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DESIGN PROCESS AND FLIGHT RESULTS FOR THE AUTONOMOUS MOBILE ON-ORBIT DIAGNOSTIC SYSTEM (AMODS)

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ABSTRACT

The United States Naval Academy is developing an Autonomous Mobile On-orbit Diagnostic System (AMODS) to provide all-purpose distributable on-orbit assessment and repair capabilities. To overcome traditional cost and technological hurdles, AMODS comprises a multiple CubeSat arrangement wherein one self-propelled transport CubeSat (BRICSat) will deliver one of several "repair" CubeSats (RSats with manipulable robotic arms and claws) to the customer spacecraft for the purpose of providing diagnostic and maintenance services designed to extend the life of that craft. The BRICSat tug will provide the only propulsion for all the RSat payloads and is responsible for locating and then transporting RSats to host spacecraft requiring diagnostic or repair services. This paper provides an overview of the AMODS mission operation concept. It commences with an analysis of the design of the BRICSat transfer vehicle and the results of preliminary on-orbit tests of the thruster system. It will also include a summary of the RSat design, its visual, assessment, and repair proficiencies and the requirements for actuations in a space environment. It concludes by addressing the status and methods of validating AMODS on-orbit.

INTRODUCTION

In October 2010, NASA publicly confirmed its "unequivocal" conclusion that developing "a meaningful on-orbit satellite servicing capability" will "advance our presence in space" and allow us "to achieve . . . key ambitions."[1] Certainly, providing a satellite with on-orbit repair capability will, among other things, increase the lifespan of spacecraft and allow for increased levels of debris management and mitigation. The ability to do so autonomously will massively reduce costs and risks. Current efforts to provide robotic servicing to on-orbit satellites are both ambitious and elaborate. NASA's Restore-L mission, for example, promises to "rendezvous with, grasp, refuel and relocate" on-orbit satellites, giving "satellite operators new ways to manage their fleets more efficiently, and derive more value from their investment."[2] With launch scheduled for late 2019, Restore-L expects to validate autonomous rendezvous and grasping operations as well as telerobotic refueling and relocation activities. Similarly, Orbital ATK Inc.'s ViviSat is developing a Mission Extension Vehicle which will breathe new life into "geriatric" satellites by offering repositioning services, upgrades, repairs and refueling opportunities. With plans to put the technology in space by late 2018, Orbital ATK promises that these new autonomous capabilities will fundamentally "change the way we manufacture satellites, and how we operate satellites."[3]

These are all remarkable breakthroughs, scaled to solve large problems. Refueling and repositioning services are complex and costly ventures, for the most part well worth the tens of millions of dollars they will require. But what about small scale failures? The space environment is unforgivingly harsh and even the most discrete malfunctions can cripple a mission. More frustrating is the valuable time spent attempting to analyze and diagnose failure points with the limited data available to the ground team. After all, one cannot simply bring the satellite back or send a technician up to determine and effect a solution. The Autonomous Mobile On-orbit Diagnostic System (AMODS) employs a modular, CubeSat design to provide data to ground teams in an efficient and cost-effective manner. The distributive system, which includes one propulsive unit and up to eight repair units, will increase the success rate of missions by both facilitating improved correlation between design and reality and providing immediate failure analysis and mitigation activities. As designed, AMODS can deploy with a satellite to provide both immediate and continuous diagnostic data, or launch independently and be distributed to on-orbit spacecraft with mission specific tools. In this capacity, AMODS can also be used as a “scouting” tool, deployed to “geriatric” spacecraft in advance of a larger scale service mission to provide more detailed information of the status of the satellite and confirming the capacity for rehabilitation.

DESIGN OVERVIEW

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 projected cost of an AMODS deployment is less than $150,000 for each BRICSat transport vehicle, and $25,000 for each RSat repair unit.

RSat Summary

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

RSat is a 3U (10 x 10 x 33 cm) cube satellite with two 60 cm, seven-degree-of-freedom robotic arms. It is intended to operate in constant contact with a host spacecraft. The robotic arms provide access to any external surface of the host and must be able to maneuver without doing any harm to the host. RSat will be equipped with a suite of equipment, including a camera to diagnose any on-orbit failures and, in some cases, perform minor on-orbit repairs or maintenance. In this manner, RSat provides ground controllers with the continued opportunity to physically interact with their spacecraft as if it was on the ground.

