Two-Stage Micro-Propulsion System Based on Micro-Cathode Arc Thruster

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The Micro-Cathode Arc Thruster (µCAT) developed at The George Washington University is one of the two electric micro-propulsion devices that have been flown on CubeSats to date. We report the development of a two-stage propulsion system based on this technology, which will enable interplanetary CubeSat missions and extended missions in low earth orbit. The device uses a modified version of the µCAT system for plasma generation, and an accelerating second stage to accelerate the plasma.

I. Introduction

Small satellites are a growing market, especially after the introduction of the CubeSat standard in 1999. These standardized satellites enable small organizations, industry, and educational institutions to launch small, affordable satellites into space. For many countries, such as Slovakia[1], Hungary[2], Switzerland[3], Costa Rica[4], and others, CubeSats represent their first means of access to space. Per SpaceWorks' 2017 forecast (Figure 1), more than 400 satellites in the 1-50 kg class were launched between 2014 and 2016. The market is expected to grow to at least 200 new small satellites per year after 2017. In the last few years, missions have increased in complexity and the mission scopes have broadened. The first CubeSat missions were merely technology demonstrating missions, but

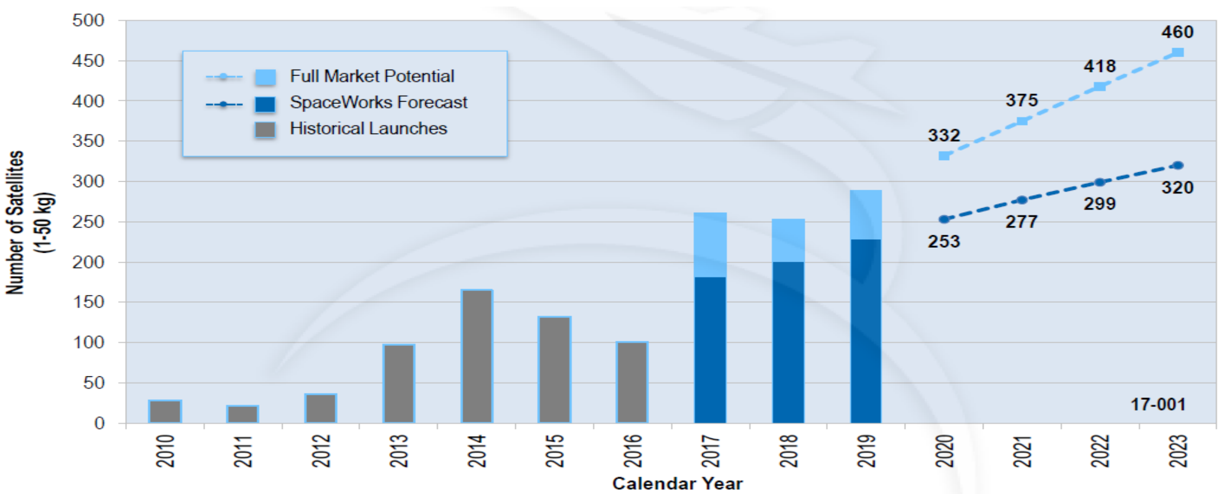

Figure 1: Nano/Microsatellite Launch History and Forecast 2017. Source: SpaceWorks

nowadays, more complex and more ambitious missions are being proposed, such as the NASA Marshall Space Flight Center MoonBEAM[5] mission, set to be launched on NASA's Exploration Mission 1 (EM-1) to orbit the moon and

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measure gamma ray bursts. The first interplanetary CubeSat mission is scheduled to fly in 2018, when JPL will launch two 6 U CubeSats named Mars Cube One (MarCO) together with the InSight Mars Lander. Missions like MoonBEAM and MarCO can only be performed with the help of propulsion systems for both main propulsive maneuvers as well as attitude control maneuvers.

