MICROCATHODE-COLD GAS HYBRID PROPULSION SYSTEM – BRICSAT

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ABSTRACT

As investment in space assets increases, activities to protect those investments are also being pursued. The United States Naval Academy's Autonomous Mobile On-Orbit Diagnostic System (AMODS) offers a low-cost solution which utilizes a fleet of 3U CubeSat-class satellites to provide on-orbit diagnostic and repair services to conventional satellites. The envisioned AMODS utilizes a BRICSat to act as a "space-tug" moving individual repair CubeSats, or RSats, to client satellites. As the only propulsive force in the AMODS repair fleet, BRICSat's propulsion system must be powerful enough to allow the spacecraft to perform orbital maneuvers yet precise and accurate enough to execute docking maneuvers. This combination of conflicting requirements results in a challenging design space for the BRICSat satellite. In order to provide the required capabilities, BRICSat will utilize a hybrid propulsion system which combines the lower-impulse Micro-Cathode Arc (µCat) thruster developed by George Washington University for proximity maneuvers, with a high-impulse cold gas thruster for orbital maneuvers. This paper provides an in-depth analysis of the hybrid propulsion system. It will characterize the capabilities of the system and demonstrate how the propulsive combination provides the optimal solution for the AMODS program. It will conclude with a discussion of the numerous possibilities the hybrid propulsion concept offers for CubeSat maneuvering.

INTRODUCTION

CubeSats are fast becoming ubiquitous space tools. Comparatively inexpensive, they offer reduced cost-of-entry for space activities ranging from providing simple imaging to implementing complex communications systems. It is perhaps an understatement to merely state that "the CubeSat represents a paradigm shift for the traditional space industry."[1] Nevertheless, as useful as they may be, most CubeSats cannot "orient or propel themselves, meaning mission functionality is limited."[2] There are a number of teams developing propulsion systems for the CubeSat platform including cold gas systems, hydrazine monopropellant systems, ambipolar plasma thrusters and liquefied gas thrusters.[3] As effective as these propulsion systems are, they are not flexible enough and/or appropriately scaled to provide the spectrum needed to affect both large-scale orbital phasing maneuvers and provide the precision and accuracy needed for proximity operations like docking. Most conventional spacecraft employ multiple sets and types of thrusters for maneuvering. The Shuttle's Orbital Maneuvering System, for example, utilized 26 thrusters[4] and Soyuz TMA-M uses 24.[5] Both offer models that cannot be effectively miniaturized for the small satellite platform. NASA proposes to solve this problem with its CubeSat Proximity Operations Demonstration (CPOD). CPOD comprises two 3U CubeSats each with a multithruster cold gas propulsion system. Expected to launch in September 2016, CPOD was designed specifically to support "CubeSat proximity operation missions utilizing 8 thrusters located at the corners of the unit."[6] The baseline design maintains efficiency for large maneuvers, but can only "support a total impulse to provide approximately 30 m/s for the 6 kg vehicle."

As an alternative with differing flexibilities and capabilities, the United States Naval Academy (USNA) has commenced development on a hybrid system which combines a cold gas thruster propulsion and an array Micro-Cathode Arc (µCat) thrusters developed by the George Washington University. A 1U-form factor cold gas thruster will allow the CubeSat to accomplish orbital phasing maneuvers. The µCat thrusters will be strategically positioned around the CubeSat to provide six degrees of freedom and deliver an impulse just large enough to move the CubeSat into docking range in a timely manner, yet small enough to achieve micrometer-resolution maneuvers. The success of this hybrid propulsion system will advance the notional concept of using the small satellite platform to service and inspect on-orbit spacecraft and generally increase the utility of CubeSats.

OPERATIONAL CONCEPT

The BRICSat propulsion system is being developed to contribute to and advance the notional mission of the Autonomous Mobile On-orbit Diagnostic System (AMODS). Below describes the operational concept of the overall mission and the key components of AMODS.

