μCAT Micro-Propulsion Solution for Autonomous Mobile On-Orbit Diagnostic System

Jonathan Kolbeck, Joseph Lukas, George Teel, Michael Keidar
The George Washington University
800 22nd St NW, Washington, DC 20052; +1-202-600-6457
jkolbeck@gwu.edu

Edward Hanlon, Jacob Pittman, Morgan Lange, Jin Kang
United States Naval Academy
Annapolis, MD 21402; +1-410-293-6411
kang@usna.edu

ABSTRACT

CubeSat technology and mission envelope has been steadily increasing in the recent years as the CubeSat platform became increasingly popular throughout space community. One of the key technologies that will advance the satellite capability to a higher level is propulsion. Commercially available propulsion system for CubeSats, including electric propulsion units, currently exist. However, the size and power consumption of the current electric propulsion units make them difficult to be integrated to smaller form factor CubeSats with lower power and volume availability. The Micro-Cathode Arc Thruster, a micro-propulsion system developed by The George Washington University, seeks to provide a solution for the power and volume limitations of smaller CubeSats. Four Micro-Cathode thrusters have been successfully integrated and tested in space onboard the U.S. Naval Academy (USNA)'s 1.5 U CubeSat, BRICSat-P. This system will enable satellite developers to plan and build more ambitious and complex CubeSat missions. The thruster gives CubeSats (and other small satellites) the ability to perform orbital maneuvers, orbital corrections, and active attitude control capabilities. The thruster utilizes a metallic propellant (e.g. nickel) to produce thrust. The propellant is ionized to a high degree (usually above 99 %) during the discharge, producing ions with velocities in the magnitude of 10^4 m/s. The AMODS mission by USNA will take advantage of these thrusters in order to perform rendezvous and docking maneuvers between two different 3 U CubeSats, RSat, and BRICSat. This paper will describe the Micro-Cathode Arc Thruster system, as well as the past, current, and future implementation of the system on USNA's CubeSat missions.

INTRODUCTION

CubeSats provide excellent platforms to test new technologies and demonstrate new capabilities. Their small and standardized size allows them to be cost efficient. Most of these small satellites are built using off-the-shelf components, which can significantly reduce the development time. The first CubeSats were launched in 2003[1, 2] and as of today, most of the over 460 microsatellites (i.e. with masses below 100 kg) launched since 2003 have been CubeSats[3]. It is expected that the demand for CubeSat launches will rapidly increase in the following years[3, 4]. More recently, there has been a shift towards increasingly complex and ambitious missions. It has been proposed to use these small satellites for missions to the moon[5], interplanetary missions[6], and other tasks. Many other missions have been envisioned and designed to perform formation flights[7] and rendezvous and docking maneuvers. This paper focuses on the latter. The mission described herein has been designed as part of the University Nanosat Program (UNP), a program established in 1999 and managed by the Air Force Research Labs (AFRL).

MOTIVATION

Satellites cannot return to Earth for repair if they are damaged, have malfunctions, or fail to deploy as planned. In addition, on-orbit repair remains a prohibitively expensive proposition. Accordingly, what might be a modest glitch on a terrestrial craft can cripple a spacecraft and severely impede or terminate research efforts. Midshipmen at the United States Naval Academy (USNA) in Annapolis, Maryland are focusing on scaling the costs of on-orbit repair down dramatically by using CubeSats to execute relatively simple imaging, diagnostic, and even repair tasks. One key enabler for such operation is orbit maneuver capability. In order for the repair satellites to place themselves in near proximity of the host satellite, a propulsion system is required. Accordingly, The George Washington University (GWU)'s Micro-Cathode (μCAT) thrusters are being developed and tested to provide such capabilities to the small satellites such as CubeSats. The latest iteration of the propulsion system is being integrated with USNA satellites for on-orbit performance and system characterization.