II. Motivation

Generally, electric propulsion systems are operated in what is called "single-stage" operation, which means that a thruster will have specific capabilities regarding thrust, specific impulse, and efficiency. Some propulsion systems can be throttled and they do indeed change the different parameters mentioned above, but these are not part of the scope of this research. Usually, the propulsion system will be operated at an optimum point, although occasions for variation exist. For specific applications such as orbit raising maneuvers where high thrust is required, a specific thruster will be needed. For maneuvers such as station-keeping, one would prefer a thruster with high specific impulse (I_{sp}). Therefore, two separate single-stage thrusters will be required if both maneuvers are to be performed efficiently. This issue can be addressed by so-called "two-stage" propulsion systems. Research has been performed using a variety of devices to operate thrusters in such a configuration. In a two-stage mode, the ionization stage is separate from the acceleration stage. In single stage operation (i.e. 2nd stage turned off), the thruster provides a high thrust-to-power ratio (TPR) and is ideal for orbital change maneuvers, whereas the two-stage operation will provide a higher specific impulse and is ideal for station-keeping and interplanetary missions, where efficient use of the propellant is more important than thrust. The use of two-stage thrusters would benefit a broad amount of missions, such as all-electric satellites for geostationary applications (high-thrust LEO[3] to GEO[4] transfer, high I_{sp} station-keeping and drift corrections once in orbit). Interplanetary probes and sample return missions to asteroids would also benefit from this development. Such devices are being studied as part of NASA's Electric Propulsion Program[6]. Some examples of two-stage propulsion systems are the P5-2 (5 kW) thruster which was designed and tested at the University of Michigan[7], the Helicon Hall Effect Thruster (600 W – 1200 W)[8], the Linear Gridless Ion Thruster (2 kW)[9], the VASIMR engine (200 kW)[10, 11], the D-80 Thruster with Anode Layer (TAL, 3 kW)[12], and the Very High Specific Impulse Thruster with Anode Layer (VHITAL, 25-36 kW)[13], amongst many others. As an example, the VHITAL thruster yields a TPR of 26 mN/kW and an I_{sp} of 6000 s in single-stage mode, whereas in the two-stage mode, the TPR drops to 19.7 mN/kW but the I_{sp} increases to 8000 s. Single-stage operation in Hall-effect thrusters (HET) and TAL systems is limited to voltages of around 1 kV and after this point, they experience a significant drop in efficiency due to severe anode heating[13]. This can be overcome by separating the ionization and the acceleration regions, i.e. with a two-stage system[13]. These systems, however, have their drawbacks.

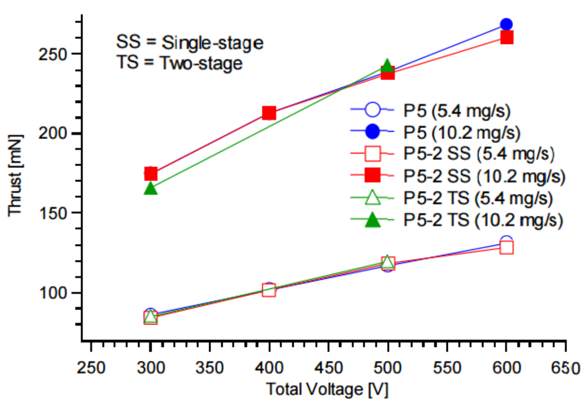

Figure 2. Thruster performance for the P5, P5-2 (single-stage), and P5-2 (two-stage) thruster from the University of Michigan. Figure taken from Hofer et al. Edited to fit this page format.

Two-stage systems tend to be more inefficient than their counterparts at lower voltages. This can be seen in Figure 2. The P5 thruster was developed by Air Force Research Labs (AFRL) and is a 5 kW HET thruster. The P5-2 is the two-stage development by the University of Michigan, also for 5 kW operation. At voltages below 450 V, the P5-2 (single-stage, SS) is equivalent to the P5, since they are practically the same thruster. With these parameters, the P5-2 (two-stage, TS) is slightly more inefficient than the P5 and P5-2 SS. At voltages above this threshold, the P5-2 SS loses performance compared to the P5 due to small changes that were made in the discharge channel but the P5-2 TS has a better performance than both single-stage thrusters. No data is available for values above 500 V due to damage to the thruster[7]. One of the most concerning issues is the higher erosion of the main thruster components such as the electrodes and dielectric components. In two-stage operation, the thruster is subject to higher powers, which are derived from the higher voltages that are applied. Consequently, the kinetic energy of the particles is significantly higher and cause a larger amount of surface sputtering on both metallic and non-metallic surfaces. Prolonged occurrence may lead to failure in the ceramic components, and the plasma could reach other electrical components,

[3] Low Earth Orbit
[4] Geostationary Orbit

resulting in short circuits. Additionally, the higher electric power causes the thruster's temperature to increase, leading to damage or deformation of specific components. Furthermore, incorporating another stage to the system increases the complexity of the system, as more complicated circuitry is required for optimum operation. Another main issue that can be seen by the power at which the thrusters operate (number in parentheses after each thruster) is that none of these thrusters cater to small satellites.