AMODS

The goal of AMODS is to assure the ability to provide the physical on-orbit interaction with a host spacecraft in generating diagnostic data, including images of the host spacecraft, in a cost-effective manner. AMODS employs a modular, CubeSat style design approach to overcome traditional cost and technological hurdles. 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, image, and potentially repair various components; and 2) the BRICSat, a "space tug" with the ability to manage ΔV, rendezvous and operations. The projected cost of an AMODS deployment is less than $150,000 per BRICSat and $25,000 per RSat.

RSat Platform

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

RSat is a 3U (10 x 10 x 33 cm) cube satellite with two 60 cm, seven degree of freedom robotic arms fitted with claws. It is intended to operate in constant contact with a 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 equipment, including 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 as if it was on the ground.

BRICSat

The mission of BRICSat is to provide the services needed to rendezvous with and successively deploy a fleet of RSats onto a distributed network of on-orbit spacecraft.

BRICSat is also a 3U CubeSat. It will provide the only propulsive force to the RSat platform. It must be able to find, travel and link to an RSat and then maneuver, while linked to the RSat, to within 1 km of a client spacecraft. Subsequently, BRICSat must then transverse that kilometer and position RSat to latch onto the client satellite without damaging any of the spacecraft involved. Among other things, this means that the propulsion system cannot be permitted to produce contaminates which would harm the client spacecraft.

Concept of Operations

AMODS is intended to be deployed in respect of a large constellation of satellites in similar orbits. BRICSat will launch with up to eight RSat units. Once on-orbit, the RSats will distribute themselves and wait, free-floating in space in a depot-like formation.

While it could theoretically carry several RSat units at once, BRICSat is designed to shunt one RSat at a time to its respective host. BRICSat will locate the RSat depot, rendezvous and dock with the first RSat. BRICSat and RSat-1 will connect autonomously using a cup and cone magnetic docking system which will include power and data pass-throughs to electrically link both spacecraft. In this way, the linked spacecraft will make up for power lost due to necessary blockage of solar panels by consolidating and sharing remaining power sources. Linkage will occur in such a way as to assure BRICSat's thrusters, and thus its mobility, are not obstructed. Each RSat's manipulators will be used to move the center of mass fully to BRICSat.

BRICSat will then use it propulsion system to move the RSat to which it is linked to the assigned client spacecraft. In order to rendezvous with the first client BRICSat will enter a phasing orbit with the RSat. The linked CubeSats will complete several revolutions before leaving the phasing orbit in order to reach the designated host.

When the combined CubeSats are within 40 m of the target host, BRICSat will downlink an image so that ground controllers can determine the best approach for grappling. BRICSat will instruct RSat to deploy one arm for grappling/docking. RSat's second arm will be deployed to counteract the movement of the first arm to assure that the BRICSat-RSat unit's orientation is not affected. In the meantime, BRICSat will continue its approach. When the unit is 5 m away, a second image will be sent to ground to reconfirm grappling capability. And then the repair unit, RSat-1, will latch on to the client spacecraft using its claw.

After confirmed capture, RSat-1 and BRICSat will disconnect and the newly independent BRICSat will locate, navigate and ultimately link to RSat-2 and successive RSats for transport to their respective spacecraft hosts.

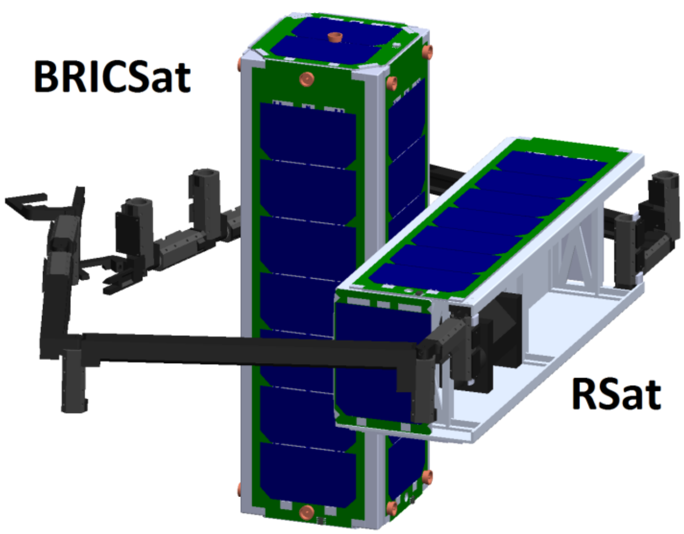

Exhibit 1: BRICSat and RSat composite Unit.