RSats will launch with a host spacecraft, or be deployed to existing on-orbit spacecraft. RSats that are deployed on-orbit will link to BRICSat, share power and assist with attitude control as they are transferred to their hosts.

Exhibit 1 is a rendering of the RSat concept.

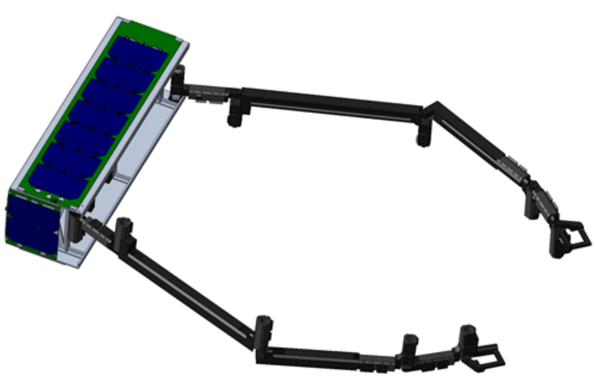


Exhibit 1: A rendering of RSat, a “repair” CubeSat with two robotic arms and manipulable claws designed to attach itself to, and maneuver around a host spacecraft providing on-orbit imaging, diagnostic and repair capabilities.

BRICSat Summary

The mission of the BRICSat platform is to provide the services needed to rendezvous with and deploy RSat onto an existing on-orbit satellite or a distributed network of spacecraft.

BRICSat is also a 3U CubeSat which functions as a completely independent spacecraft. It is a complement to RSat and provides the only propulsive force to the RSat platform in the form of both long term, sustained ΔV for travel between spacecraft (cold gas thruster), and quick pulses (electric propulsion) to allow for proximity operations. A cup-cone magnetic docking system will be built-in to BRICSat and include power and data pass-throughs to electrically link the RSat and BRICSat spacecraft and also allow for them to share power. BRICSat must be able to mirror any movements of a host spacecraft and will also provide Attitude Determination and Control (ADCS) functionality to RSat, as RSat will not need that capability when it is attached to its host. Finally, BRICSat will possess both a long range navigation system (GPS), and a short range system (Machine Vision/LIDAR) to handle the final approach to and rendezvous with spacecraft. Exhibit 2 provides a representation of the BRICSat platform.

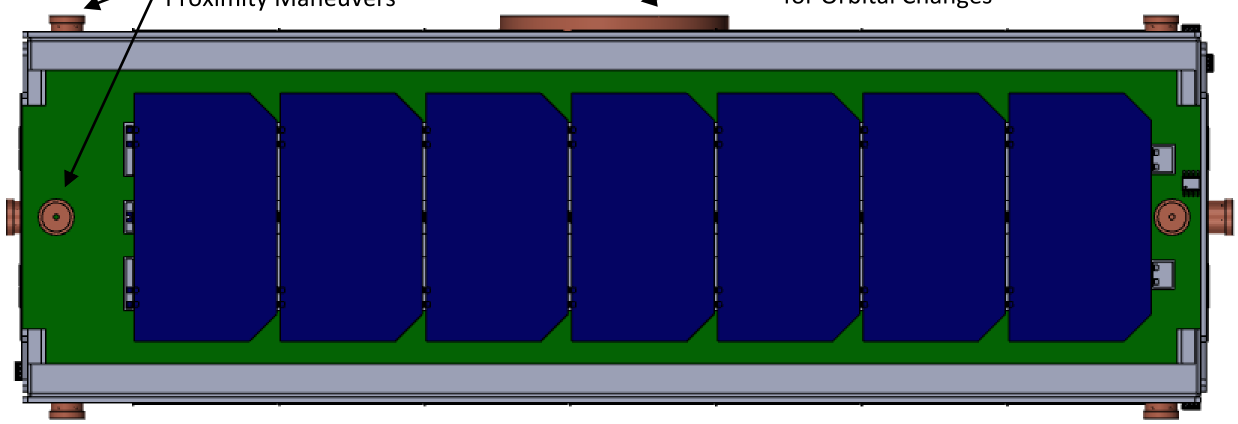


Exhibit 2: A rendering of BRICSat, a CubeSat "space-tug" which will rendezvous with, link to and transport each co-launched RSat to a host satellite,

Concept of Operations

There are two types of missions the AMODS program will support: RSat deployment on future spacecraft and RSat deployment to existing on-orbit spacecraft.