All thrusters mentioned above operate at powers of at least 0.5 kW, a power level that is unfeasible for most small satellites. The literature review currently shows no available two-stage devices for CubeSat applications in the market. To summarize, the foremost technical challenges to date for two-stage systems are the higher component erosion, higher thermal loads, system complexity, and the current unavailability for smaller-sized spacecraft. The proposed solutions for these problems will be described in detail in the remainder of the document. The result will be a propulsion system on which different parameters can be studied to potentially mitigate some of these issues. Additionally, the system will be designed to cater to small satellites.

III. The First Stage

The first stage of the device proposed herein is a modified Micro-Cathode Arc Thruster (μCAT). This produces the plasma that will then be accelerated using an electric field. The μCAT is an electric propulsion system that is based on the well-researched ablative vacuum arc or 'cathodic arc' process[14, 15]. This physical phenomenon is known to erode the negative electrode (cathode) with every discharge. In this case, this is highly desirable as the cathode is the thruster's propellant. During each discharge, a small amount of metallic propellant is eroded, ionized, and accelerated. The efficiency is enhanced by a magnetic field[16]. The magnetic field is caused by the arc current as it travels through a magnetic coil prior to arcing between the electrodes. The device and the main components can be seen in Figure 3. A spring is used as a feed system to ensure that there is always propellant available for the next discharge. The system can be pulsed and therefore, throttled by simply changing the discharge frequency. At a discharge frequency of 10 Hz, the power consumption is approximately 1 W for the current version of the μCAT. The thruster can be pulsed at frequencies between 1 and 50 Hz, depending on the requirements and mission needs. The frequency is limited by the thermal properties of the components used for the casing and most importantly, the feed system's spring, which runs the risk of getting annealed at high temperatures.

The physical nature of the arc discharge allows any conductive (solid) material to be used as a propellant. The eroded material is, to a large degree, fully ionized. Additionally, it is common that the particles are multiply ionized. In the case of tungsten, the mean ion charge state $\bar{Q}$ is 4.6+ and approximately 94% of the ions have a charge state equal or higher than 3+[17].

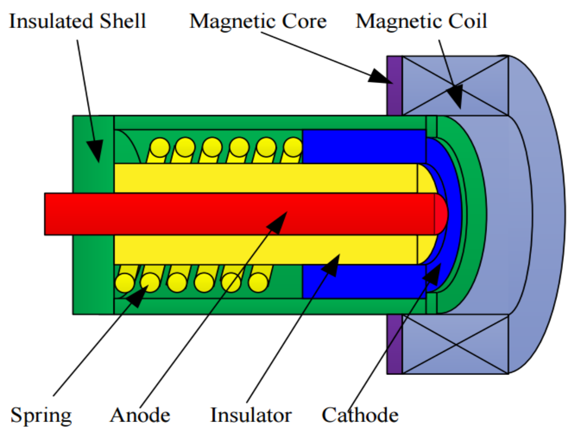

Figure 3. Schematic of a μCAT used for RCS. The size of the device shown is approximately. 2.5 cm in length.

The fact that the discharge can ablate any conductive material allows the thruster to operate with different metals, each with different physical properties, giving the mission designer flexibility when it comes to the mission's design, e.g. nickel will produce a higher thrust compared to titanium, but the latter would offer a higher specific impulse under unchanged discharge conditions. The system does not require any pressurized tanks or other components that may be required when dealing with propellants such as xenon. This is advantageous because it greatly reduces the system's complexity and risk involved. Additionally, only an electrical connection is required to operate the thruster, since the propellant and all necessary components are integrated within the thruster's structure. Therefore, the μCAT technology offers opportunities that are unmatched by most gas-fed propulsion systems, such as the ability and flexibility of attaching the thrusters to deployable booms to increase the torque for RCS maneuvers. To operate the thrusters, a voltage between 15 to 25 volts is required to energize the system. The booster circuits convert the energy, producing an instantaneous peak arc discharge of approximately 50 A. This instantaneous current ablates a small fraction of the cathode and ionizes it, producing a quasi-neutral plasma that does not require a neutralizer. The plasma plume is almost fully ionized hence eliminating potential self-contamination due to the charge exchange process in the case of a weakly ionized plasma. Nickel and Titanium cathodes (propellant) have been characterized for the use in this technology and have resulted in specific impulses of 2200 s and 2800 s. The energy consumption is approximately 0.1W/Hz for 2 micro-N-s impulse bits.

