a separate article.

Fig. 5. Picture of a thruster board containing two thruster head set-up.

Fig. 6. Picture of a thruster boards as integrated into the satellite. The red circles indicate the thruster head positions.

In addition, the entirety of the outside is covered with solar panels to generate power. Figure 6 shows a picture of the fully assembled BRICSat-P with the thruster heads circled in red, and Fig. 7 includes the solar panels. The BRICSat-P communicates with ground-stations via an Automatic Packet Reporting System (APRS) amateur radio system to relay pictures and data to verify that the thrusters are firing.

Fig. 7. Fully assembled BRICSat-P, showing the side with thruster heads.
5. Results of Laboratory Testing

The MpNL has been running life-time erosion rate tests on the thruster heads to review their performance. The erosion rate must be calculated to determine that the thruster is working properly. If the cathode ablates too much too quickly the efficiency will decrease and the life-time will be shortened. These tests are run in the vacuum chamber at 9e-4Torr. The thruster heads are pulsed at 10Hz, while the arc current and spark location are documented. Using the following equation, and necessary measured values, the erosion rate can be determined:

\[
Er = \frac{\Delta m}{\Delta t * I} \quad (7)
\]

From the data acquired, the thrusters are eroding 5.206e-6 g/C, meaning that the cathode is ablating at a small, steady rate. Figures 8 illustrates the location of the arc that is described in Figs. 9 and 10, which display how the arc location relates to the arc current with respect to time. 

![Location of Cathode Spot](image)

Fig. 8. Location of Cathode Spot.

As shown in Figs. 9 and 10, the location of the arc is related to the arc current. The y-axis in Fig. 9 is labeled with locations where the spark occurred. As the arc current changes the location moves based on this change. It is especially affected by the voltage of the magnetic coil because it will cause the spot to move in the opposing direction of the field. When the magnetic coil is introduced the current settles and the spot begins to follow a pattern. As can be seen in Figs. 9 and 10, when the magnetic field is enacted the spot location becomes more random, which is desirable because then the cathode ablates evenly, rather than in one place. This leads to uniform cathode erosion and symmetric plasma plume. The cathodes displayed adequate erosion for the length of the test.

A full-scale functionality test, shown in Fig. 11, was performed by USNA, without the solar panels, as shown. The test was conducted at room temperature, without any thermal loading. The test subject was suspended using a fishing wire from the ceiling of the vacuum chamber and wound 5 rotations for each test. Once the vacuum level reaches -4 Torr level, the satellite restraint is released, allowing it to rotate freely. These tests verified the detumbling simulations, where the thrusters fired in the opposite direction to the rotation, slows down the rotation rate. The only torque being applied is the torsion of the string. Results showed that the thrusters counteracting the torque and rotation were functioning correctly, causing the satellite to detumble much faster resulting in a decreased oscillatory amplitude, as well as an increase in time to reach the full period. Table 1 below lists averaged data for the detumble test. “Spin Time” is the time it takes for the satellite spin to go through 1.5 periods, and “Rotation Angle” shows the number of revolutions the satellite spin goes through before coming to a rest at the end of each half period. As can be seen in Table 1, thruster firing will increase the spin period while decreasing the spin amplitude, confirming the propulsion system functionality.

Rigorous test firings have been performed both at the component level and fully-integrated satellite level. During the tests, there was no abnormal discharging or arcing.

<table>
<thead>
<tr>
<th>Test Type</th>
<th>Spin Time (s)</th>
<th>Rotation 1 (rev)</th>
<th>Rotation 2 (rev)</th>
<th>Rotation 3 (rev)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prop. Engaged</td>
<td>74</td>
<td>4.75</td>
<td>2</td>
<td>1.5</td>
</tr>
<tr>
<td>Prop. Off</td>
<td>67</td>
<td>5</td>
<td>2.5</td>
<td>1.75</td>
</tr>
</tbody>
</table>

Table 1. Full-scale satellite spin results. The numbers shown are average values from multiple tests performed.
6. Experiment Update

BRICSat-P was launched in May of 2015. It is currently in orbit, but due to power issues, a consistent communication has not yet been established. Some preliminary data has been downloaded from the satellite, and it shows that the satellite has successfully operated the propulsion system. Communication received from the CubeSat thus far has also verified the thruster’s ability to detumble. The Preliminary data shows that the propulsion system was able to reduce initial tumbling from an estimated 30 º/s to within 1.5 º/s after 48 hours. This was accomplished without any additional passive or active attitude control mechanism, such as magnetic torque, permanent magnets, or hysteresis rods. Analyses showed that with an absence these attitude control systems, the satellite will continue to tumble at an average of 5 º/s continuously due to the disturbance torques, if the thrusters were to not function. However, the data showed that the two axes that are controlled directly by the propulsion system have reached the target rotation rate of 1.0 º/s at a much earlier time, and the intermediate axis is the only axis still above 1.0 º/s at the 48 hour mark. After another 48 hours, all three axes were stabilized to below 1.0 º/s. More data will give a better understanding of the performance of the propulsion system, but the preliminary results shows that the propulsion system functioned quite effectively. The initial tumbling rate for the satellite is not known, and the data shows that the satellite has performed multiple power cycles due to low voltage in the batteries. Accordingly, the exact performance parameters of the propulsion system cannot be calculated. However, as can be seen in Fig. 12, the simulation shows that the satellite cannot detumble with natural disturbance torques alone in orbit. This supports the obtained on-orbit data that the propulsion system has successfully detumbled the satellite, as predicted by simulation as shown in Fig. 13.

7. Conclusions

The integration of the Microcathode Arc Thruster micropropulsion system into the Ballistically Reinforced Communication Satellite is discussed in this paper. There is great significance in using electric plasma propulsion as the propulsion system for a CubeSat because of their small stature and lack of real estate that is normally required for a large propellant tank or solid fuel system. The µCAT system only requires about 1/3 of the space inside of the BRICSat-P and is customizable for other, specific and non-specific, CubeSat missions. On the ground, the thruster subsystem has demonstrated the capability of spinning the BRICSAT-P along its axis and, from the results, displays that it is behaving in a desirable manner. The mission was launched in late May of 2015 for on-orbit validation of the design. The preliminary data received from the satellite on-orbit shows that the propulsion system has successfully detumbled the satellite after its initial deployment.
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References


