SSC16-WK-42

RSat Flight Qualification and Test Results for Manipulable Robotic Appendages Installed on 3U CubeSat Platform

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ABSTRACT

The United States Naval Academy (USNA) is developing a system utilizing two 3U Cube Satellites to deliver diagnostic and basic repair services to on-orbit spacecraft. The Autonomous On-orbit Diagnostic System (AMODS) is comprised of 1) a CubeSat with robotic arms (RSat) with the ability to maneuver around a satellite providing images and other diagnostic information to ground-based engineers; and 2) the BRICSat spacecraft which acts as a "space tug" for RSat and houses the attitude control systems and maneuvering thrusters. Both RSat and BRICSat offer new technologies bringing tremendous flexibility and innovative opportunity to the CubeSat platform while providing cost-effective diagnostic services to on-orbit spacecraft. This paper focuses on the RSat platform, outlining the basic structure of the robotic arms and the concept of operations for the late 2017 launch of RSat-P (prototype) through the NASA Launch Initiative. The paper continues with a discussion of the results of ground tests validating the robotic arm mechanism and the RSat motors. The paper concludes with a description of the on-orbit test of the arms' motors schedule for early 2017.

INTRODUCTION AND PURPOSE

A third of commercial spacecraft failures are attributable to solar array wiring or deployment failure.[1] When deployable structures fail, the utility of a satellite can become severely limited. Such an anomaly may be relatively small and easy to find if the satellite were on the ground; anomalies discovered on orbit can be costly or impossible to diagnose.

In a world dependent on high speed communications, satellites are an increasingly critical component of global infrastructure and day to day life. Maintaining these critical space assets is paramount.

Solution

The United States Naval Academy is developing the Autonomous On-orbit Diagnostic System (AMODS) which is a combination of two separate spacecraft: one spacecraft with a set of robotic arms which have the capability to perform on-orbit diagnostics (RSat) and a second satellite that includes propulsion and attitude control (BRICSat).

As envisioned, RSat would be embedded in its host spacecraft on launch. Once on-orbit, RSat would deploy and utilize its robotic arms to "crawl" around a failed spacecraft to diagnose anomalies.

If the failed spacecraft did not initially have an RSat embedded with it, the BRICSat spacecraft could deliver one to it. The two CubeSat's would work in tandem to fulfill two separate mission sets. RSat delivers the capability to attach to a host satellite, take photographs in order to diagnose failures, and potentially make basic repairs to a system while BRICSat serves as a "space tug." This division allows for the production and launch of multiple lower costs RSats which are spread out across a constellation and are ferried around to various spacecraft by a single higher cost BRICSat. This lowers the cost and increases the efficiency of the AMODS solution.

Past Examples and Current Solutions.

On April 24, 2011 Intelsat launched the Intelsat 28 satellite. The satellite was built for the Intelsat and Convergence Partners and carried 16 Ku- and 14 C-band active transponders for voice wireless backhaul, internet, and media applications services.[2] It was placed into geostationary orbit by the European Ariane 5 ECA rocket and its primary purpose was to serve an African audience.[3]

Initially the satellite was unable to deploy its C-band antenna. This was due to a malfunction in the spring-loaded deployment system. The malfunction was eventually traced back to a billowing sun shield, originally intended to shield the satellite from the extreme temperatures, which became caught in the deployment system trapping the antenna.[4]

The same problem then occurred in the deployment of the Ku-band antenna. The Ku-band's attempted deployment occurred approximately one month after the

C-band failed to deploy. Its deployment mechanism also became stuck in the sun shield.

As a solution to the deployment problem, the ground teams maneuvered the satellite in a movement nicknamed "rock n' roll" using the ADCS system in order to shake loose the sun shield.[3] They succeeded in deploying the Ku-band antenna but only after two months of work. The C-band antenna did not deploy in response to the maneuvering and was never fixed.[4]

The Intelsat 28 satellite was valued at $250 million for the joint Washington – Luxembourg Intelsat and Convergence partners of South Africa. Ultimately, while the spacecraft was not a total failure due to the eventual deployment of the Ku-band antenna, the company lost $310.2 million by having to remove from its contracted backlog the users of the C-band capacity. The satellite was also intended to replace the aging Galaxy 11 satellite, without this replacement Intelsat will have to launch another satellite in order to continue operations.[3]

The AMODS program aims to aid in correcting anomalies such as this by providing the capacity to diagnose these small-scale-large-impact failures. By providing photos from multiple angles, which is a unique capability of RSat, flight controllers could have better planned the "unsticking" operation.

