Leveraging the Autonomous Mobile On-orbit Diagnostic System to Initiate a Doctrinal Shift in Spacecraft Operations

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1 Introduction

Satellites have become indispensable tools of modern living. From near-term benefits such as communications, navigation, agricultural development, and national security, to space exploration missions such as asteroid mining and colonization efforts, satellites are integral to both human advancement and preservation. Although the benefits of space technology is quite clear, the associated cost can often be prohibitive, especially in cases where the satellite system suffers failure in orbit, leading to loss of capability. Building a satellite that can collect data to help predict tornadoes, for example, will require at least $200 million. And while recent breakthroughs in reusable rockets suggest that launch prices can decrease, currently, a single satellite launch can range in cost from $50 million to $400 million. As such, the investment required to procure a space asset easily exceeds $250 million.

Even if a satellite is successfully placed into the desired orbit, it is not guaranteed that all systems will perform correctly. And those that actually work properly from launch can be expected, as with any machinery, to suffer the effects of wear and tear, whether over time or sudden failure of components. Some spacecraft will suffer small but costly malfunctions and some will simply cease to function. Unfortunately, satellites cannot return to Earth for repair or maintenance. As a result, even seemingly benign failures can cripple a spacecraft, severely impede research and testing efforts, and ultimately frustrate a multi-million dollar investment. Furthermore, it is more than likely that a ground-based project team will never be able to conclusively determine why a failure or malfunction occurred.

In these cases, not only is the spacecraft lost, but invaluable experience vanishes with it. This lack of knowledge in the failure mode of a satellite decreases the ability to implement preventive or other innovative measures in replacement craft which in turn severely impedes the evolution of human ability in space. It is estimated that there are approximately 2,600 nonoperative satellites currently in earth orbit.[1] All these examples of satellite on-orbit failures can potentially yield valuable information and lessons learned if some form of diagnostics can be performed on these satellites in orbit.

1.1 Current Solutions

Extensive work has been done to effect on-orbit satellite service and repairs. Some missions are optimized for human servicing, most notably the Hubble Space Telescope (HST). HST benefited from five shuttle maintenance and upgrade missions with great success. While suitable for a flagship space telescope of almost incalculable scientific value, these missions put human lives at risk and remain extremely expensive.[2]

Attempts have been made to remove the human element; the Defense Advanced Research Project Agency's Orbital Express sought to validate a spacecraft's ability to refuel and reconfigure on-orbit satellites. The United States Air Force launched two demonstration spacecraft in 2007, and validated much of the concept before the program was deactivated.[3]

The Satellite Servicing Capabilities Office (SSCO, NASA Goddard) has provided both a conceptual robotic repair mission and some of the components needed to undertake it. These components are currently undergoing testing on the International Space Station as part of the Robotic Refueling Mission, and are operated by the Dextre robot, provided by the Canadian Space Agency.[4, 5] Most recently, NASA has announced its intent to build a "satellite servicing station that can gas up and repair aging birds."[6]

One common denominator across all of these missions is high cost. As an example, NASA's Space Shuttle repair missions were valued at $900 million, while Dextre cost $200 million and Orbital Express cost $300 million.[2, 3, 4]

1.2 AMODS

The focus of United States Naval Academy (USNA) Small Satellite Program's research is on the development of a more broadly-scoped diagnostic service that can be cost-effectively applied to not just the most expensive flagship missions, but all conventional spacecraft. The Autonomous Mobile On-orbit Diagnostic System (AMODS) will measurably increase the success rate of space missions by both facilitating improved correlation between design and reality, and providing immediate failure analysis and mitigation activities. AMODS takes advantage of the cost and profile efficiency of the small satellite platform to offer satellite developers and operators a fundamentally new way to reduce risk, protect investment and effect design improvements correlated against observed space environment experience. Put simply, AMODS deployment shifts conventional launch acuity from "launch and hope" to "launch and know."

The AMODS concept embraces a multiple CubeSat system: 1) several "repair" CubeSat-class satellites (RSats) with manipulable arms designed to latch onto a host satellite and maneuver, image, and potentially repair 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 per BRICSat and $25,000 per RSat.

When fully realized in the future, there are two types of missions the AMODS program can support: RSat deployment with future spacecraft and RSat deployment to existing on-orbit spacecraft. In either case, RSat can offer generic functional services or be modified with tools to address specific issues as determined by the client spacecraft owner.

This paper provides an overview of the entire AMODS program. It commences with a review of the demonstrative mission failures, malfunctions and conceptual applications that directed required capabilities. It continues with design summaries and concludes with a discussion of the current mission status including the multistep development process and design decisions that make the mission practical.

2 Required Capabilities: On-orbit Mechanical Failure Diagnostics (RSat)

Diagnosing even a simple component failure can be time consuming – typically lasting several months and often much longer. Diagnostic activities are also expensive in terms of both financial and human resources, requiring attention from individuals extremely knowledgeable of the spacecraft system. And, unfortunately, diagnoses can be severely unreliable as their accuracy remains dependent upon the availability of relevant data.

2.1 Historical Example: Telstar 14

In 2003, Space Systems/Loral (SS/L) celebrated the delivery of its 50th SSL 1300 series , making that communication satellite bus one of the most popular spacecraft designs in the world. Less than a year later, the 53rd spacecraft of that line, the Estrela do Sul/Telstar 14 suffered a crippling solar array failure. After spending $13 million attempting to determine the root cause of the issue, SS/L abandoned the effort. Having launched so many successful 1300 series spacecraft, many "industry insiders" blamed the delivery vehicle, Sea Launch. No corrective action was recommended for future spacecraft.[7]

In 2011, after 30 more successful launches, the Telstar 14's replacement spacecraft, Estrela do Sul-2/Telstar-14R, also suffered a solar panel failure. SS/L spent an additional $22 million troubleshooting the problem, ultimately tracing the flaw to a malfunctioning nylon hook. At the time, no link was drawn between the Telstar 14 and Telstar 14R failures.