IV. Acceleration Stage

The objective of this project is to produce two small-satellite propulsion systems based on vacuum arcs, in this case, a spinoff of the µCAT as a plasma source. The system will use a scaled-up version of the µCAT as a first stage to generate a (metallic) plasma, which in turn will be accelerated by a pulsed acceleration (second) stage. Since the plasma is produced using a pulsed system, it does not make sense to have the acceleration stage operating at all times. The system will be called the Micro-Cathode Arc Thruster Main Propulsion System, or µCAT-MPS for short. The proposed design is a two-stage system, which will consist of an ionization stage an acceleration stag. The development of the µCAT-MPS will occur in two phases. The system for Phase 1 can be seen in

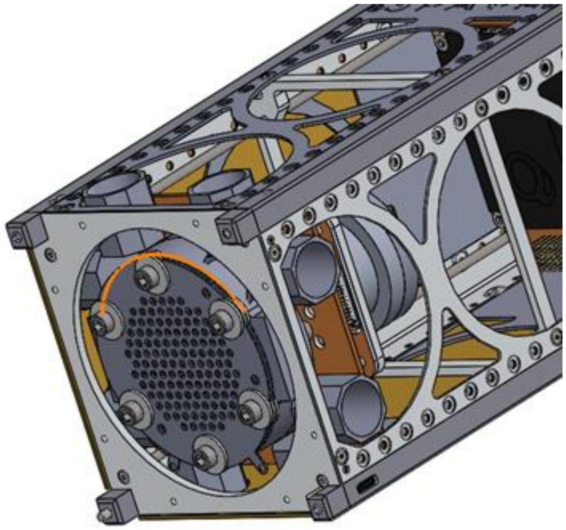

Figure 4: CAD section cut of the gridded version of the µCAT-MPS.

Figure 4. This system is a µCAT hybrid thruster with a gridded acceleration stage. The system will operate as a miniaturized gridded ion thruster. The second phase of the project will be another µCAT hybrid, but instead of a

gridded ion thruster, the acceleration stage will be a variant of a Hall-effect thruster, the TAL. The TAL version of the µCAT-MPS will be capable of working in two-stage mode, as opposed to the gridded version, which will not be able to operate in single-stage mode because the grids would block off most of the plasma. Figure 4 shows the bottom part of a 3 U CubeSat without its bottom plate and the gridded version of the µCAT-MPS. Both devices have been envisioned to fit in a 1 U to 1.5 U form factor for its use in CubeSats. Moreover, the CAD model shown in

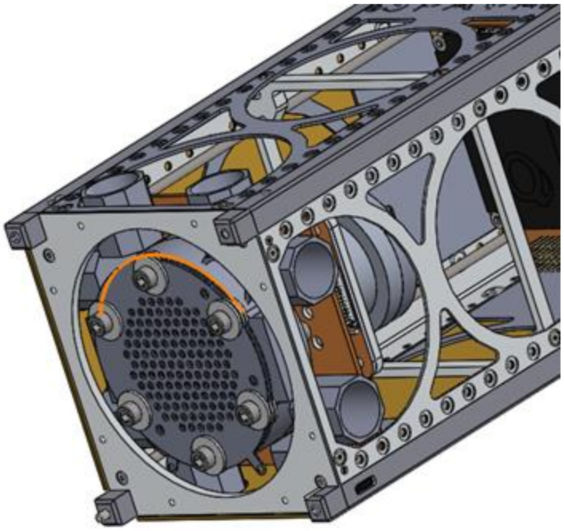

Figure 4 includes eight µCAT thrusters for attitude control. This configuration enables a CubeSat to perform full three-axis stabilization and it would have the ability to perform orbital maneuvers and drag-compensation maneuvers. The outer diameter of the grids shown in Figure 4 is approximately 80 mm, but it can be modified so that it fits within the standard "tuna-can" compartment of a 3 U CubeSat. The first prototype of the gridded µCAT-MPS has also been built and is currently in the process of being characterized thoroughly in its single-stage configuration, specifically as a modified µCAT. Second stage operation will begin shortly.

V. Test Campaign and Next Steps

In the following weeks, the gridded thruster will go through a thorough test campaign. The first round of tests will investigate the discharge characteristics of the first stage, which includes different plasma properties inside the discharge chamber, as well as the properties of the acceleration stage, which include a characterization of the electric field to measure the field strength, stability, and the ability to transport ions out of the acceleration chamber. Since this electric field is pulsed, it needs to last enough to accelerate all the ions emitted from the cathode during the discharge. The tests will include different ion beam characterization measurements, such as the ion current prior and after acceleration, and retarding potential analyzer (RPA) measurements. Furthermore, Langmuir probe, time-of-flight and ion current measurements will be performed. In addition to these plasma and ion beam measurements, the gridded µCAT-MPS will be placed on a newly developed thrust stand designed for micro-Newton thrust measurements. The measurements will allow for a precise calculation of the specific impulse of the system. The data obtained throughout this test campaign will be used to improve the device and will also be used to design the TAL version of the µCAT-MPS. This version