MICRO-CATHODE ARC MICRO-PROPULSION SYSTEM

The Thruster

The thrusters are based on the physical phenomenon of vacuum (cathodic) arcs. The term cathodic refers to the fact that the discharge is produced on the cathode on so-called cathode spots. These are the source of electrons and ions, i.e. plasma, required to sustain the discharge. For this type of propulsion system, the cathode functions both as electrode for the discharge and as propellant. The µCAT (micro-cathode arc thruster) system has been designed and manufactured at GWU. As of May 2016, the development stage of the thruster is at TRL-7.

Figure 1 shows an example of the circuit board with the components used to operate the µCAT system. This particular board configuration was flown on USNA's BRICSat-P CubeSat, the predecessor to the BRICSat satellite in the AMODS mission. The flight result is described in more detail below. A similar but more complex system will be flown on the AMODS mission, which is a follow-on USNA CubeSat mission. This mission is also described in detail below.

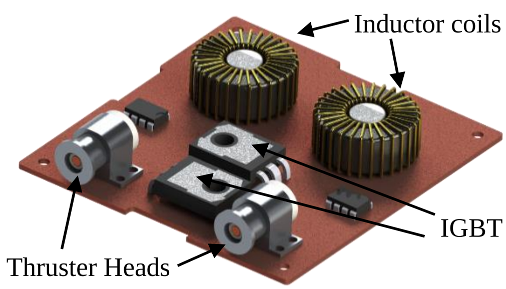

Figure 1: CAD image of the thruster control board flown on BRICSat-P

Figure 2 depicts a schematic of the circuitry used to power the µCAT devices. A DC voltage of approximately 15-25 V is applied to charge an inductor. The IGBT is set in such a way as to close Loop 1. Once the inductor is fully charged (within fractions of a second), a square-wave pulse is sent to the IGBT, which stops the flow of current through it, forcing the inductor to release its stored energy in the form of a voltage spike of hundreds of volts through Loop 2 onto the thruster head. The ceramic interface between the cathode and the anode is covered in a thin layer of graphite with a resistance in the 1000s of ohms. The resistance of the graphite causes it to heat up locally and ionize. This cloud of ionized graphite produces a highly conductive path between the cathode and the anode, allowing a high current of approximately 40 A to flow to the anode. This flow of current is known as an electric arc, and it originates in small spots on the cathode known as cathode spots. These are high temperature and high luminosity spots with a diameter of only a few micrometers and a life-span of only a few nanoseconds. These spots are known to have high current densities of up to 10^{12} A/m^2.[8] An increase in the cathode current does not further increase the current density at these spots above the aforementioned value, but rather contributes to the production of more cathode spots. The thrust produced by a system using this phenomenon is proportional to the amount of emission (cathode) spots. Therefore, it is desired to have many emission spots at the same time in order to increase thrust. While this may be beneficial from the thrust point of view, a large amount of cathode spots also increases the temperature of the cathode significantly, as these spots are known to have temperatures of over 4000 K. An increased cathode temperature leads to zones of gross melting and an increase in the production of detrimental particles called macroparticles. These particles are slow-moving molten metal droplets that do not contribute significantly to thrust but considerably increase the erosion rate of the cathode, leading to an inefficient use of the propellant.

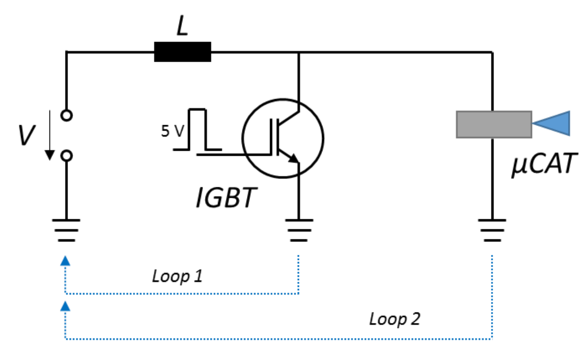

Figure 2: Thruster circuit diagram

The aforementioned cathode spots are the source of ionized cathode material (i.e. ionized propellant) and electrons, which are required to close the circuit. Acceleration of ions occurs mainly due to hydrodynamic pressure gradients in the near-cathode region[9]. The µCAT system is equipped with a magnetic coil near the exit region of the plasma. The magnetic coil has been shown to further accelerate the ions[10] by using the magnetic nozzle effect, increasing the axial momentum of the ions. This effect further increases the efficiency of the system. The magnetic coil also serves a secondary purpose. The arc discharge is heavily influenced by nearby magnetic fields. The topology of the magnetic field created by the coil on the thruster causes the arc spots to "move" in a $-j \times B$ (anti-Amperian) direction, i.e. around the circumference of the cathode. The effect is beneficial to the lifetime of the thruster as it contributes to the uniform erosion of the cathode.