In 2012, the solar panels on SS/L-built IS-19 also failed. Much like the Telstar investigations, the initial investigation of this malfunction reached no definitive conclusion. On this third failure, and after $422 million in insurance claims, SS/L partnered with Sea Launch to hire a third party firm to investigate the root cause of the malfunction. After combing through launch vehicle telemetry, Boeing engineers found an anomalous event 72 seconds into flight that registered on microphones and pressure sensors.[8]. This anomaly corresponded with one other launch – that of the 2004 Telstar 14. Armed with this data the investigating body reached the conclusion, eight years after the original failure, that defects in the honeycomb structure of the solar panel caused explosive decompression, destroying the panels.[9]

This entire eight year diagnostic process could have been reduced to a period of just days if an image of the malfunctioning solar panel on Telstar 14 from the correct angle had been available. An image, captured near the deployment mechanism, of the deployment seals themselves, would have made it readily apparent to ground controllers that the mechanism had explosively decompressed. Immediate capture of this information would have allowed for remediation steps in all future spacecraft, preventing the two successive SS/L solar panel malfunctions. Unfortunately, the SSL 1300 Bus is not capable of gathering this information, leaving the SS/L President to lament "You can only act on the data you have."[9]

The goal of the AMODS program is to provide that data.

2.2 AMODS Solution: RSat

The AMODS team first investigated the methodology of delivering necessary diagnostic equipment to the non-functional (client) spacecraft. The current conventional solution dictates that a dedicated launch is necessary, if only to get a diagnostic vehicle into the same orbit as the client spacecraft. Such a launch must be planned years in advance and will cost at least $50 million dollars – not a sustainable model for a company that launches tens of spacecraft with the potential to malfunction per year. Once on-orbit, approaching the client spacecraft requires sophisticated (and therefore expensive) navigation and propulsion systems – systems that will never again be utilized after close proximity is achieved. And all this effort and investment may be wasted if the malfunction is not readily apparent from a surface inspection. When a diagnostic mission equals the cost of a substantive one, the adoption of a "launch and hope" mentality is not only not surprising, it is sensible.

However, most large spacecraft, including the SSL 1300 Bus have provisions for hosted payloads – payloads that are embedded on launch and ride alongside their host all the way to the final orbits. These hosted payloads are small and lightweight (1 to 100 kg), and impart a minimal performance degradation.[10]

The AMODS team determined it would be optimal for imaging equipment to fit into this space already available on conventional satellites. Launching with a client spacecraft obviates the need for dedicated launch and rendezvous operations. It allows for the immediate provision of diagnostic support and mitigation activities as soon as the host has reached orbit. If no malfunction is detected, or suspected the diagnostic unit can remain dormant with negligible impact to standard satellite operations. In the event a failure occurs, the unit will be available to provide diagnostic information in a matter of days. However, as a hosted payload that will not be needed in normal operations, it is important to minimize mass, volume and resource consumption. Thus the CubeSat platform was adopted as the frame for the proposed diagnostic vehicle: RSat.

By leveraging the existing CubeSat standards, AMODS ensures satellite designers do not have to worry about incorporating self-repair into their satellite architecture. CubeSats are small, they do not add significant weight to launches and, in fact, most satellites already launch with CubeSats for a variety of different purposes. The numerous flight opportunities for CubeSats make iterative demonstration of operating capability both practical and inexpensive.

RSat will be fitted with arms and manipulators allowing it to locomote around its client spacecraft and perform simple diagnostic acts. One manipulator will always be in contact with the host, thereby removing the need for any form of guidance, navigation or control equipment (GNC). By removing these expensive and heavy systems, the cost and budget impact of embedding an RSat is greatly reduced.

2.3 The RSat Platform

RSat is optimized around its core mission (provide basic diagnostics) to ensure absolute minimum utilization. In order to perform effective diagnostics, RSat needs to be able to:

1. *Locomote*: RSat must be able to interact with every critical area of the client spacecraft.
2. *Investigate*: The data returned must be useful to facilitate maintenance, failure analysis and possible salvageability and otherwise enhance understanding of material degradation.
3. *"Do no harm"*: RSat manipulators must be accurate enough to not damage the host spacecraft.

This capability has a very strong foundation in terrestrial robotics, from children's toys to industrial pipe inspection robots. The size of these robots continues to decrease, to the point at which an extremely versatile robotic arm, capable of conducting the above objectives can fold to the size of a paper towel roll, if not smaller.

For these reasons, the AMODS team selected a 3U (10 x 10 x 33 cm) cube satellite as the basis for the RSat spacecraft. The design is optimized to provide a mobile platform to survey and possibly repair any standard conventional spacecraft. In order to access all areas of a spacecraft like the SSL 1300 series, RSat is equipped with two 60 cm, seven degree-of-freedom robotic arms. The combined 14 degrees of freedom allow RSat to reach anywhere inside a 1.5 m radius sphere. By using the arms as a locomotion device, and "spidering" along the outside of its host spacecraft, transferring from point to point while operating in constant contact with a client spacecraft, RSat will be able to access any external surface of the host. It is capable of these maneuvers without the need for an attitude control system, propulsion, or navigation systems.

To meet diagnostic requirements, in line with terrestrial robotics, RSat will be equipped with multiple cameras to image and diagnose any on-orbit failures and other instruments as may be required to perform minor on-orbit repairs or maintenance. In this fashion, RSat provides ground controllers with the continued opportunity to physically interact with their spacecraft as if it was on the ground.

Figure 1 illustrates the arm and claw concept of RSat.

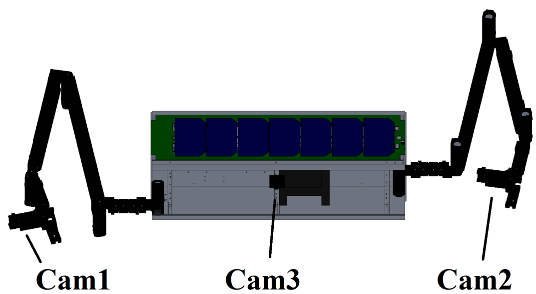

Fig. 1 Depiction of RSat with both arms extended.