ORBITAL OPERATIONS

The following limiting constraints exist for AMODS constellation operations.

1. AMODS rides along with a spacecraft destined for the same altitude and inclination as the remaining hosts in the constellation [Ex: GPS, Iridium, etc.]. This limits maneuvers to minor inclination changes and phasing operations to minimize ΔV requirements.
2. Location of host spacecraft is known at an accuracy of 1 km. This ensures that the phasing operation will end in close proximity to the host.
3. Host spacecraft has stable attitude control, and is not rotating or tumbling. A stable spacecraft removes the propulsive intensive requirement of matching rotations.

Working within these constraints, the BRICSat-RSat system will be able to distribute itself effectively across a host constellation in the manner described below.

Outside Visual Range (R>1000m)

AMODS staff will use BRICSat's internal GPS and data from the United States Space Catalog to compute necessary phasing maneuvers. These maneuvers will be the most propellant intensive as they require the largest ΔV in order to quickly move around the constellation.

Visual Range (100m<R<1000m)

BRICSat is expected to be able to acquire visual contact with the spacecraft while still in its phasing orbit. Once BRICSat has achieved visual contact with the host spacecraft (approximately 1000 m away) and is able to establish a bearing to the host spacecraft, additional phasing maneuvers will be calculated and executed using relative position vectors determined by onboard imaging systems.

Enhanced Visual Range (R<100m)

Within 100m, BRICSat will have both range and bearing to the host spacecraft. At this point, closed loop control and small velocity changes will be used to complete a "z-bar" based docking. The use of the "z-bar" approach allows for relatively easy stationkeeping, provided small enough control inputs are possible.

Exhibits 2 and 3 show the results of STK analysis on a theoretical constellation in Medium Earth Orbit. The analysis assumes use of Hohmann Transfers and an average "cruise" time of 40 days (80 orbits). Results were calculated for a series of two 60 degree phase changes (one delivery, one returning to the RSat depot). Exhibit 3 indicates there are two types of velocity changes—small sustained stationkeeping/proximity operations, which occur when picking up or delivering RSat and substantial impulsive maneuvers for phasing operations.

ΔV #	Description	Required ΔV	Mass
1	Initial velocity change to enter phasing orbit to begin transit to host spacecraft.	2.00 m/s	8 kg
2	Velocity change to reduce phasing orbit closing speed.	1.00 m/s	8 kg
3	Velocity change to exit phasing orbit in proximity (~1km) of host.	0.75 m/s	8 kg
P1	Assorted velocity changes for undocking & departure operations.	0.25 m/s	8 kg
4	Initial velocity change to enter phasing orbit to begin transit to RSat depot.	2.00 m/s	4 kg
5	Velocity change to reduce phasing orbit closing speed.	1.00 m/s	4 kg
6	Velocity change to exit phasing orbit in proximity (~1km) of next RSat.	0.75 m/s	4 kg
P2	Assorted velocity changes for RSat grappling and proximity operations.	0.25 m/s	4 kg
	Total ΔV required per delivery:	*8.00 m/s*	
	ΔV Scaled for mass:	*12.00 m/s*	

Exhibit 2: Table of velocity changes needed to deliver one RSat to host spacecraft and return to the depot.