Vacuum arcs are known to produce small, measureable forces; these were first observed in the late 1920s[11]. Due to the nature of the discharge, any metal can be used as a propellant, although titanium and nickel are the two cathode metals of choice at the Micro-propulsion and Nanotechnology Laboratory at GWU. Titanium is a light-weight metal with an atomic mass of 47.9 u, whereas nickel has an atomic mass of 58.7 u. The choice of cathode material depends largely on the requirements set to the propulsion system. Titanium ions can be accelerated to higher speeds and therefore have a higher specific impulse than nickel ions. The use of nickel offers a higher thrust production than titanium, but at a lower specific impulse. The thrusters that will be provided to USNA for the AMODS project will be thrusters with nickel cathodes and will be an improved version of the ones launched on BRICSat-P. Rather than having an aluminum casing, the new thrusters will have a PTFE housing in order to increase the quality of the electrical insulation around the electrodes. This will also prevent any interactions between the ejected plasma and the casing. A rendered image of the improved thruster can be seen in Figure 3.

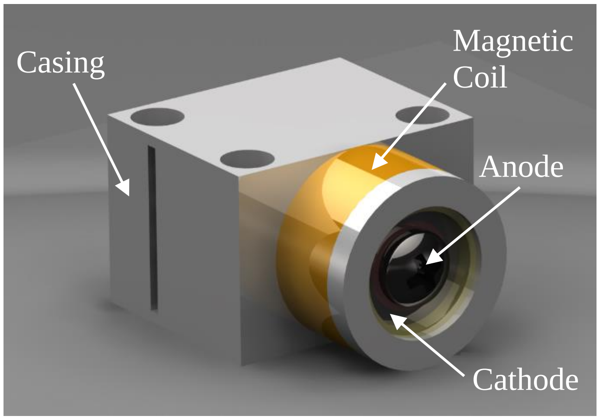

Figure 3: Rendered image of the improved µCAT system.

A list of important parameters of the µCAT system can be found in Table 1. This list includes information such as size and power consumption.

RECENT DEVELOPMENTS

In the previous months, research has been performed in order to increase the efficiency of the µCAT system. In the vacuum arc community it is known that approximately 90 % of the arc discharge current is carried by the electrons and the remaining 10 % of the current is conducted by the ions[9].

Table 1: Thruster Parameters for the AMODS mission

Thruster Parameters	
Casing Material	PTFE
Propellant	Nickel
Size	Length: 27.6 mm Width: 20.1 mm Height: 14.0 mm
Required structural opening on side panel for plume	Diameter: 14 mm
Total system mass	< 200 g
Power consumption	Approx. 1 W at 10 Hz firing rate
Firing rate	1-50 Hz
Trigger	5 V square wave signal
Charging Voltage	Approx. 15-25 V

Thrust is produced mainly by the high-velocity ions that leave the cathode, which means that the energy carried by the electrons does not contribute towards the production or increase in thrust. Therefore, the aim of the current research is to use part of the energy carried by the electrons to produce additional thrust without increasing the total energy consumption of the thruster.

