

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

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Abstract: With over 272 attempted launches since 2000, CubeSats have 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 (μ CAT) micro-propulsion subsystem that allows these satellites to perform missions without reliance on their launch vehicles. The propulsion system has a volume of approximately 541cm^3 that can produce specific impulse values up to 3000s. Each μ CAT onboard is used for the CubeSat's attitude control, orbit change, de-orbiting, and movement. The μ CAT system was integrated into the USNA's 1.5U

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BRICSat-P to be used to perform three maneuvers while at an orbit of 500km: 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 μ CAT subsystem's circuitry, thruster head design, and development will be reviewed to provide the information used to reach CubeSat flight standards.

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

Nomenclature

ϕ	=	pulse frequency
C	=	Coulomb
cm	=	centimeter
DC	=	duty cycle
E_r	=	erosion rate of the cathode
g	=	gram
Hz	=	hertz
I	=	current
I_{sp}	=	total impulse
kg	=	kilogram
km	=	kilometer
L	=	inductance
Δm	=	change in mass
μNs	=	micro Newton second
P	=	cathode impulse
S	=	seconds
Δt	=	change in time
t	=	firing time
t_p	=	time of pulse
T	=	thrust
U	=	units
V (or VDC)	=	voltage (Direct Current Voltage)

1. Introduction

Today's industry is realizing the potential of the CubeSat, but is facing a great challenge with respect to the propulsion system 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, and 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.

Small satellites started being used in the 1960s, but in recent years mini-, micro-, nano-, pico-, and femtosatellites have gained a significant amount of popularity in the scientific community.⁶ The cubesat boom started in the late 1990s and early 2000s due to their versatility. Cubesats cost less to make and have a turn-around of around 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 10cm x 10 cm x 10cm, and are named as such because they measure to one cubic liter in volume. However, they can be stacked in 1, 2, 3, and 6U (1kg = 1U)⁷ formations in the vertical plane. 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.^{9,1} This type of system is ideal because it is a compact way to propel the cubesat without the use of heavy tanks or risk of explosion, while also being triggerless, which creates more free-space with the absence of a trigger system. In addition, they also have low energy consumption and require less fuel to stay alive longer.¹ However, the standard vacuum arc thruster cannot achieve a large enough I_{sp} for effective propulsion, and cannot control the back flux.³

To solve this, the MpNL has constructed a Micro-Cathode Arc Thruster (μ CAT) 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 3000s, impulse-bits of approximately 1 μ Ns 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 a μ CAT in 2007. The technology used to create the μ CAT was derived from the Vacuum Arc Thruster (VAT), which was identified as a valid form of spacecraft propulsion in the 1960s.¹ Vacuum arc thrusters are ideal for small spacecraft because they are able to utilize small quantities of solid metal for the propellant. Cube satellites are classified as 10cm x 10cm x 10cm nanosatellites used for research purposes. They are employed primarily by universities and private companies to conduct small-scale experiments in space. CubeSats can vary in their vertical dimension by combining multiple modules and stacking them as 1, 2, 3, or 6U. The United States Naval Academy, in conjunction with The George Washington University MpNL, has created a 1.5U CubeSat that integrates the MpNL micro-propulsion system.

3. Thruster Design

3.A. 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. 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%.¹ Each of the four thrust heads has a nickel anode and titanium cathode, also known as a bi-modal Micro-cathode arc thruster. A CAD model of the system is portrayed in Figure 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 "potential hump" that provides enough energy to the electrons to ionize neutral particles and generate thrust; this aides in accelerating the electrons to ionize the neutral particles. A schematic of the acceleration mechanism in a cathode spot is shown in Figure 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 and helps with uniform erosion and aides 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.²