New (Future) Spacecraft Incorporating RSat

RSat can be incorporated directly into the design of new spacecraft. This will allow RSat to launch along-side or within its host, rather than require delivery by BRICSat. A few modifications to potential host satellites will be needed to simplify RSat operations.

1. *Modified P-POD*: The P-POD container is the vessel from which CubeSats are traditionally deployed, and can be conceptualized as a box with a push-spring. Typically, a CubeSat is ejected into space from the P-POD container when the door opens. Rather than simply being pushed out into space, RSat will be temporarily fixed to the spring, allowing RSat to slide out on a drawer.

2. *Contact Points*: Where possible "grab" points will be situated around the host spacecraft to ease robotic maneuvering. Ideally, these locations will be located 1 m apart. They will consist of a small flange of metal, with a small lip, which will allow for confident manipulator capture.

3. *Known Design:* RSat will be pre-loaded with a structural and locational knowledge of the host satellite, translated from a CAD model of the spacecraft upon which it is operating. This will allow RSat to intelligently plan out its maneuvers and facilitate autonomous navigation operations.

On launch, RSat will be embedded in the spacecraft in the modified P-POD container. Immediately after the spacecraft reaches orbit, or when the operator of the host satellite desires, RSat will be deployed. Exhibit 3 shows a depiction of this deployment concept.

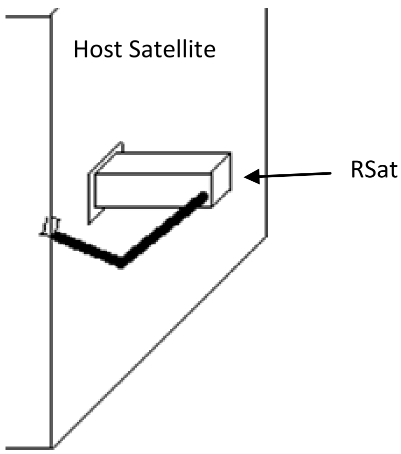


Exhibit 3: RSat deployed with a host satellite.

After the drawer upon which RSat sits slides out of the P-POD, RSat will commence a series of system diagnostics. At the conclusion of these tests, RSat will latch onto a contact point on the host spacecraft, and await commands from the ground. It will broadcast a periodic message that details its status.

At this point, it will enter a standby mode and wait for components of its host to fail. In the event a failure occurs, RSat will be awoken by ground controllers and commanded to navigate to the point of failure using its robotic arms to maneuver. After reaching the targeted failure location, RSat will perform a detailed analysis of the situation, including providing imagery from all relevant angles, and if possible, attempt to make repairs. Otherwise, it will downlink data on the failure so that ground controllers can learn exactly what has failed and how in order to prevent future failures.

RSat may also be used for periodic inspections to monitor system health, survey material degradation and anticipate or even mitigate failures. It can provide detailed imagery of the spacecraft at a certain interval to detect events such as micrometeorite impacts, sputtering, and radiation effects. This could provide ground controllers a better sense of the state of health of their spacecraft, as well as a more comprehensive understanding of how their components, equipment and systems weather the space environment.

Servicing Existing Spacecraft

While a RSat may be deployed singularly with one BRICSat to rendezvous with a solo client satellite, the existing spacecraft mission assumes an AMODS will be deployed on a large constellation of satellites in similar orbits. Conceptually, one BRICSat will be launched with multiple RSats (RSat-1, 2, 3, etc). The number of repair modules deployed per BRICSat will depend upon the constellation and deployment time constraints. However, for premium fiscal efficiency, there should be a minimum of two RSats, or a fleet of up to eight RSats (RSat-1, 2, 3, etc), launched with each BRICSat. The assembly of CubeSats would launch as a standard CubeSat launch, possibly even as a secondary payload.