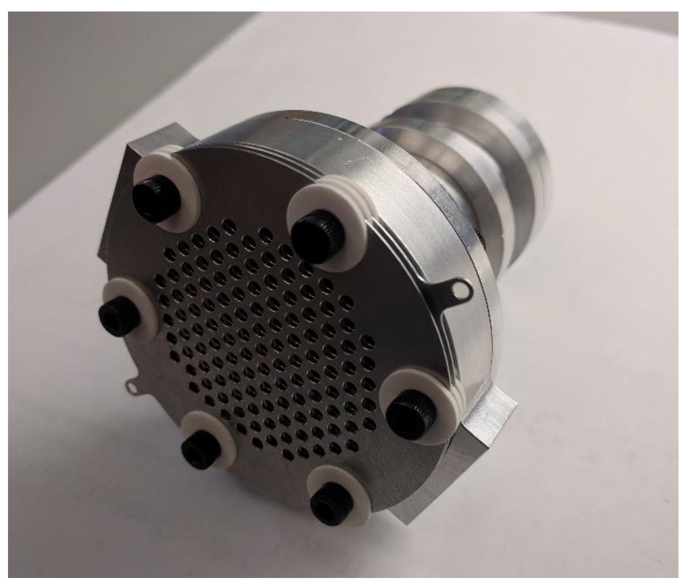

Figure 5. Image of the laboratory model of the gridded µCAT-MPS system made from aluminum.

will require additional testing, such as in-channel measurements of the plasma characteristics. Single and two-stage operation will be tested with this device on the thrust stand.

VI. Expected Performance Data

Both µCAT-MPS thrusters are expected to be a significant improvement over the original µCAT system in terms of efficiency due to the highly-efficient additional acceleration second stage. Table 1 shows the expected performance data for the different µCAT systems. The systems are expected to have a total efficiency of over 50% after improvements are done to the initial designs. Verification of these values will occur using the equipment and methodology described in the previous section. The technology is expected to have a large impact in the field of electric propulsion for CubeSats, since as of today, only ten CubeSats out of over 400 have had a propulsion system on board, and from those ten, only two have been electric propulsion systems[18], one of them was the Naval Academy's BRICSat-P CubeSat which carried four µCATs on board[19]. The µCAT-MPS is designed to enable complex missions such as interplanetary CubeSat missions and to extend missions in low earth orbit. The current µCAT system will continue to be improved as a reaction control system thrusted for attitude control operations.

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

	µCAT	µCAT-MPS (gridded) (Estimated Data)		µCAT-MPS (TAL) (Estimated Data)	
Figure of Merit	Current Status	Current Status	Target / Goal (mid 2018)	Current Status	Target / Goal (mid 2018)
TRL	TRL-6	TRL-3	TRL-4/5	TRL-2	TRL-4/5
I_{SP}	~ 2000 s	3000 s – 4000 s		2000 s – 3500 s	
Power	< 10 W	Up to 60 W		Up to 60 W	
Efficiency	~10-15 %	> 50 %		> 50 %	
Thrust to Power ratio	10 µN/W @ 10 Hz	> 100 µN/W @ 10 Hz		> 100 µN/W @ 10 Hz	
Size / Volume	2-4 thruster heads + PPU per PC104 PCB	Approximately 1-1.5 U including PPUs and thruster		Approximately 1-1.5 U including PPUs and thruster	
Voltage		1 – 2 kV		~1 kV	
Relative cost to comparable technologies	Very low	low		low	

VII. Conclusion

The development of the Micro-Cathode Arc Thruster at The George Washington University has shifted towards higher-power applications within the small satellite community. The current development focuses on increasing the overall system efficiency of the µCAT system by adding a secondary acceleration stage to the system. This will occur in two phases, where a gridded version of the µCAT will developed and tested. This device will go through extensive testing and will be improved with the gained knowledge. After this process is completed, a second thruster based on a thruster with anode layer, a variant of the well-known Hall Effect Thruster, will be developed. The systems have been designed to be used for CubeSat applications, ideally for spacecraft larger than 3 U given the expected power consumption of these systems and their form factors. These thrusters will enable mission designers to push the boundaries of what is currently possible with conventional CubeSat propulsion systems.

Acknowledgments

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