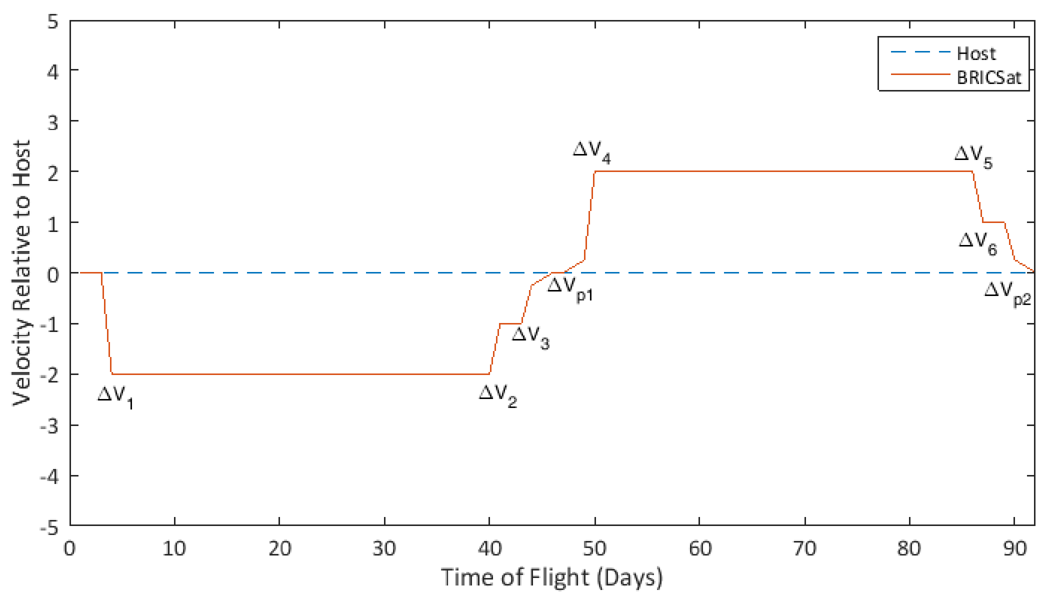

Exhibit 3: Graph of velocity changes needed to deliver one RSat to host spacecraft and return to the depot.

REQUIREMENTS

The AMODS mission requires a combination of long term, sustained ΔV for travel between spacecraft and quick pulses to allow for proximity operations:

First, BRICSat modules must have the ability to create large changes in velocity to transverse space to rendezvous with host satellites and deliver RSat diagnostic units. In order to be commercially useful, these changes must be completed in a reasonable timeframe.

And second, 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. As AMODS must be designed to “do no harm,” to either RSat or the client spacecraft to which the RSat will dock, precision and accuracy are vital.

Each “outbound” operation, from the location of the RSat depot to the host spacecraft, will require approximately twice the thrust, as the BRICSat-RSat combination weighs 8 kg, 4 kg more than BRICSat. Thus, the BRICSat-RSat combined system consumes twice the propellant as BRICSat operating alone. A “round trip” to the target spacecraft and back to the next RSat requires the equivalent of three BRICSat transits.

Finally, the entire system is constrained by the 3U CubeSat form factor. Power is severely limited; with body mounted solar panels, BRICSat can only generate approximately 5 watts of electrical power, 40% of which must be allocated for basic spacecraft operations (command/control, attitude control, navigation, etc.). Additionally, the total BRICSat volume is limited to 10 x 10 x 33 cm, while the mass is limited to 4 kg. Just under half of these allotments are allocated for propulsive systems.

Exhibit 4 summarizes the requirements of the BRICSat propulsion system.

Parameter	Volume	Mass	ΔV (4 kg)	Control	Force
Requirement	≤ 1U+	≤ 1500 g	≥ 75 m/s	6DOF	Variable

Exhibit 4: BRICSat propulsion requirements.

TECHNOLOGY SURVEY

Cold Gas Thrusters

The most common propulsion system for small spacecraft is cold gas. Cold gas thrusters are well suited for CubeSat operations. They are fairly easy to make compact, they are “safe” in that they don’t contain corrosives or other chemicals that could present a hazard to launch vehicles or the primary payload, and they consume low amounts of power. Numerous commercial off-the-shelf (COTS) thruster systems are available. Narrowing the products by the requirements described in Exhibit 4, the AMODS team divided the systems into two categories—ΔV and maneuvering.

ΔV Focus

These propulsion systems have just one thruster nozzle and are reliant on rotating the spacecraft to provide directionality. A sampling of these thrusters is shown in Exhibit 5.