Figure 1. CAD Model of Thruster Head.²

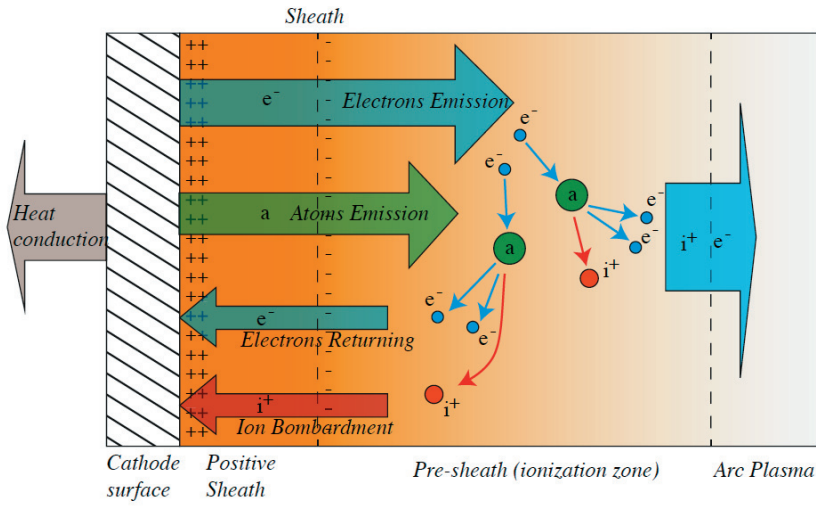


Figure 2. Illustration of vacuum arc in the cathode spot region.

USNA desires an I_{sp} of 3000s. 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 equations³:

$$T = \phi * P \quad (1)$$

$$t = I_{sp} / T \quad (2)$$

$$DC = t_p / \phi \quad (3)$$

$$\Delta t = DC * t \quad (4)$$

$$\Delta m = E_r * I * \Delta t \quad (5)$$

Where I_{sp} is the total impulse, P is the cathode impulse, ϕ 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, Δt is the change in time, and Δm is the mass for the cathode required to reach the desired impulse. The calculated mass result is 200g, which is used to develop the volume of the cylindrical cathode. Following this deduction, each corresponding pieces' dimensions are determined.

3.B. Power Processing Unit (PPU)

In the design of the μ CAT there is an inductive energy system, the Power Processing Unit (PPU) as shown in Figure 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 Eq. (6), is produced

$$L \frac{dI}{dt} \quad (6)$$

surging between the electrodes. 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.^{1,3,4}

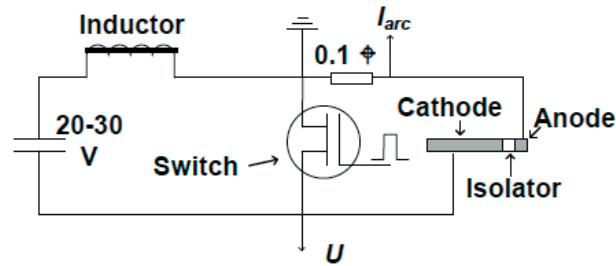


Figure 3. PPU Circuit Diagram.⁵

3.C. Control Unit (CU)

Separate from the PPU are a series of Printed Circuit Boards (PCBs) that make up the 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 Cube SAT 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.² Utilizing 6-36VDC, the CU outputs impulses to all channels at a maximum firing rate of 55Hz to regulate the pulses sent to the PPU to produce the thruster discharge. The entire system is shown in Figure 4.

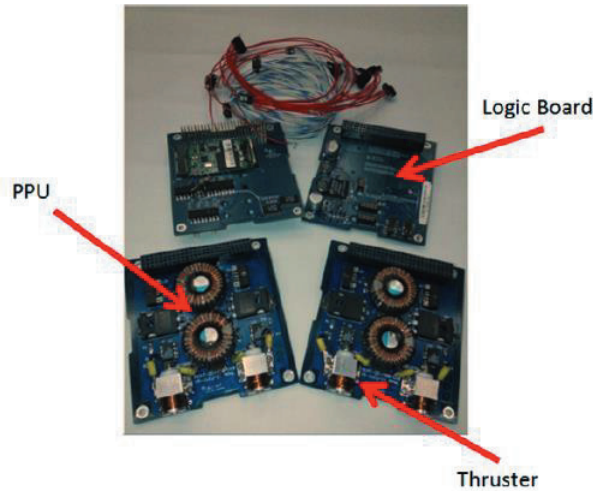


Figure 4. μ CAT full set-up.

4. Mission Parameters

The focus of the mission is to integrate the μ CAT into the CubeSat system 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.² 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 has to prove that it can withstand a series of vibrational and thermo-vacuum tests to ensure it is able to endure lift-off and the harsh conditions 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 structure of the CubeSat itself had to remain within the mass limit of 2kg (1.5U), leaving 1kg for the thruster subsystem. Due to the fact that the thruster system is only 600g in total, a decision has been made to have four separate power units – rather than two units with a switch interface.² In addition, the entirety of the outside is covered with solar panels to generate power. 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. The system has been scheduled to launch in March of 2015.