Once on-orbit, the repair units will be free-floating in space in relatively close proximity, forming a loose “depot” of RSats. Their sole activity is to deploy their arms once detumbling is completed and await rendezvous with BRICSat. BRICSat will locate the first RSat using star tracking and machine vision. It will use machine vision and LIDAR to develop the proper bearing and then use a combination of cold gas and microcathode thrusters to navigate to the target RSat. BRICSat and RSat will link 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. RSat's robotics arms will be used to move the center of mass fully to BRICSat. This is represented in Exhibit 4.

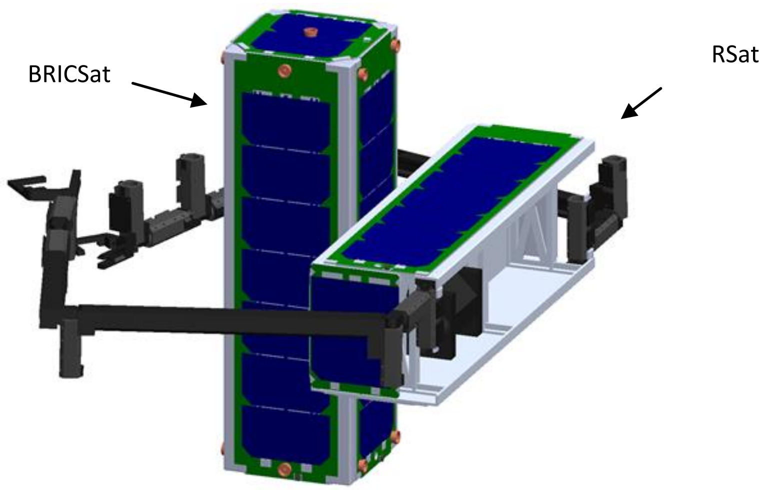


Exhibit 4: BRICSat and RSat will link autonomously using a cup and cone magnetic docking system which will include power and data pass-throughs to electrically link both spacecraft. RSat's arms will be used to move the center of mass fully to BRICSat.

Once linked, BRICSat will perform an orbital phase change using cold gas thrusters to navigate the combined BRICSat-RSat system to the client spacecraft. When the transport vehicle and its cargo are within one kilometer of the host spacecraft, BRICSat will use a star tracker algorithm to locate and remove all stars allowing BRICSat to "see" the host satellite. BRICSat will use machine vision and LIDAR to identify, and prepare a navigational plan to reach the target host. At this point, BRICSat will switch to microcathode propulsion. Machine vision will maintain closed-loop control of the microcathode system.

It is anticipated that the RSat will grapple on to the host satellite's existing launch vehicle mating adapter. Of course, when a host constellation is identified for RSat deployment, RSat can easily be customized to meet specialized grappling requirements based on host satellite design.

When the combined BRICSat-RSat unit is 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 use machine vision and its microcathode thrusters to 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. Exhibit 5 depicts the approach to a rendezvous with the host spacecraft.

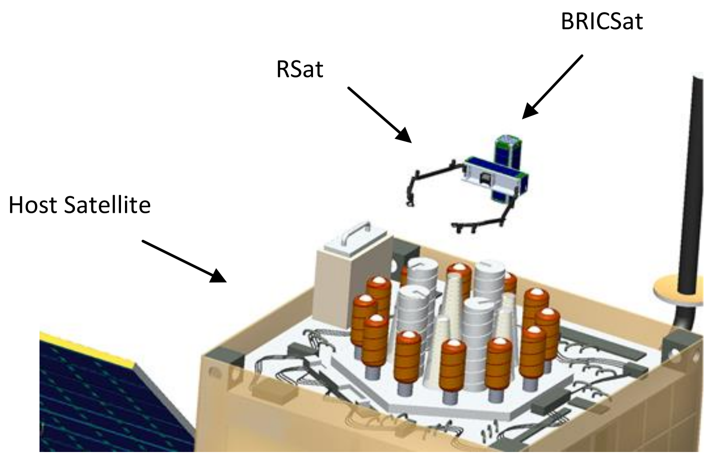


Exhibit 5: BRICSat/RSat linked vehicle rendezvous with host spacecraft. BRICSat will use a star tracker algorithm to locate and remove all stars allowing BRICSat to "see" the host satellite. BRICSat will use machine vision and LIDAR to identify, and prepare a navigational plan to reach and rendezvous with the target host.