	Model	Size	Mass	ΔV (4 Kg)	I_{sp}	Force
AFRL-Vacco[7]	AFRL PUC	1U+	835 (dry)	167 m/s	70 s	5.4 mN
Vacco[8]	X14029003-19	1U+	1420 (wet)	78 m/s	40 s	10 mN
Tethers[9]	Hydros	1U	-	100+ m/s	300 s	≤ 800 mN

Exhibit 5: Sampling of current ΔV focused cold gas units available.

ΔV focused cold gas thrusters are capable of high changes in velocity—all of those sampled meet AMODS ΔV performance requirements—and are compact and lightweight. However, their focus on providing just one axis of thrust means that any proximity operations would require numerous complex attitude maneuvers to ensure thrust is provided in the correct direction. These actions would preclude the ability to position RSat's claws in a very specific location. Individually, these thrusters are not capable of supporting the AMODS mission.

Maneuvering Focus

Thrusters optimized for maneuvering, such as those set forth in Exhibit 6 below, have multiple nozzles positioned around the spacecraft. These allow for effective proximity operations, and are being flown on demonstrations like the CPOD mission.

	Model	Size	Mass	ΔV (4 Kg)	I_{sp}	Force
Vacco[10]	NASA CPOD	0.8U	1244 g	~50 m/s	40 s	0.025 N
Busek[11]	Micro Resistojet	1U	1250 g	60 m/s	150	0.010 N
Vacco/JPL[12]	MarCO MIPS	2U	3490 g	188 m/s	-	-

Exhibit 6: Current maneuvering focused cold gas units.

Both of these thrusters are capable of full 6 degree of freedom motion. The NASA CPOD module is only rated to 50 m/sΔV, which renders it unsuitable for AMODS operations. The MarCO MIPS meets all requirements, but was optimized for 6U spacecraft and would not fit in BRICSat. COTS cold gas thrusters that meet the size constraints are simply not capable of providing both the ΔV and maneuverability that AMODS needs.

Electric Propulsion

The primary advantage of electric propulsion is their high I_{sp}, which allows them to function with much less propellant to produce the same overall effect. However, electric thrusters work with very small forces, which translate into very slow movements. Thus electric propulsion is not useful when high acceleration is critical, as in orbital phasing maneuvers. Nevertheless, these small forces allow electric thrusters to regulate the impulse applied to spacecraft very accurately, making it possible to control the spacecraft's position and orientation along its orbit with incomparable precision.

The Micro-propulsion and Nanotechnology Laboratory at the George Washington University has constructed a miniaturized propulsion system for small-scale spacecraft it terms the Micro-Cathode Arc (µCat) thruster.[13] The µCat thruster is a small pulsed plasma thruster with volume of about 9 cm^3.[14] It provides small controlled and symmetric pulses with a variable pulse rate between 1 and 50 Hz. Each pulse provides a force of 1µN. 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, a 1.5U CubeSat prototype developed and built at USNA. Launched in May 2015, BRICSat-P's primary mission was to test the use of the µCat thrusters on orbit. The thrusters were used for rudimentary attitude control, and completely detumbled the spacecraft after its deployment from the delivery vehicle. 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.

In the wake of this success, 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.

Exhibit 7 is a plot of translation vs frequency for a fixed time block. This shows how that, in controllable 30 second bursts, it is possible to translate the spacecraft extremely small distances. This deliberate slowness and precision greatly reduces the potential of harming the client spacecraft during the docking process.