2.4 Host Spacecraft Modifications

A few modifications to potential host satellites will be needed to simplify RSat operations.

1. *Modified P-POD*: The Poly Picosat Orbitable Deployer (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*: The host spacecraft will have a series of contact points to ease robotic maneuvering. Ideally, these points 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 Computer-aided design (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.

2.5 Core Capabilities

The AMODS team has developed a series of core RSat capabilities to complete a variety of missions. These capabilities serve as the building blocks for all AMODS operations.

2.5.1 Locomotion

In order to perform effective diagnostics, RSat needs to be able to transition from point-to-point on its host spacecraft. RSat uses its arms to climb around a spacecraft. One manipulator will always be in contact with the host.

2.5.2 Operation, Command, and Control

RSat needs to be a stand-alone satellite, not dependent on the host satellite for any of its functionalities because use of RSat will most likely mean that the host satellite is not functioning correctly. Accordingly, the arms are commanded from the ground. Each arm command is made up of the series of joint positions necessary to accomplish the operation. The command is then uploaded to RSat via radio uplink.

Situational awareness of arm locations is provided from two sources. The primary source of arm positioning knowledge is the integrated motor encoders that provide shaft positioning knowledge for each joint. This information is converted into joint angles, which are used to generate a model of the spacecraft. This model provides operators with an excellent understanding of the current state of the spacecraft.

Using the location of the manipulator in contact with the host, this model can be combined with a model of the host to plan new maneuvers. This allows controllers to simulate arm maneuvers on the ground before they occur, and monitor the simulation for conflicts or flaws. This model is further enhanced using RSat's three on-board cameras (shown in Figure 1). Images from these cameras are captured and downlinked after every arm maneuver, and can be superimposed on the model. This allows for model verification and conformation.

Routes are planned and optimized by ground controllers on an as needed basis. RSat's expansive arm span and 14 degrees of freedom provide the ability to maneuver along unmodified spacecraft easily, moving from small feature to small feature. This allows controllers to plan effective routes that will minimize the time en-route and complexity of maneuver. Operations are conducted at a rate of one arm maneuver per orbit. They are only conducted in daylight to ensure clear situational awareness . Before an arm detaches from the host, a photo from the other arm's navigation camera is used to confirm positive capture. The claws "fail-closed," so that in the event of a loss of power or other emergency RSat remains attached to its host.

2.5.3 Diagnostics

RSat has a variety of diagnostic tools available to it. Its primary diagnostic equipment is its three cameras. These are capable of providing high resolution images of any component of the host spacecraft, at a wide variety of ranges and positions. The two navigation cameras located on the ends of the arm are well suited for "close-in" work, while the center mounted camera is best for wide area investigation.

Additionally, with appropriate modifications to the host spacecraft (a process that would be undertaken prior to launch), RSat can be modified to interface directly with electrical components, and will be able to provide diagnostics similar to plugging the spacecraft back into its ground interface. It will also be capable of supplying logic power, and thereby isolating the affected system to better refine the diagnostics.

2.6 Notional Operation Example of Future Satellite Incorporating RSat

On launch, RSat will be embedded in the spacecraft in the modified P-POD container. Immediately after the spacecraft reaches orbit, or when the host satellite desires, RSat will be deployed. Figure 2 shows a depiction of this deployment concept.

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 grab onto a contact point on the host spacecraft, and await commands from the ground. It will broadcast a periodic message that details its status.

RSat may also be used for periodic inspections to monitor system health 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.

Between these missions, RSat will enter a standby mode and wait for necessity for repair and/or servicing to arise. 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 "spider" its way along the host spacecraft.

Once a failure is detected, the host spacecraft operator will work with the AMODS team to gather diagnostic information. The host will provide AMODS staff with information on what components they would like to have imaged. Based

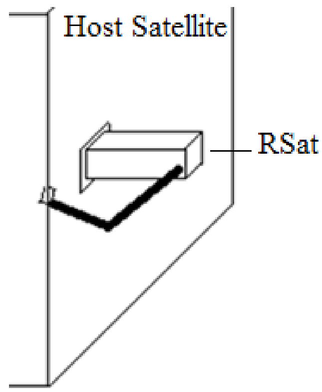

Fig. 2 Sketch of RSat deploying from host spacecraft after launch.

on the AMODS core capabilities, RSat can be commanded to maneuver to the malfunctioning component and capture images of the unit for transmittal to Earth crews.

After reaching the targeted failure location, RSat will perform a detailed analysis of the situation. After the first set of images is shared, the host spacecraft team will provide AMODS with new angles/areas they would like imaged. This process can be repeated and perfected as detail of the failure becomes apparent on Earth. If possible, based on the host's input, an attempt may be made to make repairs. If not, this imaging process can be expanded to areas surrounding the failure to provide a full 3D vision of the incident and the condition of the component.

This data could be used to effectively provision and equip a “full size” repair spacecraft (similar to NASA's Restore-L) with only the appropriate tools and spare parts needed to repair the flaw.

3 Required Capabilities: Constellation (BRICSat)

In the future, RSats can be included in the initial spacecraft design to provide on-orbit diagnostics function to the mission, as described above. However, this architecture does not provide diagnostics capability to the current satellites operating in space. For these satellites requiring on-orbit diagnostics services using RSats, the RSats must be delivered to the host satellite by a third satellite. A ”space tug” or ”shuttle service” is required in order to deliver RSats to host satellites.