After confirmed capture, RSat-1 will disconnect from BRICSat and conduct maneuvers as described in the "New Spacecraft" section above, using its manipulators to propel itself around the craft providing visual data and other diagnostic function.

Thereinafter, BRICSat will locate, navigate to and ultimately link to RSat-2 and later RSat-3 for transport to their respective spacecraft hosts. The RSats will remain on their hosts, monitoring the satellites, visually documenting any features of interest and performing diagnostic and repair tasks as needed.

AMODS PROGRAM STATUS

BRICSat will undergo a three stage test program. BRICSat-P: Prototype launched in May 2015; BRICSat-D: Demonstrator is scheduled for launch in September 2016; and BRICSat-T: Tug Validator is expected to launch in late 2017 or early 2018.

RSat will undergo a two stage test program. RSat-P: Prototype is targeted for launch in early 2017; and RSat-1,2,3: the Demonstrators are expected to launch with BRICSat-T in late 2017 or early 2018.

The entire AMODS program will be validated with the combined BRICSat-T RSat-1,2,3 launch in late 2017 or early 2018.

BRICSat-P Prototype – Launched May 2015

The BRICSat-P spacecraft is a technology demonstrator designed to validate the "in transit" propulsion system and Attitude Control System portions of the AMODS BRICSat platform.

BRICSat-P is a 1.5 U (10x10x16cm) spacecraft with four Micro-Cathode Arc Thrusters (µcat). Its propulsion system was designed by the George Washington University. A depiction of the propulsion system's thruster head is shown in Exhibit 6.

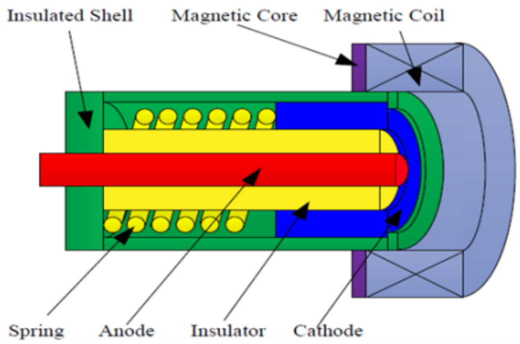


Exhibit 6: BRICSat Propulsion System Thruster Head.[4]

The thrusters are a form of electronic propulsion which utilizes a titanium cathode propellant to provide a specific impulse of 3000 s with a thrust of 1 µN. An electronic arc creates a cathode spot that ablates the cathode to produce high velocity plasma. Thrust level is controlled by increasing or decreasing the firing rate.

When firing continuously, the thrusters draw one watt and can last for 10 years, depending on the size of the propellant rod.[5] The thrusters are compact; 1 cm in diameter and 2.3 cm long. This allows them to be placed in optimal locations on the spacecraft, and allows the full size BRICSat to contain significantly more thrusters.

The BRICSat-P mission was the first flight test of these thrusters. The mission confirmed the ability of BRICSat to use its thrusters to detumble, demonstrating the thrusters ability to act as an attitude control system.

BRICSat-D Demonstrator – Launch September 2016

BRICSat-D is the evolution of the BRICSat genus. The BRICSat-D mission, scheduled for launch in September 2016, will conduct two primary flight experiments: 1) a rotational experiment wherein the thrusters will be utilized to rotate the spacecraft up to 6 rpm, which will evaluate the thrusters performance against known quantities; and 2) a micro-stepping/ΔV experiment wherein thrusters will be used to change BRICSat's orbit in a controlled manner.

Based on the results from the P flight, flight D's propulsion system will consist of micro-cathode thrusters, used for long duration cruise and coarse attitude control/pointing, in order to demonstrate proximity and rendezvous operations. The goal is to confirm that the micro-cathode thrusters are capable of providing consistent, effective translational movement – as required for rendezvous and docking operations. Thus, BRICSat-D will also launch with a sophisticated inertial measuring unit that is tuned to examine translational movement, and with improved flight software optimized for translational mission.