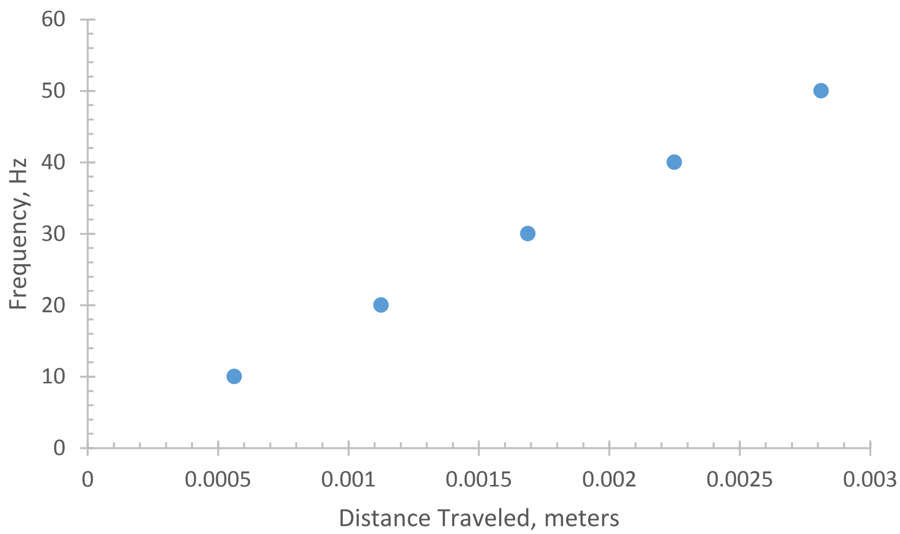

Exhibit 7: Primary analysis of the distance traveled at varying frequencies by using 4 thrusters firing for 15 seconds continuously, and then the opposite face thrusters firing for 15 seconds continuously, for a net ΔV of 0 m/s.

SOLUTION: INTEGRATING THE HYBRID PROPULSION SYSTEM FOR AMODS

While both cold gas and the µCat propulsion systems perform their functions well on the CubeSat platform, neither meets both the size and the operational requirements of the AMODS program. Rather than work to modify one or the other system to produce the desired results, the AMODS team decided to create a hybrid propulsion system that would take advantage of the ΔV performance of cold gas thrusters and the accuracy and precision of the µCat thrusters.

Internal volume of BRICSat is limited. Thus, a significant issue in designing a system which will combine both a notional cold gas thruster and the µCat thruster is volume allocation. The cold gas unit will take up 1U, or 1/3 of the total internal volume. Based on the design of the prototype BRICSat that is currently in orbit, the total volume of the propulsion system and other avionics is 1.4U. For the next iteration of the full-scale BRICSat, 14 µCat thrusters were included in the design of the hybrid propulsion system: four thrusters are placed on the X faces, two on the Y faces, and one each on the Z faces as illustrated in Exhibit 8. The cold gas thruster is placed directly on the positive X face on the centerline of the spacecraft.