3.1 Historical Example: DMSP-F13

In February 2015, a military weather satellite, DMSP-F13 exploded in orbit. Air Force Space Command originally attributed the satellite's demise to old age. Ultimately, it was determined that "a design flaw in the satellites battery charger led to the accident."[11] Six more spacecraft in orbit carry the same battery as DMSP-F13, and could also explode. At present, there is no way to eliminate the risk on the six remaining spacecraft. If a fleet of RSats were available to Air Force Space Command, they could be deployed to each of the remaining six spacecraft with the same faulty battery as the DMSP-F13 and directed to perform specific inspections. Given such access, engineers may even be able to develop a solution to assure that the remaining craft would not explode due to this particular issue.

3.2 AMODS Solution: BRICSat

One solution is to develop a "space tug" that can deliver RSats from a pre-stationing orbit to the host satellite. A group of RSats can be launched into a temporary orbit where the constellation of RSats will await the arrival of a space tug. The tug satellite will then rendezvous with individual RSat and deliver it to the host satellite. The tug satellite will then return to the RSat staging-constellation and repeat the process to deliver each RSat. The tug vehicle would have to connect itself to an RSat and provide all propulsive and navigational requirements to transport the repair unit to the waiting satellite. The vehicle would have to be able to launch with a group of RSats and preserve the cost efficiencies embraced by the small platform modules. In order to increase launch flexibilities and cost-efficiencies, and also to facilitate pairing with the CubeSat-based RSat, the "space tug," (named BRICSat) was determined to utilize the same CubeSat framework.

3.3 BRICSat Platform

The mission of the BRICSat platform is to provide the services needed to rendezvous with and deploy RSat onto an on-orbit host spacecraft, a distributed network of operating spacecraft, or onto an obsolete spacecraft. BRICSat is also a 3U CubeSat. Equipped with its own propulsion system, it is a complement to RSat, and provides the only propulsive force to the RSat platform. BRICSat defrays the cost of expensive attitude control, rendezvous and propulsion systems across multiple RSats, greatly reducing the cost of deploying RSat across an existing constellation.

BRICSat must function as a completely independent spacecraft and be able to provide:

1. *Propulsion*: A combination of long term, sustained ΔV for travel between spacecraft, and quick pulses to allow for proximity operations.
2. *Linkage*: 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.
3. *Attitude Control*: BRICSat must be able to provide Attitude Determination and Control (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.
4. *Navigation*: BRICSat will need both a long range navigation system (GPS), and a short range system (Machine Vision/Light Detection and Ranging (LIDAR)) to handle the final approach to the target spacecraft.

Figure 3 provides a representation of the BRICSat platform.

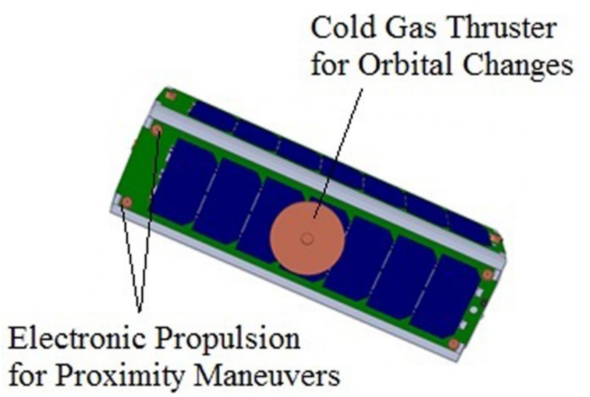

Fig. 3 Solidworks model of BRICSat-T depicting thruster placement.

3.4 Core Capability: Delivery

BRICSat will use machine vision and LIDAR to identify, and prepare a navigational plan to reach the target host. Machine vision will maintain closed-loop control of the microcathode system. It is anticipated that the RSat will grapple on to the client 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 units orientation is not affected. In the meantime, BRICSat will use machine vision and its microcathode thrusters (developed by the George Washington University) 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. After confirmed capture, RSat-1 will disconnect from BRICSat and begin its operational life.[12]

3.4.1 Example Operations Utilizing BRICSat "Space Tug" Concept

A diagnosis mission to already existing on-orbit host spacecraft assumes that an AMODS will be deployed on a large constellation of satellites in similar orbits. The number of repair modules deployed per BRICSat will depend upon the constellation and deployment time constraints. However, to be fiscally sustainable, 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. Figure 4 expresses the cost per RSat transported.

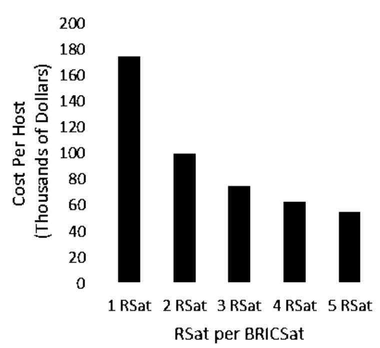

Fig. 4 Graph showing cost per host based on RSats per BRICSat

On-orbit, the RSats will distribute themselves and wait, free-floating in space. Their sole activity is to deploy their arms once detumbling is completed and await rendezvous with a 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 manipulators will be used to move the center of mass fully to BRICSat. This is represented in Figure 5.

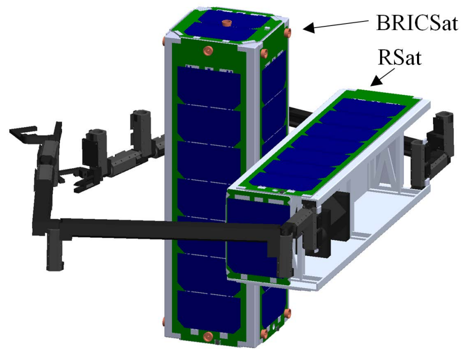

Fig. 5 Rendering of BRICSat-RSat "plus" flight configuration.

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 1 km of the host spacecraft, BRICSat will use a star tracker algorithm to locate and remove all stars allowing BRICSat to deliver RSat to the client satellite. 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.

Figure 6 illustrates the final stages of a rendezvous approach.