RSat-P Test Vehicle – Launch 2017

The first RSat launch (targeted for early 2017) is a project demonstrator that will prove RSat's on-orbit suitability, capability, and accuracy. RSat will conduct on-orbit performance assessments by moving its appendages through a test pattern or patterns intended to simulate simple diagnostic or repair tasks.

RSat Spacecraft Systems

RSat-P will be launched into low earth orbit, making the low-cost satellite bus a viable option. The low-cost bus consists of a power supply system developed in-house, two commercial off-the-shelf (COTS) amateur data radios, three COTS TTL serial cameras, and four Arduino microprocessors.

Despite the low-cost COTS hardware, it is designed as an extremely robust system. This high resilience is made possible because RSat is subdivided into two systems. Each Arm (Arm1 and Arm2) has its own microcontroller pair, radio, camera, and electrical power system (EPS). Some of these subsystems are capable of cross linking to the other arm as well to provide redundancy. To accomplish the initial mission, the ability to move and control a single arm in space must be validated. However, in order for RSat to be useful in its notional mission, it must have two arms. The second arm provides resiliency in the event the first arm fails, while still serving a purpose in our concept of operations. All the support systems for the arms (Electrical Power System, Radio, Attitude Control System, etc.) embrace this resilience concept. The Command and Data Handling (C&DH) system underscores its benefits. Where traditional CubeSats use an expensive (~$4,000) purpose built processor to control their spacecraft, RSat uses a distributed system of four Arduino to serve the same role, a change that dramatically reduces cost while adding functionality.

All four main processors listen to both communication rails (that is both radios), but only execute commands when their specific function is tasked. They also have crosslinking capability via I2C to assume most of another processors' functionality.

RSat has two onboard radios, operating at the same frequency. Under typical operations, one operates as an intermittent beacon, while the other is used for high bandwidth tasks. After a set period of time, these radios rotate those duties, allowing for communication even if one has failed.

A bespoke EPS allows for a near fully redundant EPS design. EPS control and telemetry can be provided from any functioning processor, while each arm has its own voltage converters and fuses—however all components are sized 2x max current draw, allowing a single component to drive both arms. No single component exists in the EPS that could cause complete spacecraft failure.

While the notional RSat will not require an ADCS system, such a system will be needed for the initial free floating launch of RSat-P. In order to operate the arms, RSat must detumble to a rotation rate of less than 1 º/s. To facilitate this, RSat will use a passive magnetic hysteresis system that favors the hysteresis material over a permanent magnet.

RSat Robotic Systems

In designing RSat's robotic manipulators, great weight is given to establishing as standard a profile as possible while emphasizing speed and functionality. The CubeSat frame will be modified to create a secure storage for the arms which will be mounted directly to the shaft of the motor. Ultimately, the system must be accurate to within 10 mm at full extension. This equates to ± 0.25 º at each motor. Actuations must be smooth and controlled to avoid damaging the host spacecraft. Materials and lubricants chosen must be space rated or at least space-suited.

In addition, RSat has three cameras, one at the end of each arm and one that is center-mounted. The center-mount camera will monitor the arms. The cameras at the end of each arm will monitor the manipulators.

RSat Prototype Mission

All of these components will be tested on-orbit to validate the accuracy and reliability of the arm system. There are four primary flight demonstrations:

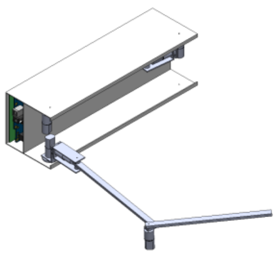
1. *Navigate to Coordinate*: to demonstrate that each of the arms is capable of navigating to a precise location, which will indicate that the spacecraft is capable of flexible orbital operations.

2. *Handshake:* to demonstrate that RSat is capable of operating the arms in proximity to each other. This is a key requirement in any potential imaging/servicing missions.