5. Results of Laboratory Testing

The MpNL is 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 of the cathode too quickly the efficiency will decrease and the life-time will be shortened. These tests are run in the vacuum chamber at $9\text{e}^{-4}\text{Torr}$. The thrust 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 determined⁴:

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

From the data acquired, the thrusters are eroding $5.206\text{e}^{-6} \frac{\text{g}}{\text{C}}$, meaning that the cathode is ablating at a small, steady rate. Figures 5 illustrates the location of the arc that is described in Figures 6 and 7, which display how the arc location relates to the arc current with respect to time.

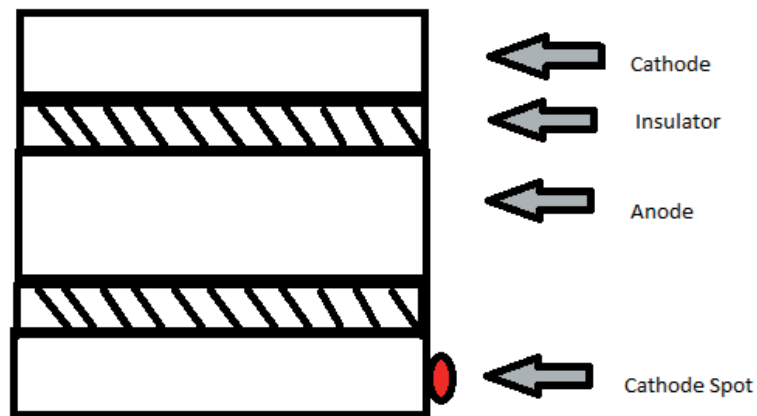


Figure 5. Location of Cathode Spot.

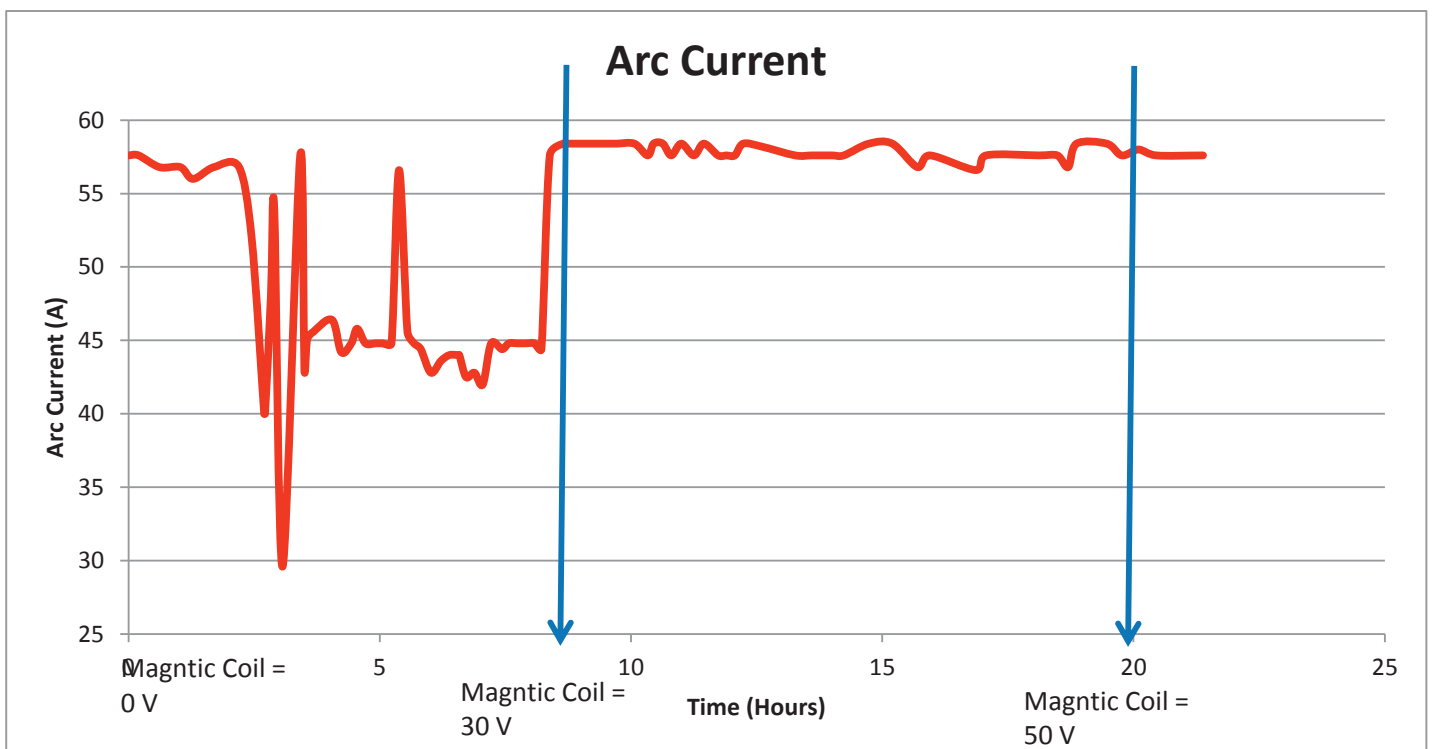


Figure 6. Plot of the Arc Current versus time.