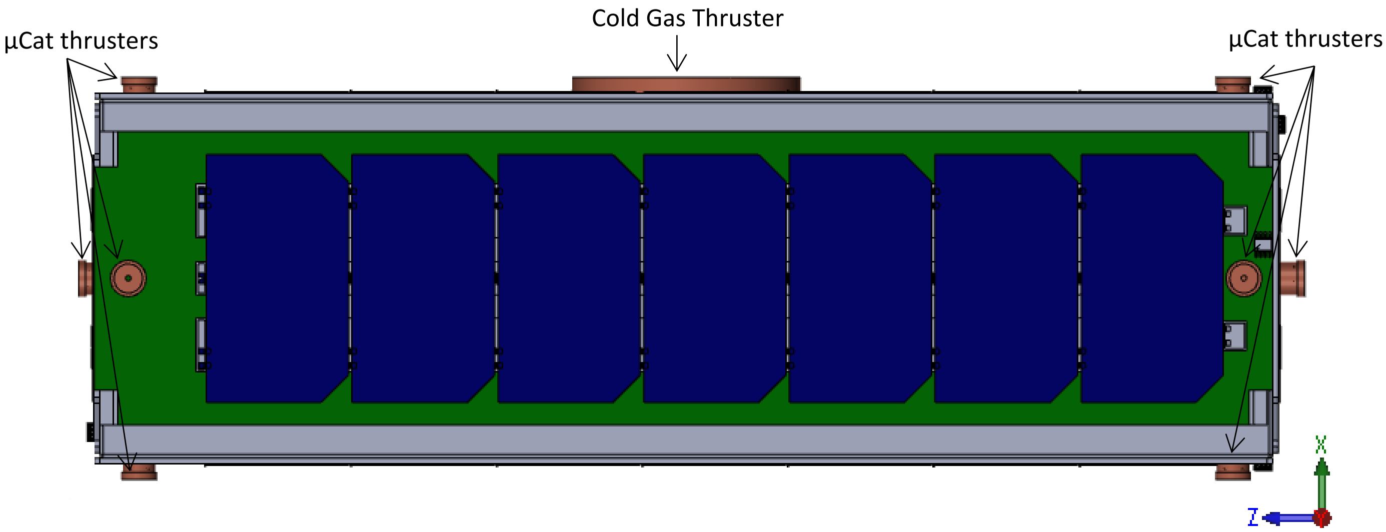

Exhibit 8: Preliminary BRICSat Propulsion System Layout. µCat thruster placement is mirrored on each of the faces opposite the ones shown.

The 14 µCat thrusters will allow BRICSat to have six degrees of freedom in proximity operations. The intended orientation of BRICSat is with the negative X-face towards the client spacecraft to allow for the four µCat thrusters to provide the maximum amount of force when performing proximity maneuvers. This orientation also allows for BRICSat to achieve the necessary ΔV for approach in the shortest amount of time. The time required to transverse a specified distance is shown in the plot of Exhibit 9.

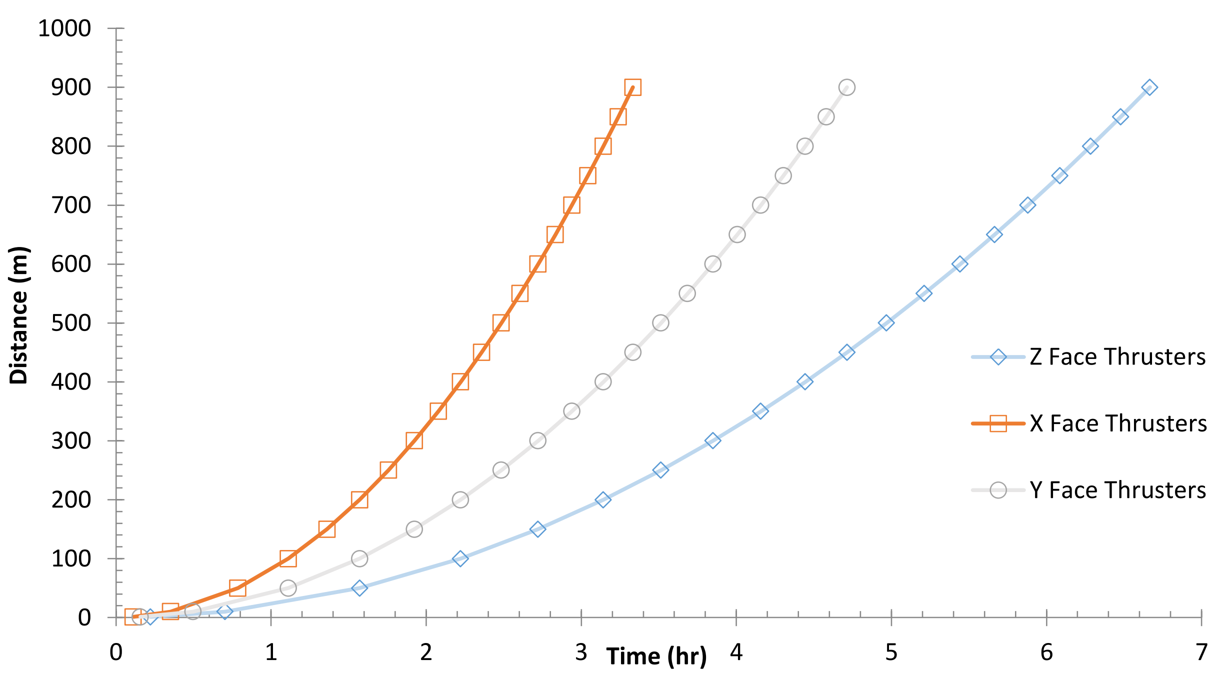

Exhibit 9: Distances transversed using all of the µCat Thrusters on one face. Calculations were made using a 50 Hz pulse rate and an 8 kg total spacecraft mass. Traversed distances based on Vbar movements.