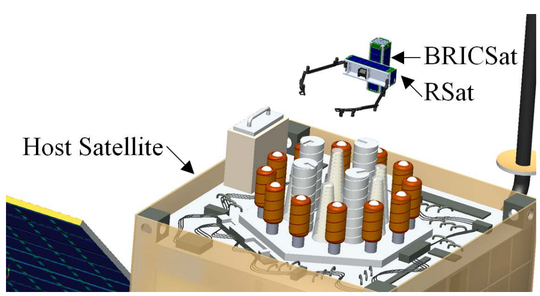

Fig. 6 BRICSat-RSat system on final approach to host spacecraft.

4 Conceptual Applications

AMODS can also be custom-fitted to meet multiple alternative missions, some of which are listed below.

4.1 Electrical Failure

If a component on the host satellite fails to respond, and a visual inspection does not reveal a probable cause, RSat can interface electrically with the failed object and attempt to gather additional data. RSat will be able to interface with the spacecraft bus and provide an opportunity to inject commands directly bypassing failed components in order to isolate and diagnose systems.

4.2 Material Degradation Survey

The best ground modeling may still be insufficient in predicting the effects of the space environment on materials. To reduce this uncertainty, RSat can be tasked with routinely imaging a specific area or component of the spacecraft so that the degradation can be modeled. Data can be gathered over a term of months or years to assist future design development and material upgrades.

4.3 Advance Missions

The AMODS platform can be launched in advance of a larger – and considerably more expensive – salvage or repair mission and provide time saving information that will assure efficiencies of the larger committed deployment. RSat can be tasked with both general and mission specific tasks. AMODS could be deployed as a matter of routine and prepare an on-orbit inventory of parts that can be kept in a database as a resource for future use. Each of these actions would provide considerable information to a salvage or repair mission, allowing the much more costly deployments to be planned with heightened efficiencies of scale and reduced risk contingencies.

4.4 Synergy with Manned Missions

RSat can assist directly in human space exploration by deploying with manned space missions. Launched with a manned vehicle, once on-orbit, RSat can be released immediately to commence imaging and analysis to determine if any systems or materials were compromised during the launch process. If an anomaly is discovered, ground crew can immediately commence amelioration activities. On the International Space Station, or a successor spacecraft, one or multiple RSats can augment human crews by providing constant imaging and diagnostic services, built-in as part of the station's mission. These RSats would be optimized to be commanded by both the ground and astronauts on the station.

5 Mission Status

AMODS is an ambitious project and will take many years of research and development before the full system can become operational. The goal of the Naval Academy's Small Satellite Program is to develop and test key technology enablers in order to advance the required overall capability. Multiple satellites will be developed and launched to demonstrate the key technologies needed to realize the overall AMODS concept. Accordingly, a multi-tiered development approach is taken in developing RSat and BRICSat.

Figure 7 displays the proposed mission timeline for AMODS. The program is proceeding simultaneously on two platforms: the propulsion unit (BRICSat) and the repair unit (RSat). BRICSat will undergo a three stage test program. P: Prototype launched in May 2015; D: Demonstrator is scheduled for launch in September 2017; and T: Tug Validator is expected to launch in early 2018.

RSat will undergo a two stage test program. P: Prototype is targeted for launch in early 2017; and -D: the Demonstrator is expected to launch with BRICSat-T in late 2017 or early 2018. A concept validator that focuses on the coupling and transport systems, the Modified BRICSat-RSat Space Experiment (MBSE), will launch in late 2017 or early 2018, and the entire AMODS program itself will be validated with the combined BRICSat-T RSat-D launch also in late 2017 or early 2018.

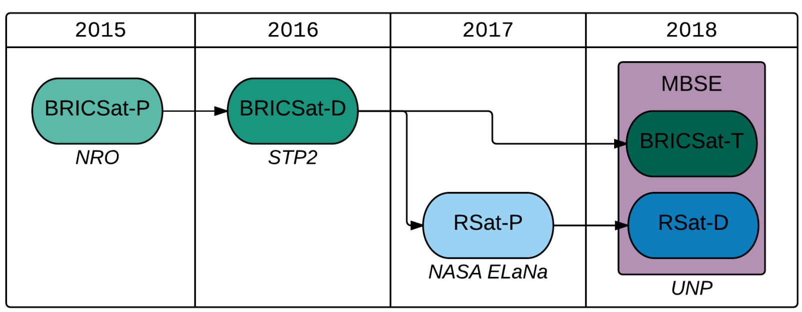

Fig. 7 Timeline showing AMODS launches and launch providers, which include the United States Department of Defense Space Test Program (STP2), NASA's Educational Launch of Nanosatellites (ELaNa) and the University Nanosat Program (UNP).

5.1 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 (10x10x16 cm) spacecraft with four Micro-Cathode Arc Thrusters (μcat). Its propulsion system was designed by The George Washington University. A depiction of the propulsion systems thruster head is shown in Figure 8.

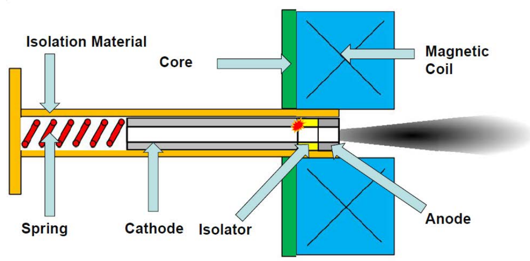

Fig. 8 George Washington University μcat thruster head.[13]

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 1 W each, and can last for 10 years, depending on the size of the propellant rod [14]. The thrusters are compact; 10 mm in diameter and 23 mm 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.

5.2 BRICSat-D Demonstrator – Launch September 2017

BRICSat-D is the evolution of the BRICSat genus. The BRICSat-D mission, scheduled for launch in September 2017, will conduct three primary flight experiments:

1. *Rotation*: The rotational experiment uses the thrusters to rotate the spacecraft up to 6 rpm, which will evaluate the thrusters performance against known quantities.
2. *Micro-stepping/Delta V*: BRICSat-D will use its thrusters to change its orbit in a controlled manner.