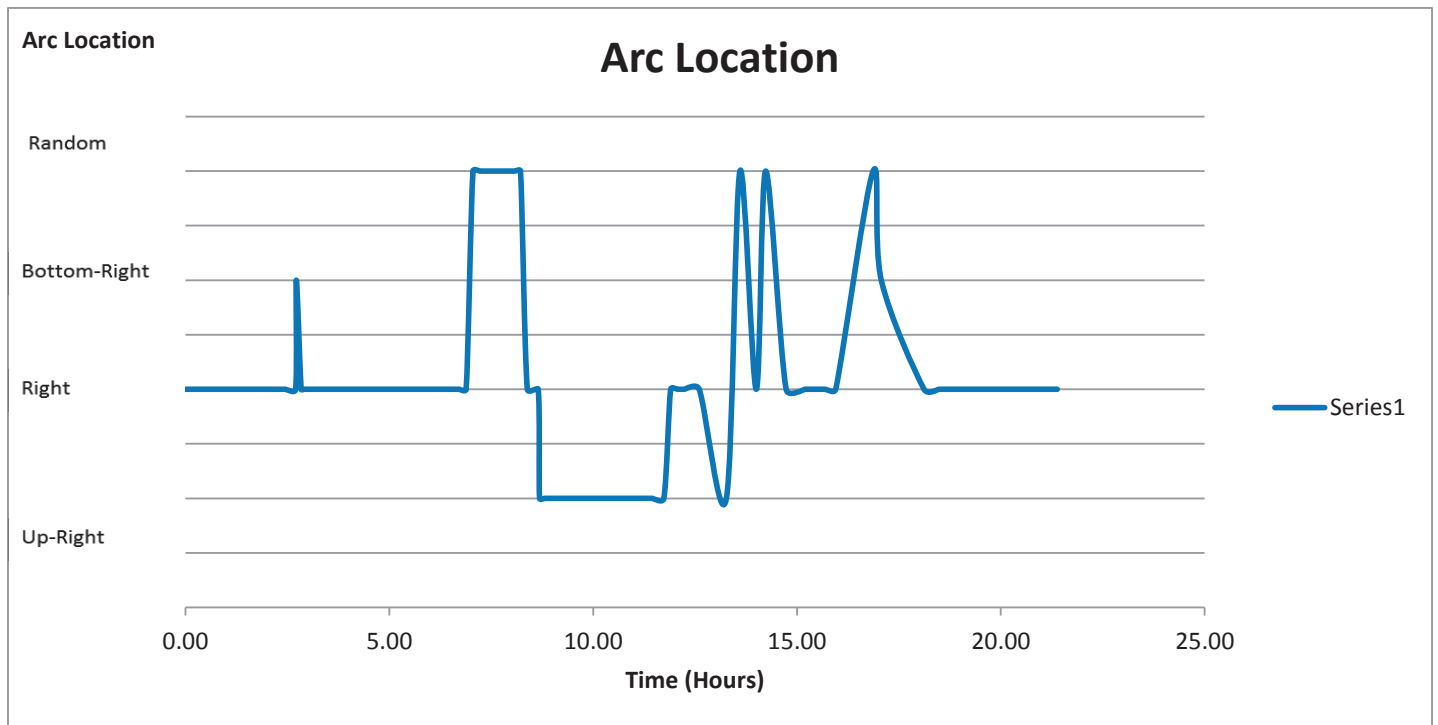


Figure 7. Plot of the Arc Location versus time.

As shown in figures 6 and 7, the location of the arc is related to the arc current. 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.¹ When the magnetic coil is introduced the current settles and the spot begins to fall in a pattern. As 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.

6. Conclusions

The integration of the microcathode arc thruster micropropulsion system into the Ballistic 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 for a large liquid tank or solid fuel system. The μ CAT 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 has been postponed, but is scheduled to launch in late May of 2015.

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