As of today, the thruster only uses the cathode material to produce thrust. The anode, on the other hand, remained unused and served only the function of an electrode to close the circuit. Work performed by J. Lukas[12] focused on changing the material of the thruster's anode from titanium (and stainless steel) to a metal with a lower melting temperature. As it was mentioned before, the electrons flow to the anode to complete the circuit. Joule heating causes the anode to heat up and increase in temperature. This does not have an effect when using stainless steel anodes. When using metals with low temperatures, on the other hand, the electrons heat up the anode material and melt it locally, producing metal vapor of the anode metal. Measurements performed with an ion collector showed an increase in the total ion current for certain firing frequencies. At a firing rate of 1 Hz and 2 Hz, the measured total ion current was 45 % and 38 % higher compared to the non-ablatable anode, respectively. Further research is planned in order to find out if the increase in the ion current leads to a measureable and proportional increase in thrust. For this reason, a micro-newton thrust balance is being developed at the Micro-propulsion and Nanotechnology Laboratory at GWU. Performing experiments with a thrust balance together with and ion collector will give clue as to whether the hypothesis is correct.

THE MISSION

A mission titled Autonomous Mobile On-orbit Diagnostic System (AMODS)[13] is being pursued in order to assure the ability to provide the physical on-orbit interaction needed to generate diagnostic data and thereby stimulate immediate failure analysis and mitigation activities.

The AMODS concept embraces a multiple CubeSat system: 1) several "repair" CubeSats (RSats) with manipulable arms designed to latch onto a host satellite and maneuver around, imaging, and potentially repairing various components; and 2) one self-propelled transport CubeSat (BRICSat), a "space tug" with the ability to manage ΔV and rendezvous operations. The BRICSat, employs μCAT thrusters provided by GWU for three axis stabilization and proximity maneuvers, and a cold gas thruster for orbital maneuvers

RSat Platform

The mission of RSat is to provide a mobile platform to survey and possibly repair a much larger, conventional spacecraft.

RSat is a 3 U (10 x 10 x 33 cm) CubeSat-class satellite with two 60 cm, seven degree of freedom robotic arms fitted with a simple end-effector. RSat is designed to perform its mission while in constant physical contact with its host spacecraft. The robotic arms provide access to any external surface of the host. The claws will grapple to the host satellite and also function as tools. RSat will be equipped with a suite of sensors that also includes a camera to diagnose any on-orbit failures and, in some cases, other instruments as may be required to perform minor on-orbit repairs or maintenance. RSat provides ground controllers with the continued opportunity to physically interact with their spacecraft.

RSat has been manifested on NASA's launch initiative program, and will go through space validation in the 2017-2018 time frame.

Previous Mission: BRICSat-P (Prototype)

The Micro-propulsion and Nanotechnology Laboratory at GWU has constructed a miniaturized propulsion system for small-scale spacecraft it terms the Micro-Cathode Arc Thruster (μCAT)[14]. It is capable of creating small, reproducible impulse bits producing a thrust in the range of 1 to 10 μN depending on the duty cycle. While this small force is inadequate for orbital phasing maneuvers, it is extremely precise and controllable, making it the ideal solution for close proximity operations.

The μCAT propulsion system was initially space-qualified on the BRICSat-P spacecraft, (Ballistically Reinforced Communication Satellite)[15]. This satellite, a 1.5 U CubeSat, and was launched on May 20, 2015 atop an Atlas V rocket. The back side of the satellite is shown in Figure 4.

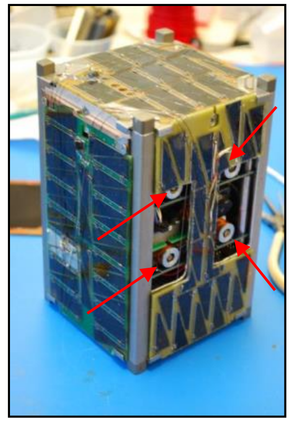

Figure 4: BRICSat-P 1.5 U CubeSat with four GWU micro cathode arc thrusters (see arrows).

BRICSat-P's primary mission was to test the use of the μCAT thrusters on orbit. The thrusters were used for rudimentary attitude control. Initial reports show that the thrusters were capable of detumbling the satellite from an estimated 15 °/s to less than 1.5 °/s within the first 48 hours. This occurred without the use of any other passive or active attitude control systems. The satellite's rotation rate reached a level of less than 1 °/s on all axes after another 48 hours, which was the target detumble rate. Through these demonstrations, BRICSat-P validated the ability of the μCAT thrusters to provide a propulsive force in space by creating measurable difference in the spacecraft's rotation. The μCAT thrusters were adopted by AMODS as the primary solution for close proximity maneuvers, including linking to and disengaging from successive RSat units. While the force provided by each of the μCAT thrusters is small, continuous operation will provide sufficient ΔV for close proximity approaches and docking maneuvers. Moreover, though proximity movement will be relatively time-consuming, the small force delivered by the μCAT thrusters provides BRICSat with the capability to control movements to within 0.1 cm.