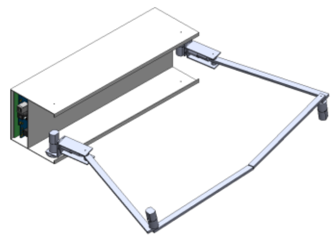
3. *Imaging:* to establish RSat's ability to take pictures of other spacecraft. RSat's arms will move to a variety of positions around the spacecraft and image all six faces.

4. *Manipulation*: to simulates the use of the manipulators to interact with another spacecraft. (A) Arm 1 will pick up a demonstration object from one of the ends of the spacecraft, and move it to within camera range. (B) Arm 2 will then take control of the object. This validates the manipulator design, and demonstrates the precision of the arm.

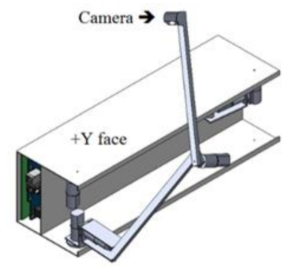
Exhibit 7 illustrates the various tests contemplated by the RSat-P prototype mission.



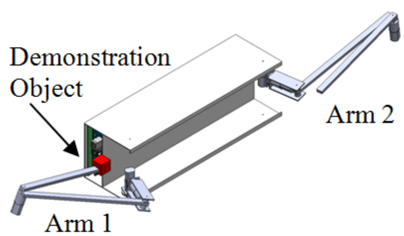
1. Navigate to Coordinate



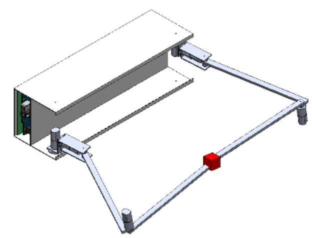
2. Handshake



3. Imaging



4A. Manipulation (pick up object)



4B. Manipulation (transfer object from Arm 1 to Arm 2)

Exhibit 7: Rendering of the various segments of the RSat-P prototype mission to validate the accuracy and reliability of the robotic arms.

BRICSat-T Tug Validator – Launch 2017/18

As RSat development moves forward, the BRICSat-T team will incorporate the lessons learned from the previous two BRICSat flights to create a fully operational Space Tug. After launch, targeted for late 2017 or early 2018, it will conduct simulated rendezvous and proximity operations to confirm core functionality.

Propulsion

The mission 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, there is ±2 cm tolerance for the propulsion system on final docking operations.

BRICSat-P tests confirm that the µcat system is extremely precise and accurate while relative change in force is very small. However, although the µcat system adequately executed orbital changes, analysis suggests the timeframe in which these changes are effected is not optimal. AMODS requires that its BRICSat transport modules have the ability to create large changes in velocity to transverse space in order 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.

Each “outbound” operation, from the location of RSats to the target spacecraft, utilizes approximately twice the thrust, as the BRICSat-RSat combination weighs 8 kg. Thus, the BRICSat-RSat 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.

BRICSat’s ΔV is limited by the capabilities of existing COTS CubeSat propulsion systems. Currently, the most capable CubeSat propulsion systems use cold gas propellant. Utilizing a mid-range cold gas thruster, BRICSat-T is capable of generating more than 80 m/s ΔV (based on a 4 kg satellite.) This ΔV provides sufficient capability to distribute a complement of six RSats across a hypothetical MEO constellation in less than one year.

While the cold gas system is well suited for large orbital maneuvers, the complexity of the valve system, coupled with the relative lack of accuracy and precision of a typical cold gas thruster eliminates it as a viable option for rendezvous and docking operations. As a result, the AMODS team will deploy a hybrid propulsion scheme by integrating the µcat and cold gas thrusters in one propulsion system. The integrated systems will allow the satellite to both change orbits in a timely manner and perform rendezvous and grappling/docking operations with an extremely high level of precision and accuracy.

In order to enhance accuracy, BRICSat-T will have µcat thrusters on all six faces – for a total of 14 thrusters – allowing for easy on-axis translations. It will have just one Cold Gas thruster for substantial orbital changes.

Linkage

BRICSat must be capable of berthing and electrically linking with successive RSats. A cup-cone magnetic docking system will be built in to BRICSat and include power and data pass-throughs to electrically link the spacecraft and also allow for them to share power. During docked operations, BRICSat-T will control all of RSat’s components via I2C.