Currently, such diagnostic work is being developed by the Robotic Servicing of Geosynchronous Satellites (RSGS) program which is a project from the Defense Advanced Research Projects Agency (DARPA). This program's aim is to create an on-orbit servicing vehicle to perform operations in Geosynchronous Earth Orbit (GEO). Similarly to AMODS, the program has a component named The Front-end Robotics Enabling Near-term Demonstration (FREND) which is a robotic arm that performs autonomous maneuvers to rendezvous using a common adapter ring.[5] Because of its involved mission and capabilities this system's cost is roughly three orders of magnitude larger in cost than the RSat system. RGRS aims to complete exceptionally complex repairs and completing these repairs requires an exceptionally complex spacecraft to match. RSat is primarily intended to diagnose spacecraft and that difference in missions allows RSat to produced at a lower cost spacecraft.

PROJECT TIMELINE

The AMODS program is a multistep program with various iterations of spacecraft in order to build up to the eventual integrated mission. Figure 1 shows a graphical representation of the program timeline. There are two classes of satellite that are produced for AMODS and although they have two different mission objectives,

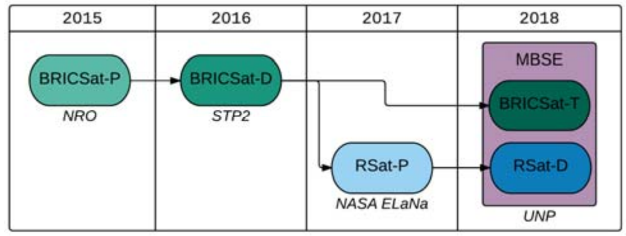

Figure 1: AMODS Program Timeline

RSat and BRICSat are developed concurrently to build towards the mission where the spacecraft are flown together.

BRICSat, with propulsive capability to serve as a "space tug" for RSat, launched the first spacecraft, the P (prototype) variant, in 2015 and is launching the D (demonstrator) in September 2016. The T (tug) spacecraft is expected to launch in early 2018.

RSat development is broken into two stages: the P spacecraft is expected to launch in early 2017 and the D satellite will launch with BRICSat-T in 2018.

The combined mission with BRICSat-T and RSat-D is called The Modified BRICSat-RSat Space Experiment (MBSE). The spaceflight's primary mission is to validate the overall AMODS concept. During this flight the two separate systems will be launched together and then separate before rendezvousing and conducting test operations.

This paper focuses on the development of the RSat-P mission which is the first validation of the arms in space before the MBSE flight.

RSat SYSTEM OVERVIEW

The mission of RSat is to demonstrate the feasibility of using a CubeSat for on-orbit diagnostics and servicing missions through the employment of capabilities afforded by robotic manipulators. RSat is a 3U (10 x 10 x 33 cm) cube satellite with two 60 cm, seven-degree-of-freedom robotic arms as seen in Figure 2.

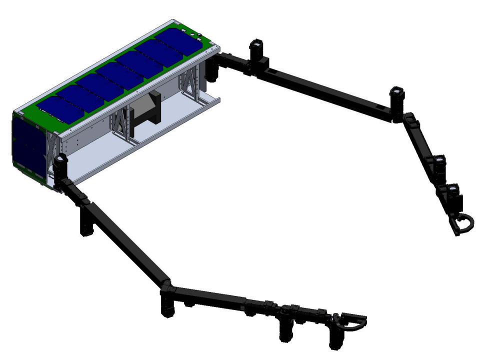

Figure 2: RSat System Overview

The robotic arms allow RSat to access and maneuver about any external surface on a host spacecraft without causing harm to the host. In order to ensure this capability, RSat is equipped with an array of sensors, including a camera to diagnose any failures while on orbit and potentially perform minor on-orbit repairs or maintenance.