BRICSat Platform

The mission of the BRICSat platform is to provide the services needed to rendezvous with and deploy RSat onto a distributed network of spacecraft.

BRICSat is also a 3 U CubeSat. Equipped with its own propulsion system, it is a complement to RSat, and provides the only propulsive force to the RSat platform. BRICSat will be equipped with 14 μCATs for attitude and orbit control. These thrusters will be used in order to provide 3 axis stabilization to the satellite. The μCATs will also be used as described previously to perform fine adjustments in the positioning of the satellite to rendezvous and dock with RSat. BRICSat must function as a completely independent spacecraft and be able to maneuver to within 1 km of a client spacecraft, with an RSat attached. Subsequently, BRICSat must then traverse that last kilometer and position RSat to latch onto the client satellite without damaging any of the spacecraft involved. This requires a combination of long term, sustained ΔV for travel between spacecraft, and quick pulses to allow for proximity operations. Given that the standard launch mating adapter is 3 cm across and the standard RSat claw will have an open-span of 5 cm, the BRICSat propulsion system must able to come within a ±2 cm tolerance on final docking operations.

AMODS-UNP

AMODS-UNP combines the BRICSat and RSat concepts for the first time. It will validate the AMODS notional mission by validating combined, interactive and rendezvous capabilities in a series of three phases.

Phase One: RSat and BRICSat will initially launch together as a conjoined 6 U entity.

1. BRICSat will control ΔV capability and perform in-track, retro burns to rotate and translate in three axes showing that the conjoined orbit can be controlled and modified.
2. RSat will confirm its full range motions necessary to spider around and diagnose spacecraft.

Phase Two: BRICSat and RSat will separate to a distance of 10-15 feet and execute a rendezvous operation.

1. BRICSat will perform precise orbital phasing maneuvers simulating the notional mission of AMODS and encompassing a total of 50 m/s of Delta V.
2. USNA's three-stage Electromagnetic-Ferromagnetic Interface Docking System (EFINDS) will release and capture RSat, delinking and linking the two units electrically.

Phase Three: BRICSat and RSat will separate again to a distance of one kilometer and execute a second rendezvous operation to demonstrate USNA's Small Satellite Navigation System (SSNS):

1. BRICSat will identify and track RSat against a star field and use machine visions to produce a position vector to RSat in order to rendezvous.
2. The guidance system on-board BRICSat will take inputs from the Navigation system and ADCS and turn them into outputs for the Propulsion system to create precise and accurate translational and rotational movement.

The µCAT will be a key technology for BRICSat and will therefore be of great added value to the AMODS mission. It will give BRICSat the ability to perform complex rendezvous and docking maneuvers. This is key to proof the concept of the mission and if successful, will allow small spacecraft to be used to inspect and possibly troubleshoot other spacecraft in orbit

CONCLUSION

With a total volume of less than 8 cm^3 per thruster head and a low power consumption of approximately 1 W at a firing rate of 10 Hz, the µCAT system is a compact and low power system that caters specifically to the small satellite community. Its small size allows it to be positioned in very compact spaces within the satellite and it fits between circuit boards, since the standard distance between PCBs in CubeSats is approximately 15 mm. The thruster can be used for precise pointing maneuvers as well as for general attitude and orbit control maneuvers such as detumbling of the spacecraft. The µCAT can be fired at higher rates (e.g. 50 Hz) allowing the system to function as main propulsion system. The highly ionized plasma produced by the discharge results in almost no back-flux to the satellite, a characteristic that is particularly important for missions with sensitive equipment such as optical systems.