3. *Motor Qualification*: A motor identical to those intended for RSat's arm will be embedded inside BRICSat-D to conduct in-situ motor qualification testing.

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 Micro-Cathode thrusters are capable of providing consistent, effective translational movement – as required for rendezvous and docking operations. Thus, BRICSat-D will launch with a sophisticated inertial measuring unit that is tuned to examine translational movement, and with improved flight software optimized for translational mission.

Finally, BRICSat-D will also commence capability validation of the motor for RSat arms. More than 250 compact motors were examined, ranging from linear actuators to servos, and samples of several types were lab tested for accuracy. These tests focused on long term precision; the motors were commanded to rotate to a certain point, then on to another point, then back to the initial point. The magnitude of these rotations varied throughout the test course to examine both large and small movements. Many of the movements were designed to be similar to the expected orbital operations. The motors were evaluated both on the intermediate positions and the final ending location.

After minimizing motor diameter and motor length for the given accuracy, and specifying the need for zero backlash, only one motor met the AMODS requirements: A 10 mm diameter, 40 mm long stepper/encoder/gearhead combination. This motor is available with a vacuum safe lubricant, which simplifies the assembly process. This motor will evaluated through a series of diagnostic tests throughout the six-month BRICSat-D mission.

5.3 RSat-P Test Vehicle – Launch 2017

The first RSat launch (early 2017) will fly a mission similar to a typical CubeSat and will float freely in space. The mission is designed as a project demonstration 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.

5.3.1 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.

Resilience:

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 (Arm 1 and Arm 2) 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 ($\sim$\$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.

Command and Data Handling:

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 to assume most of another processors' functionality.

Communications:

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.

Electrical Power System (EPS):

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 for 200% of max current draw, allowing a single component to drive both arms. No single component exists in the EPS that could cause complete spacecraft failure.

Attitude Control System:

While RSat does not require pointing capability, it is required to detumble to a rotation rate of less than 1°/s, both to operate the arms and allow for rendezvous with BRICSat. To facilitate this, RSat will use a passive magnetic hysteresis system that favors the hysteresis material over a permanent magnet.

5.3.2 RSat Robotic Systems

The robotics subsystem is the primary facet of interest on RSat. In designing RSat's robotic manipulators, it was important to establish 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. Figure 9 shows the arms mounted inside the modified frame.

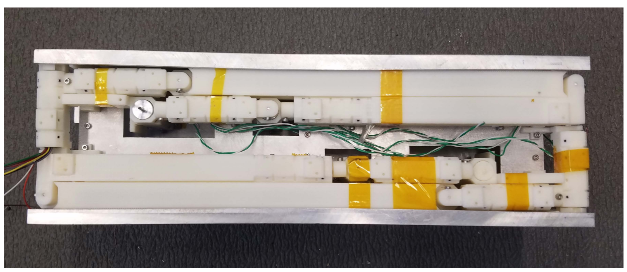

Fig. 9 RSat arms inside of engineering model of frame during initial fit check.

Robotics Porch:

In order to maximize the length of the arms, some deviations from the traditional CubeSat frame were required. A front porch design was adapted, which removes one face of the Cube, while maintaining the rails, to allow the arms to rotate outward. RSats robotics bay is shown in Figure 10.

Arm Design:

In designing RSat's robotic arms, great emphasis was given to establishing as standard a profile as possible while emphasizing speed and functionality.

Extensive observation and research of satellites currently or soon-to-be deployed on-orbit determined that a typical payload faring is approximately 5 m in diameter and 13 m in length. This results in a total of 18 m of traversable area. RSat is ex-

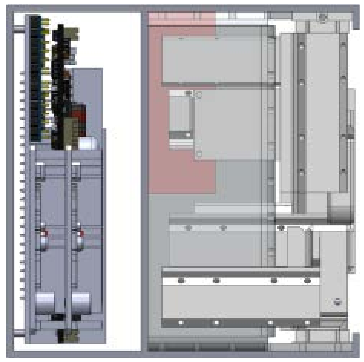

Fig. 10 Cross section of RSat spacecraft showing A-frame and front ”porch” design.

pected to be able to execute one operation per orbit. Its goal is to be able to reach any problem site within 24 hr. Thus, building arms of 1.5 m in length allows RSat to completely circumnavigate an entire typical spacecraft in 12 arm movements or 12 orbits. Ultimately, the system must be accurate to within 10 mm at full extension. This equates to $\pm 0.25\,^{\circ}$ 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.

Claw Design:

Claw development was also based on extensive research and observation of the typical size of objects, or contact points. RSat will be able to grasp as it moves around a host satellite. Four typical grappling locations have been identified:

1. Round truss member up to 25 mm in diameter.
2. Thin planes (radiator, solar panels, etc.) down to 5 mm thick.
3. Protruding antennae (minimum 10 mm in diameter).
4. Plugs, fixtures and other small outcroppings minimum of 10 mm by 20 mm.

The plugs and outcroppings described in 4 above provide the smallest requirement. Thus, RSat must be able to position its arm within $\pm$ 10 mm. Over the entire length of the 1.5 m arm, that requires joint accuracy of approximately $0.25\,^{\circ}$. In addition, each claw will house a laser beam between the two claw components. When obstruction is detected between the components, the claw will close. This allows the manipulator to automatically dock with the spacecraft as soon as it is sufficiently close. Arms will be mounted directly to the shaft of the motor simplifying the assembly process. This will allow for easy replacement and reduce friction points. Moreover, each segment has its own microcontroller capable of independent operation. Thus, one motor failure will not cripple the spacecraft.

Arm Layout:

The porch allows each arm to utilize the full length of the spacecraft, maximizing the overall length of each arm. A bi-fold design was selected to allow a maximum arm span of 1.5 m. To ease construction and simplify the overall design, the motor unit directly drives the arms. This is primarily possible due to the gearhead built into the motors. It also allows for near complete modularity.