The space environment simplifies robotic operations. In zero-gravity, any torque output will allow RSat's arms to move components or maneuver the spacecraft over time which allows for the arm design to focus on maximizing length, dexterity, and accuracy rather than strength. Basing the arm's design on less powerful but more accurate motors has also enabled the design of a fully capable robotic arm system scaled down to fit within the CubeSat form factor.

The custom frame of the RSat spacecraft allow the robotic arms to reach a 1.5 m arm span making RSat capable of maneuvering across the average satellite in less than 12 maneuvers. The accuracy of RSat's joint actuators afford an overall end effector positional accuracy of ±10 mm at full extension.

DESIGN OF RSat-P

RSat-P is the first prototype of the RSat system and includes some unique design consideration due to its mission and the constraints of the CubeSat platform.

Robotics Porch

In order for the arms to be able to extend and perform diagnostic work, the CubeSat layout was altered such that one side panel was completely removed. This is called the "front porch" design which maintains the rails required by the CubeSat standard, while at the same time allowing the arms the freedom to move.

Arm Design

The arms were designed with the intention of being able to have the right length in order to perform efficient, fast diagnostic work. An average large communication satellite is 13 m by 5 m for a total traversable surface of 18 m. In order to be able to service that entire area the arms were constructed to be 1.5 m in overall length. This allows the arms, operating at one movement per orbit due to power constraints and move around an average satellite in 12 orbits.

The arms must be able to "do no harm" to a host satellite and therefor movement must be smooth and accurate. The arms were also designed to be accurate to 10 mm at full extension. This breaks down to a range of accuracy of ±0.25° at each motor joint. The shaft of the motor is mounted directly to the arm to allow for a reduction in friction points and easy replacement. Each motor has its own microcontroller in order to keep the failure of one motor from crippling the entire system.

RSat has three cameras in order to perform diagnostic work. One is located in the center of the spacecraft and the other two are located on the end of each arm as seen in Figure 3.

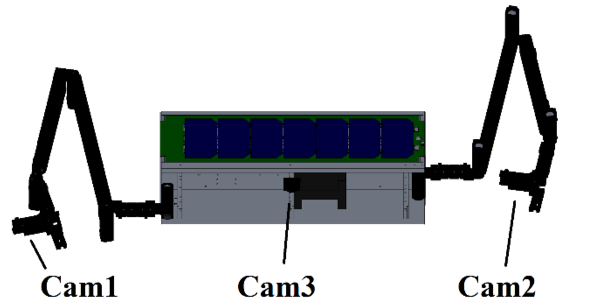

Figure 3: RSat Camera Positioning

End-effector Design

The end-effector ("claw") allows RSat to latch onto and maneuver around the failed spacecraft. The claw was designed based on the shape of various objects on a spacecraft that it would be required to grab onto. These objects include: round trusses less than 25 mm in diameter, thin planes, protruding antennae, and other small outcroppings.

Each claw has a laser beam positioned between each of the two separate components of the claw. The laser is used to detect if there is an obstruction between both pieces and will use that as a signal to close the claw. This means that the claw will automatically attach to the host spacecraft (Figure 4) without a command from the ground.

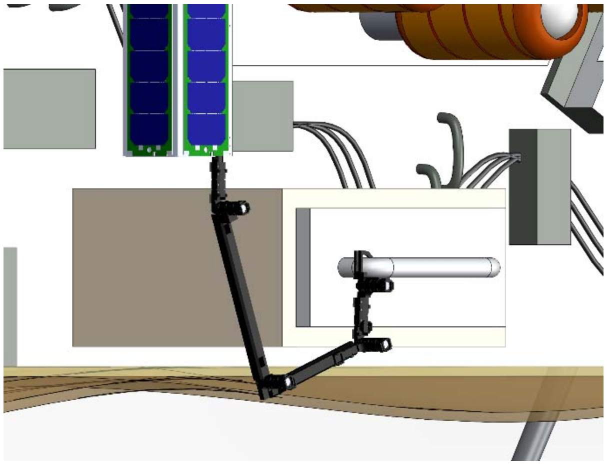

Figure 4: RSat Attached to a Host Satellite

Arm Layout

The porch design means that the space in the satellite is most effectively laid out, as shown in Figure 5. In order to achieve the largest wingspan a bi-fold design was used to store the motors for launch. There is space behind the arms that is used to house power and communications equipment so as to effectively use the void space behind the arms.