Attitude Control

As noted above, the docking process requires ±2 cm accuracy. Additionally BRICSat must be able to provide ADCS functionality to RSat, as RSat will not need that capability when it is attached to its host. BRICSat must also be able to mirror any movements of the host spacecraft.

Attitude control must be accurate to 0.5°. However, the RSat manipulator’s combined 14 degrees of freedom present a unique attitude control problem. When BRICSat-T is linked to RSat, RSat will necessarily have to move one of its manipulators to prepare to grasp the host satellite. During the maneuvering process and other proximity operations, the very movement of the robotic arms will disrupt stability. As one of the manipulators moves, the center of mass and rotational inertia of the spacecraft will change. Rather than relying solely on the ADCS, the second, non-grasping arm will be manipulated to produce balancing counter-torque.

Due to space, cost, and power constraints, BRICSat-T will employ a COTS ADCS system that provides a torque of 0.635 mNm, which is approximately 25% of the motor’s expected torque. Thus, the counter-acting arm must reduce the torque input movement of the mission arm to 25% of its original value.

An algorithm is being developed to guide automatic balancing movement between the arms. This will ensure the center of mass and rotational inertia remain constant throughout robot arm operations and the spacecraft remains pointed in the correct direction for docking.

Navigation

BRICSat-T will employ machine vision, a star tracker, a long range navigation system (GPS) and a short range system to handle the final approach to the target spacecraft. Operators on the ground will inform BRICSat-T where to find each RSat. Machine vision and LIDAR will be used to develop vectors to the target spacecraft. During the approach, machine vision will provide feedback to the thrusters, creating a closed-loop control of the microcathode system. BRICSat-T’s thruster system allows for translations in any axis without rotating the spacecraft. In this manner, the overall workload of the navigation system is reduced and the control system is simplified.

AMODS Technology Demonstrator

The current plan for the subsequent development is for BRICSat-T and RSat-1,2,3 to deploy together to validate linked proximity and transit capabilities and further establish flight heritage and reliability. With the cooperation of a research partner, the AMODS program will have the ability to deploy RSats to a host satellite already on-orbit. The prototype mission will include the following steps:

1. *BRICSat Navigate to RSat-1*: This first step will validate the navigation and propulsion systems.

2. *BRICSat Link to RSat-1*: This is the first opportunity to validate on-orbit autonomous linkage between the two spacecraft. In addition to testing the linking mechanism, it will confirm the simple sharing of power.

3. *BRICSat Transports RSat-1 to host satellite*: The transport of RSat-1 will validate both the hybrid propulsion system and the hybrid ADCS system which will rely in part on counteracting arm movements to maintain stability of the combined spacecraft. Should a host satellite not be available, RSat-1 will be transported to RSat-2 and put the two spacecraft in a position to lock claws.

4. *Navigate to RSat-2/RSat-3:* If RSat-1 is deployed to a host satellite, succeeding RSats will need to be delivered to hosts as well. Alternatively, BRICSat-T will further validate navigation, propulsion and ADCS systems by navigating to RSat-3 and delivering RSat-3 to the linked RSat-1 and RSat-2.

This technology demonstrator will include refinements from the P, D and T designs; it will utilize previously unused payload space for tool stowage to provide increased arm functionality, and will demonstrate the advanced radiation hardened processors to conduct some maneuvers autonomously.

CONCLUSION

Providing a spacecraft with on-orbit assessment and repair capability will increase the success rate of missions by both facilitating improved correlation between design and reality and providing immediate failure analysis and mitigation activates. AMODS will provide this function on a cost efficient basis. After Phase Three, the AMODS concept will be validated. At this point, AMODS can commence deployment onto satellites, both new and legacy. Currently, the RSat-P project is midway through the development process and tracking to a 2017 launch, BRICSat-P has been demonstrated in space, BRICSat-D is scheduled for a September 2016 launch and the full AMODS Technology demonstrator is anticipated to take place in late 2017 or early 2018. Fundamentally, the system has the potential to demonstrate an inexpensive, reliable repair system that can be placed – or deployed to – any spacecraft. This technology will prove invaluable to extending the life of spacecraft and transitively the effectiveness of humans in space.

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