Arm Material:

In order to maximize space and design efficiency, the arms are developed and constructed using rapid prototyping technology. This allows for additional fast printing of parts for vibration and vacuum testing, as well as for intricate shapes to mitigate some of these effects. The arms are required to be able to withstand launch forces and must be carefully and exactly secured until deployment. Such exactness in turn requires complex geometries as optimal storage security is tested. The arms and claws will be 3D printed. RSat is currently considering a space-rated 3D plastic and manufactured using selective laser sintering (SLS). This material has flight heritage, while the SLS process provides the high accuracy needed for the components.

Arm Restraints:

One of the biggest challenges was determining how to restrain the arms so that they survive vibration testing and launch. A system of has been developed to reduce undesirable motions of the arms. A burn-wire system was also implemented to fasten the arms to the supports. Wedges allow for manufacturing inconsistencies and are tolerant of geometric variation. Wedge receptors will be 3D printed with the same material as the arms so thermal coefficients will be the same, allowing for concurrent expansion.

Tests of the design iterations were performed using a vibration table. The wedge system has been qualified pursuant to the NASA GSFC-STD-7000A Generalized Random Vibration Test.[15] This test is based on the worst case launch vehicle configurations, and is generally accepted as a comprehensive test.

Four successive iterations of the arm design were subjected to the NASA test levels. After each trial (and therefore any possible damage), a sine sweep was run to determine the resonant frequencies of the arm. Peaks should be as low as possible, and occur at the highest possible frequencies. For flight testing, vibration testing is a pass fail evolution, based on the following criteria:

1. Arm passes auditory inspection (no unusual sounds during testing).
2. Arm passes visual inspection (no broken hardware or loosened bolts).
3. All shifts in modes less than 20% in amplitude and 10% in frequency.
4. First fundamental frequency above 100 Hz.

The results of Vibration Test 1 (VT1) is shown in Figure 11. The first resonance is at 100 Hz indicating that the fundamental frequency is very close to the prescribed lower limit. During the test, the arm broke free from its securing mechanism. As a result, this test was classified as a failure. The AMODS team determined 12 different modifications to implement prior to VT2, primarily focused on the horizontal restraints.

Vibration Test 2, the results of which are shown in Figure 12, emphatically demonstrated that it is possible to build an arm of this basic design to withstand launch forces. Note the substantially higher fundamental frequency, with lower overall peaks. The arm came close to passing the visual inspection, however one area had particularly high stress concentrations and showed signs of fatigue. Additionally, the VT2 arm took over eight man-hours to construct, and would not have been possible in the confines of the RSat frame in proximity with another arm. 14 areas of improvement were noted, and the design was refined for Vibration Test 3 (VT3).

Vibration Test 3, the results of which are shown in Figure 13 attempted to reduce the complexity and assembly requirements. The result, as indicated by the sine sweep created an arm that had a lower fundamental frequency and larger peak amplitudes. In the random vibration test, the arm again broke free of its housing, signifying a severe step backwards from VT2. As a result, the restraint concept was modified to minimize long cable runs and further maximize structural rigidity.

Vibration Test 4 increased assembly time to 11 man-hours, but this assembly is possible inside the confines of the spacecraft. It produced a satisfactory test result, as shown in Figure 14. The fundamental frequency is very close to VT2, and while the peak amplitudes are high, the arm passed both visual and auditory inspection after the test. This test conclusively demonstrated that the arm is vibration qualified.

The next steps following this successful test is a deployment demonstration. Accurate wiring harnesses and actual motors will be used to affirm that stresses are within limits. The final arm design will be characterized to determine range of motion and capability.

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*: The purpose of the coordinate test is 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. This is shown in Figure 15.
2. *Handshake*: The “Handshake” maneuver will demonstrate that RSat is capable of operating the arms in proximity to each other, as shown in Figure 16. This is a key requirement in any potential imaging/servicing missions.
3. *Imaging*: The “Imaging” portion of the demonstration phase establishes 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. Figure 17 shows RSat imaging its +X face.
4. *Manipulation*: This mode simulates the use of the manipulators to interact with another spacecraft. Arm 1 will pick up a demonstration object from one of the

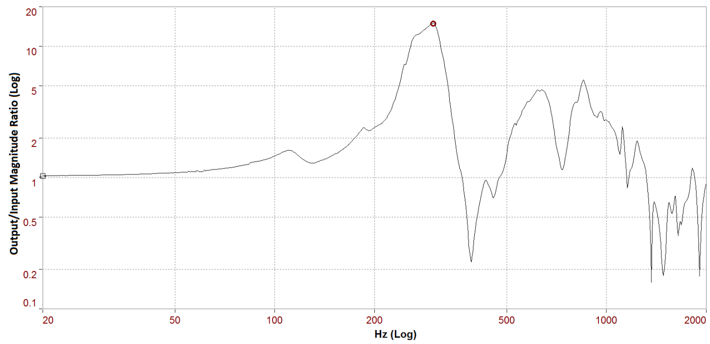

Fig. 11 RSat Arm Vibration Test #1 X-Axis Sine Sweep, September 2015.

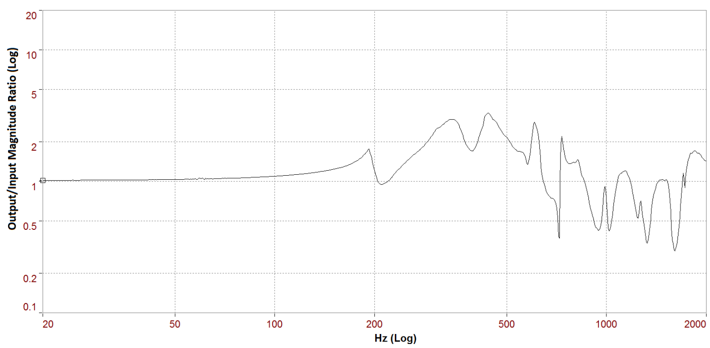

Fig. 12 RSat Arm Vibration Test #2 X-Axis Sine Sweep, October 2015.