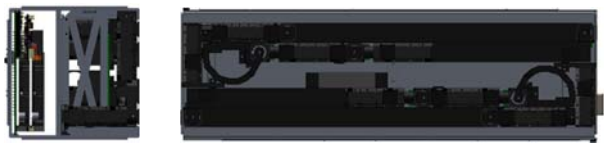

Figure 5: RSat Side and Front View

Arm Material

The arms were developed using additive manufacturing technology. This allowed for an increased number of design iterations based on numerous physical tests conducted in development of the spacecraft. The arms and claws are 3D printed of space-rated carbon fiber particle reinforced composite material and manufactured using Selective Laser Sintering (SLS). This technique provides high accuracy for the parts being printed and has extensive space flight heritage.

Arm Restraints

Restraining the arms during launch is a difficult task because the arms have to be able to both withstand launch forces in excess of 22 G_{RMS}, depending on the launch vehicle, while maintaining the ability to quickly and reliably deploy on-orbit. RSat uses wedges which reduce the possible movement of the arms during vibration to one axis. To prevent movement in this last axis, a burn wire system was developed in order to hold the arms in place for launch. Once the arms are safe to be deployed, resistors are used to burn the wire holding the arms in place in order to release the arms.

COMMAND AND DATA HANDLING

The software used for RSat is based on a redundant system in order to ensure that a failure at any one point does not result in a complete system failure which is laid out in Figure 6. The system is made up of three Arduino Pro Minis designated Mini 1, 2, and 3 for this project. Mini 1 and Mini 2 control the higher level operations of each arm and receive commands sent directly from the ground. Mini 3 controls the central camera with input from the ground.

Mini A is a redundant system in order to be able to continue operations in the event of an RX (radio receive) failure. Mini A is preloaded with a database of commands so that if the arms do not hear from the ground for two weeks it will send commands to the arms and camera without ground input.

The system is set up with multi-drop serial in order to be able to use the same TX (ratio transmit) and RX lines to communicate with Mini 1, 2, and 3. This allows for direct communication with any of the main processors from the ground.

Mini 1 and Mini 2 communicate with each individual motor and motor control unit. The Pro Minis will send step commands to each motor which will be executed by the stepper motor driver boards. Each Pro Mini is connected to an SD card which backs up data so that it can be retrieved later in the event of a power failure or a system reset.