The relatively low power consumption and size of this propulsion system has the potential to greatly increase the capabilities of the future CubeSat missions. Adaptation of such technology can make CubeSats maneuverable in orbit, greatly increasing the mission envelope of these satellites, spanning from LEO operations to interplanetary missions. The first iteration of the design has been tested in space onboard BRICSat-P mission, and the follow-on BRICSat missions will demonstrate and characterize the enhanced capability of this propulsion system.

Acknowledgments

The United States Naval Academy and The George Washington University teams would like to thank DARPA, PEO-IWS, AFOSR/AFRL (UNP) for their support.

References

1. Lee, S., Toorian, A., Clemens, N., Puig-Suari, J., and Twiggs, B. "Cal Poly Coordination of Multiple CubeSats on the DNEPR Launch Vehicle," 2004.
2. Puig-Suari, J., Turner, C., and Twiggs, R. "CubeSat: the development and launch support infrastructure for eighteen different satellite customers on one launch," 2001.

3. Schaire, S. H., Shaw, H., Altunc, S., Bussey, G., Celeste, P., Kegege, O., Wong, Y., Zhang, Y., Patel, C., and Raphael, D. "NASA Near Earth Network (NEN) and Space Network (SN) CubeSat Communications," 2016.

4. Buchen, E. "SpaceWorks' 2014 Nano/Microsatellite Market Assessment," 2014.

5. Conversano, R. W., and Wirz, R. E. "CubeSat lunar mission using a miniature ion thruster," *47th AIAA Joint Propulsion Conference,(San Diego, CA), AIAA Paper*. Vol. 6083, 2011.

6. Staehle, R. L., Blaney, D., Hemmati, H., Lo, M., Mouroulis, P., Pingree, P., Wilson, T., Puig-Suari, J., Williams, A., and Betts, B. "Interplanetary CubeSats: opening the solar system to a broad community at lower cost," *CubeSat Developers' Workshop, Logan, UT*. 2011.

7. Bandyopadhyay, S., Subramanian, G. P., Foust, R., Morgan, D., Chung, S.-J., and Hadaegh, F. "A Review of Impending Small Satellite Formation Flying Missions," *Proceedings of the 53rd AIAA Aerospace Sciences Meeting, Kissimmee FL*. 2015.

8. Jüttner, B. "Erosion Craters and Arc Cathode Spots in Vacuum," *Beiträge aus der Plasmaphysik* Vol. 19, No. 1, 1979, pp. 25-48.

9. Keidar, M., and Beilis, I. *Plasma Engineering: Applications from Aerospace to Bio and Nanotechnology*: Elsevier Science, 2013.

10. Keidar, M., Schein, J., Wilson, K., Gerhan, A., Au, M., Tang, B., Idzkowski, L., Krishnan, M., and Beilis, I. I. "Magnetically enhanced vacuum arc thruster," *Plasma Sources Science and Technology* Vol. 14, No. 4, 2005, p. 661.

11. Tanberg, R. "On the Cathode of an Arc Drawn in Vacuum," *Physical Review* Vol. 35, No. 9, 1929, pp. 1080-1089.

12. Lukas, J., Teel, G., Kolbeck, J., and Keidar, M. "High thrust-to-power ratio micro-cathode arc thruster," *AIP Advances* Vol. 6, No. 2, 2016, p. 025311.

13. Hanlon, E. A., Keegan, B. H., Bailin, B., and Kang, J. S. "AMODS: Autonomous Mobile On-orbit Diagnostic System," 2015.

14. Hurley, S., Teel, G., Lukas, J., Haque, S., Keidar, M., Dinelli, C., and Kang, J. S. "Thruster Subsystem for the United States Naval Academy's (USNA) Ballistically Reinforced Communication Satellite (BRICSat-P)," *34th International Electric Propulsion Conference and 6th Nano-satellite Symposium*, . Kobe-Hyogo, Japan, 2015.

15. Samudra, E. H., Christopher, K. D., Michael, K., and Tae, L. "Quad channel Micro-Cathode Arc Thruster Electric Propulsion subsystem for the Ballistic Reinforced Satellite (BRICSat-P)," *50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*. American Institute of Aeronautics and Astronautics, 2014.