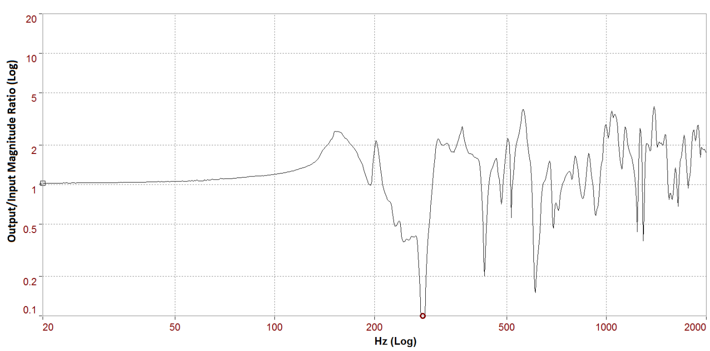

Fig. 13 RSat Arm Vibration Test #3 X-Axis Sine Sweep, November 2015.

Fig. 14 RSat Arm Vibration Test #4 X-Axis Sine Sweep, January 2016.

ends of the spacecraft, and move it to within camera range. Arm 2 will then take control of the object. This validates the manipulator design, and demonstrates the precision of the arm. Figure 18 and shows the manipulation movement of the RSat's arms.

5.4 BRICSat-T Tug Validator – Launch 2018

As RSat development moves forward, the lessons learned will be incorporated into BRICSat-T from the previous two BRICSat flights to create a fully operational "space tug." After launch, targeted for early 2018, it will conduct simulated rendezvous and proximity operations to confirm core functionality.

5.4.1 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 30 mm across and the standard RSat claw will have an open-span of 50 mm, there is a $\pm$20 mm tolerance for the propulsion system on final docking operations.

BRICSat-P tests confirm that the μCat system is extremely precise and accurate while the thrust generated is too small for significant ΔV maneuvers. However, although the μCat system adequately executed orbital changes, analysis suggests the time-frame 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 conventional 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 host spacecraft utilizes approximately twice the thrust of the return trip, 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 capability is limited by the performance 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 Medium-Earth Orbit 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. The AMODS team will deploy a hybrid propulsion scheme by

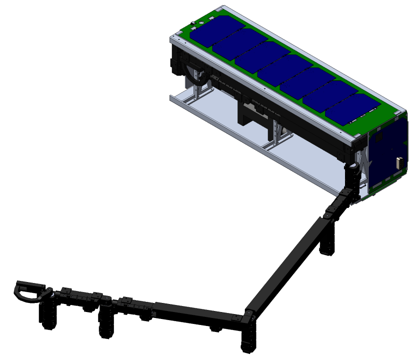

Fig. 15 RSat's arm navigating to a coordinate to demonstrate arm accuracy.

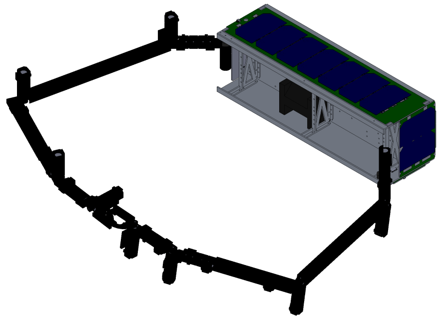

Fig. 16 RSat's arms handshake to demonstrate interoperability.

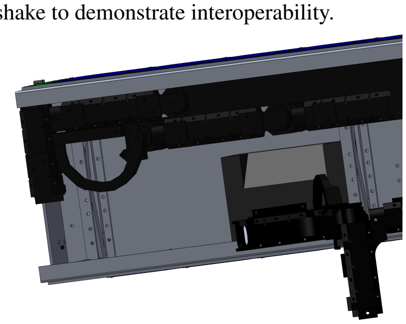

Fig. 17 RSat's arm using the navigation camera to image the +X face to validating imaging capability.

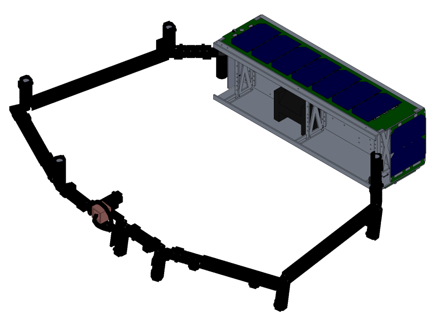

Fig. 18 RSat's arms pick up the demonstration object.

integrating the μcat and cold gas thrusters in one propulsion system. This integrated system 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 of the satellite – for a total of 14 thrusters – allowing for easy on-axis translations. It will have just one cold gas thruster reserved for orbit-change maneuvers.

5.4.2 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 link the spacecraft and also allow for them to share power. During docked operations, BRICSat-T will control RSat's components via a serial connection.

5.4.3 Attitude Control

As noted above, the docking process requires ± 20 mm relative position 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. Accordingly, 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 motors expected torque. Thus, the counter-acting arm must reduce the torque input movement of the mission arm by a factor of four. 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.

5.4.4 Navigation

BRICSat-T will employ a star tracker, a long range navigation system (GPS) and machine vision 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 Micro-Cathode 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.

5.5 AMODS Technology Demonstrator

The current plan for subsequent development is for BRICSat-T and RSat-1, -2, and -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 the two spacecraft will be placed in 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 navigate to RSat-3 and deliver 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.

6 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 activities. The AMODS project is intended to 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 2017 launch and an integrated RSat-BRICSat AMODS Technology demonstrator is anticipated to take place in early 2018. Fundamentally, the system has the potential to demonstrate an inexpensive, reliable repair system that can be placed on any spacecraft. This technology has the potential to transform space operations, extending the life of spacecraft and greatly increase the efficiency and effectiveness of humans in space.

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