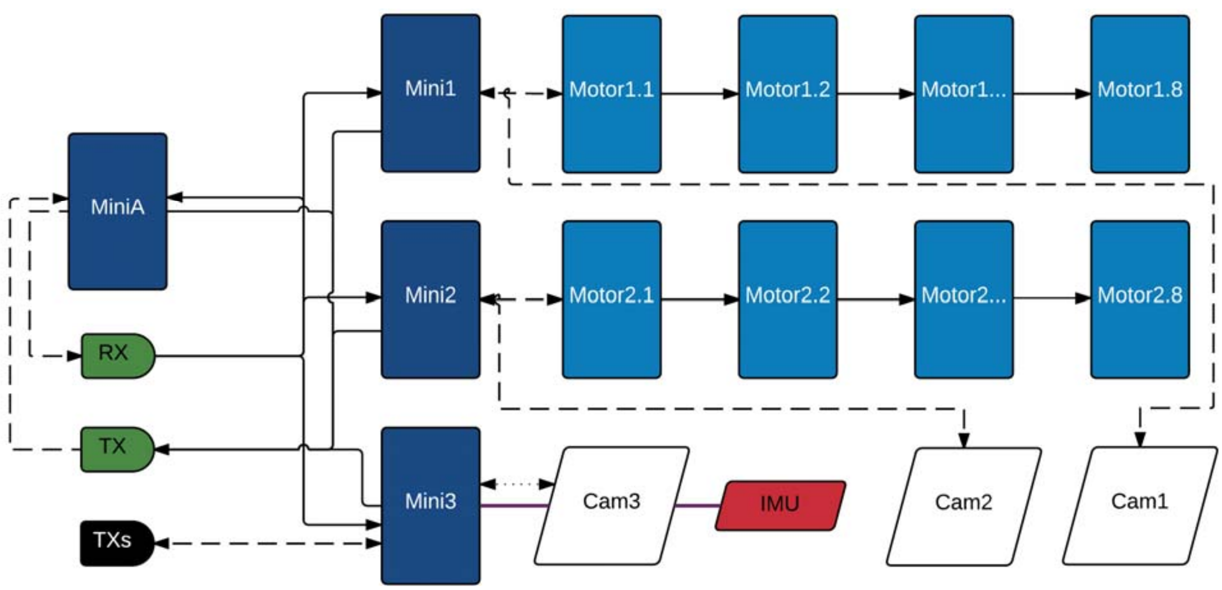

Figure 6: RSat C&DH Overview

At each arm joint is a custom built microprocessor optimized for the small size of the arm controller board; it is labeled by which arm it is on and which joint it controls. It receives the motor commands from Mini 1 or 2. It then sends the number to steps and direction to the A3967 motor driver. The motor driver executes the step count. The encoder in the stepper motor records each step and sends that information to the LS7366R encoder counter which reports the actual step count for the complete movement back to the microprocessor once the motor has finished moving. These operations are shown in Figure 7.

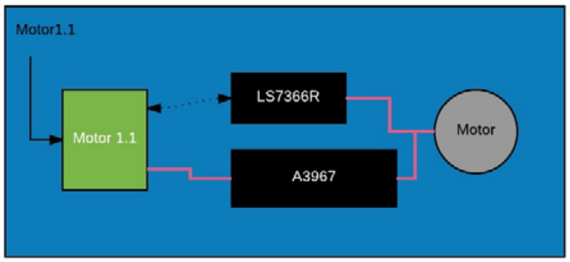

Figure 7: Stepper Motor Control

CONCEPT OF OPERATIONS: RSat-P

The purpose of the RSat-P flight is to demonstrate the maneuverability, diagnostic capabilities, and safety of the spacecraft. The concept of operations for the spaceflight was designed around demonstrating those three criteria.

Initial Movement Tests: These tests include the initial deployment of the arm to full extension and the movement of each motor at each joint in order to observe basic maneuvers in space. These movements are preprogrammed and set to execute once a "go" signal is received from the ground station. (Figure 8)

Coordinate Maneuverability: Following the initial motor tests the arms will be tested in their ability to maneuver to a specific coordinate. This test will be conducted with directions from the ground station. The ground will send a command to begin the coordinate maneuvers as well as a coordinate the arm is to navigate to. The positional accuracy of the arms will be based on images taken by the cameras of the arms in their end position. (Figure 9)

Handshake Operations: These movements involve the movement of both arms to a central coordinate and perform a robot "handshake." This demonstrates the arms ability to move to a specific spot and for each arm to be safe to maneuver in close proximity to one another. (Figure 10)

Object Maneuver: The maneuver test follows the handshake as the next level of operating complexity. Beyond simple moving to a central coordinate one arm will exchange an object with the other in order to demonstrate the accuracy of the arms and their ability to perform advanced maneuvers. (Figure 11)

Diagnostic Imaging: Throughout the arm movements the three cameras will be taking photographs in order to observe and collect data from the arm tests as well as to test the ability of the cameras themselves.