Another advantage of integrating 14 µCat Thrusters is that it allows the µCat system to supplement the Attitude Control System on BRICSat. As the first flight of the µCat thrusters on BRICSat-P demonstrated, the thrusters are able to produce a torque large enough to detumble the spacecraft. With this in mind, the µCat thrusters will be interfaced with the Attitude Determination system and, when necessary, will provide the torque needed to prevent the saturation of the reaction wheels of the Attitude Control System. This capability keeps the reaction wheels from being overworked and therefore extends their lifespan, thus extending the lifespan of BRICSat.

The placement of the centerline cold gas thruster allows the force which it imparts to be directed along the center of mass of both the lone BRICSat system and the BRICSat and RSat composite unit. Since BRICSat and RSat will be docked in a “+” configuration for orbital maneuvers, as depicted in Exhibit 1, the center of mass for each spacecraft will be aligned so that the force will be unidirectional.

With each µCat thruster having a mass of less than 15 grams, a system of fourteen thrusters will have a total mass of around 500 g.

MODES OF OPERATION

Since the µCat thrusters are not sufficient to change orbits and the cold gas thruster is not optimal for use near a client spacecraft, BRICSat will have two primary modes of operation.

Close Proximity Operations

The first operational mode is for close proximity operations. In this mode, the cold gas thruster will not be used and any ΔV will be solely produced by the µCat Thrusters. This mode of operation has two sub-methods of producing the correct ΔV.

Close Proximity – Solo Unit Operations

This method of operation will be used while BRICSat is leaving the client spacecraft and returning to a distance where the cold gas thruster can be used without causing any harm, nominally 1 km from the client spacecraft. It will also be used while BRICSat is approaching the RSat depot to dock with an RSat unit. While operating as a lone BRICSat unit, the µCat thrusters actuate to produce a composite force aligned with the center of mass. This allows the BRICSat µCat thruster system to produce a force in the desired direction of motion without producing an unbalance torque. In this mode of operation, the µCat thrusters will actuate cyclically to reduce power consumption, and will only fire the thrusters on the face opposite the desired direction of motion.

Close Proximity – Composite Unit Operations

This method of operation will be used while BRICSat and RSat are operating as a composite unit, both near the RSat depot, and while operating within 1 km of the client spacecraft in an approach. The added RSat unit moves the combined center of mass off of BRICSat’s Z and Y axes where the thrusters on those respective faces are aligned. This creates an imbalance, as thruster operation on the Y and Z faces will also produce a net torque on the spacecraft. This torque would very quickly saturate the reaction wheels in the Attitude Control System. To address this issue, in order to counteract the torque produced, the AMODS Guidance team is working to create an optimal firing solution utilizing thrusters on multiple faces to counteract the torque and produce net movement only in the desired direction.

Phasing Operations

This mode of operation will be used both when BRICSat is solo and when it is linked to an RSat unit, and the distance to the RSat depot or the client spacecraft is nominally greater than 1km. In this mode of operation, the primary means of thrust will be provided by the cold gas thruster. The Attitude Control System, supplemented by the µCat thruster system, will point the spacecraft or combined spacecrafts and the cold gas thruster will actuate producing a unidirectional force. Since the cold gas thruster is aligned along the center of mass, whether BRICSat is operating as a lone spacecraft or a composite unit, there is no need to have a secondary method for phasing maneuvers. However, the same solution implemented for composite unit close proximity operations will be used to determine the optimal firing solution for pointing the composite unit, should the µCat thrusters be necessary.

The intended method of phasing maneuvers is a Hohmann Transfer. Since BRICSat and the RSat depot will be placed into an orbit identical to the constellation of satellites that they will be working with, there is no need to do any other phasing maneuvers, such as inclination changes.

CONCLUSION

Combining the ability to affect small, precise and careful proximity movement with the ability to perform orbital phasing maneuvers offers new options for on-orbit satellite inspections and servicing. The hybrid propulsion system provides an alternative course for small satellite missions requiring diverse maneuvering capabilities. This capacity will increase the opportunities that the comparatively inexpensive small satellite platform offers space explorers and continue to decrease the cost of entry to space.

ACKNOWLEDGEMENTS

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