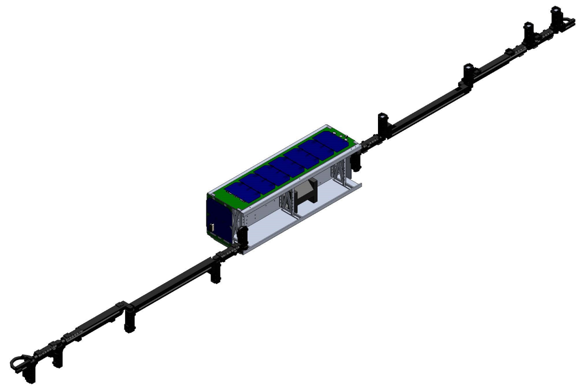

Figure 8: Initial Movement

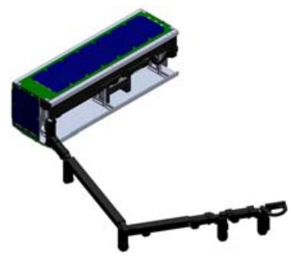

Figure 9: Coordinate Maneuverability

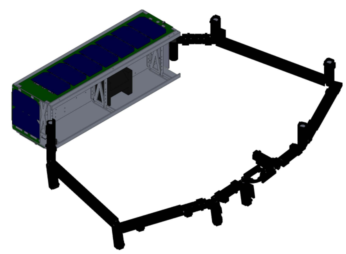

Figure 10: Handshake Operations

Figure 11: Object Maneuver

GROUND TESTING RESULTS

Various components of the RSat system have been tested in USNA facilities on the ground. By accounting for the space environment as well as the required accuracy of the arm before flight, the program increases the chances for a successful flight of the spacecraft.

Thermal Testing

It is crucial that the motors be able to operate in the space environment. One aspect of that environment is the increase in temperature due to the movement of the arm. A lack of convective cooling and limited convective cooling in space and a reliance on radiative cooling limits the thermal performance of the motor which has a maximum operating temperature of 70 °C. A vacuum test was conducted because in order to effectively accomplish its mission, RSat must be able to operate each motor for up to 10 minutes at a time.

In order to test the motor's movement in this environment a heating curve was measured. The motor was run continuously in a vacuum for 14 minutes and the increase in temperature was measured using thermistors. The resulting plot is shown in Figure 12.

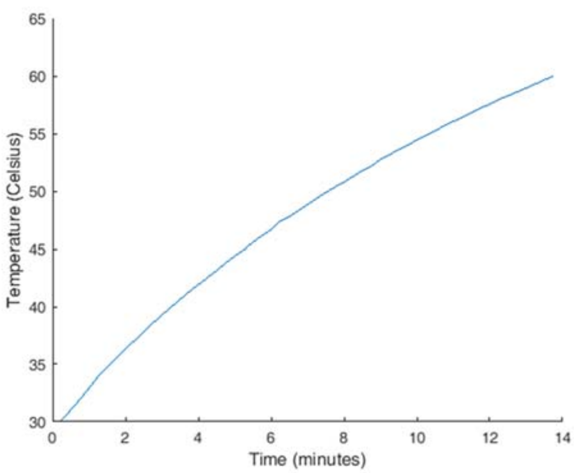

Figure 12: Temperature Curve of a Continuously Operating Motor in Vacuum

The results demonstrate that the motor can run continuously for more than ten minutes. Over that period of time the motor conducted the equivalent of 20 arm maneuvers which is well over the requirement. The arms will perform only two arm movements per orbit. In addition to that the average arm maneuver also takes less than 30 seconds, changing the arm temperature by at most 2 degrees Celsius. The arm will spend the rest of the orbit at rest, allowing the motor to passively cool. Since this test demonstrated that temperature of the motor is less of a concern while on orbit it is not necessary to include thermistors at each motor on the arm in order to monitor the temperature of the motors while conducting maneuvers.

Motor Accuracy Testing

One of the most important tests conducted on the motors was the test for the accuracy of the motor. This fulfils the design requirement that the accuracy of the arm at full extension is ±10 mm. That requirement exists so that the RSat arms will "do no harm" to a host satellite. The Faulhaber AM1020 Stepper Motor used in the arms needed to be capable of maneuvering within that required accuracy so as to guarantee the safety of the failed satellite.

The test was setup such that the motor received step commands from the microcontroller which simulates communications from the ground controller. Commands were sent in units of steps for the motor to execute. 100 steps is approximately 13 degrees. The step commands were in 100 step increments from 100 to 900 steps. The motor was first commanded to step in a clockwise direction then followed by a counterclockwise direction. The clockwise direction was considered positive degree values and the counterclockwise direction was negative degree values. Multiple tests were run in order to produce the averages shown in Figures 13 and 14.

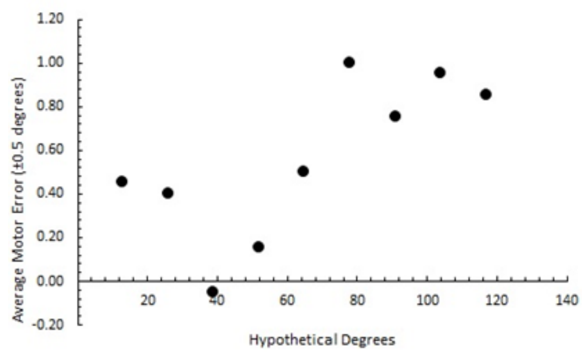

Figure 13: Positive Direction

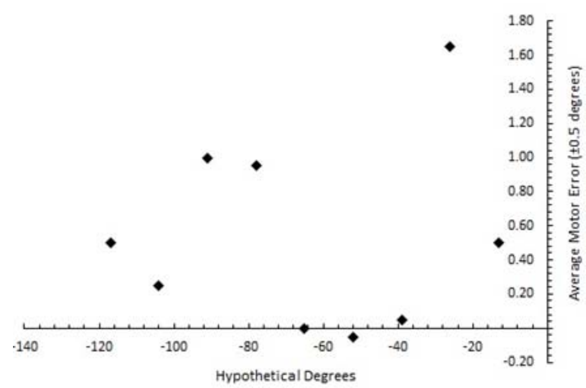

Figure 14: Negative Direction

The reason that error arises in the movement of stepper motors is due to an occasional irregularity in the actual number of steps the motor executes versus the number of input steps the motor was given. As the motor does not provide feedback to the motor driver, it is possible for the motor to miss a step (under stepping) or take an extra step (overstepping) without registering it. The results show that the motor, at most angles, does not exceed an error of ±1°. By demonstrating that motor accuracy is high the program can verify and begin the process of demonstrating the safety of operating the RSat system in proximity with other spacecraft.

The main solution to this problem was to create the closed loop motor control system which receives motor step outputs and the actual steps taken as measured by the encoder. The system can then correct so as to ensure that the motor is not over or under stepping. By adding this layer of protection RSat is even safer for use in proximity with other spacecraft.

Vibration Testing

In order to stimulate the environment of a launch the RSat spacecraft underwent vibration testing to demonstrate that it can survive the launch environment. Figure 15 is a picture of the setup of the RSat arm hardware on the vibration table.

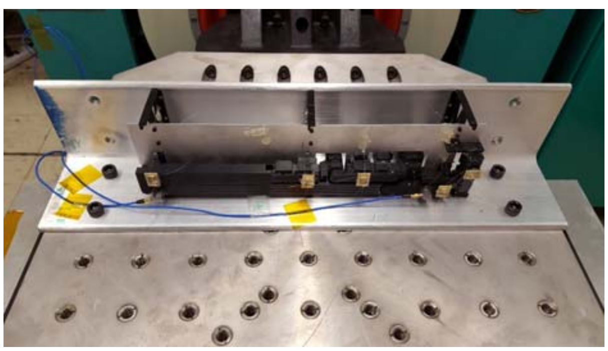

Figure 15: RSat's Robotic Arm on Vibration Table

Four prototypes of the arm were tested on the vibration table in order to identify structural weaknesses. The structure was subjected to the test profile provided in NASA GSFC-STD-7000A Generalized Random Vibration Test. A low-level sine sweep was performed before and after each random vibration test in order to characterize any changes in the system resonance frequencies. Each prototype of the arm demonstrated improved dynamics during vibration testing. The results of each successive vibration test are shown in Figure 16 through 19. Peaks should be as low as possible, and occur at the highest possible frequencies. The results of each test were used to generate design revisions for the next test.

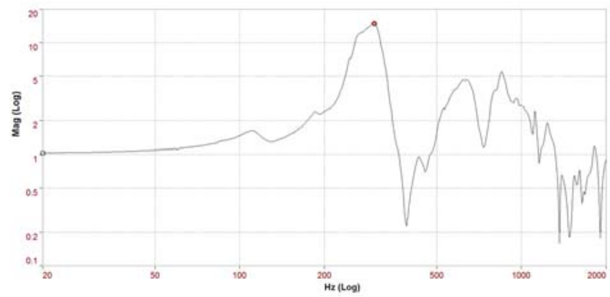

Figure 16: RSat Arm Vibration Test #1 X-Axis Sine Sweep, September 2015

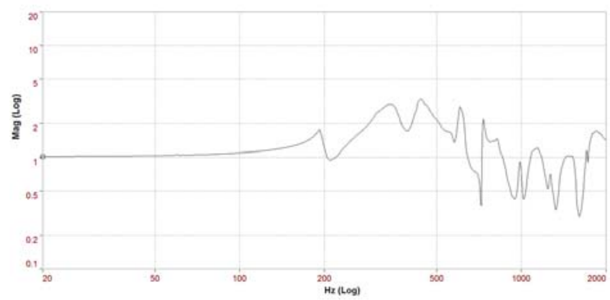

Figure 17: RSat Arm Vibration Test #2 X-Axis Sine Sweep, October 2015

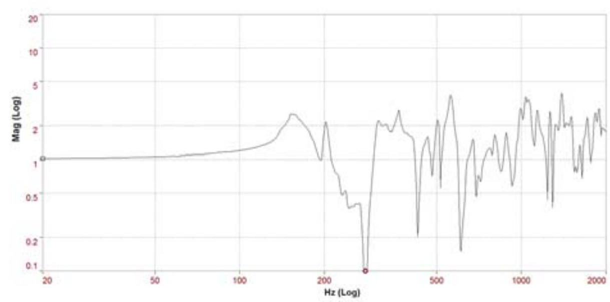

Figure 18: RSat Arm Vibration Test #3 X-Axis Sine Sweep, November 2015

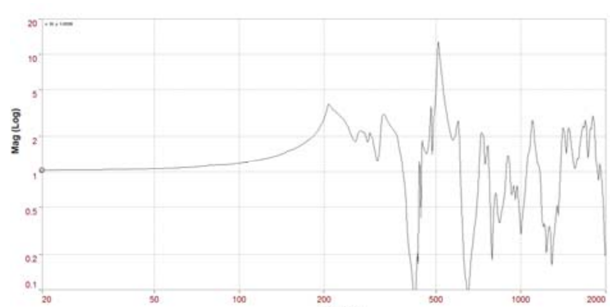

Figure 19: RSat Arm Vibration Test #4 X-Axis Sine Sweep, December 2015

The 4th vibration test was a success and was the final step in the development of the arm design for the first prototype to be tested in space. One of the major improvements that increased the stability of the design was the use of the arm restraints, shown in Figure 20, which are used to secure the arm in place. Through the use of resistors and fishing line these blocks allow the arm to be effectively bolted to the side of the spacecraft. This secures the arms for launch and the vibrations during that period of the mission and then severs the fishing line so that the arms can be deployed on-orbit.

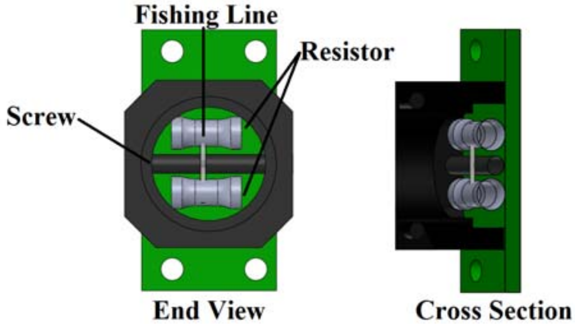

Figure 20: Arm Restraint Design

The resistors and printed circuit board are mounted to the frame of the spacecraft. The fishing line is tied the screw which connected to the black motor casing and to the resistors. To deploy, current is run through the resistors, melting the fishing line and allowing the screw to move freely.

SINGLE MOTOR ON-ORBIT TEST

The AMODS program progression focuses on building up from the ground in terms of technology demonstrations. The "crawl, walk, run" approach to layers of complexity allow for more basic systems to be tested before progressing onto more advanced technology. This allows for diagnosis of problems to occur in the development process rather than post launch.

Because of the advantages that come from a step by step developmental and diagnosing process, the AMODS program will launch a motor, which is a duplicate of the motors that are used on RSat, on a BRICSat spacecraft in order to demonstrate that the motor can operate in the space environment. The casing is mounted onto the interface board of the BRICSat-D satellite, a spacecraft produced by the AMODS team whose primary mission is to demonstrate a new electronic propulsion system for future BRICSat use. The casing is shown in Figure 21.

The motor will execute a test sequence similar to the test used to determine motor accuracy on the ground. This allows the data to be compared between the ground tests and the flight tests.

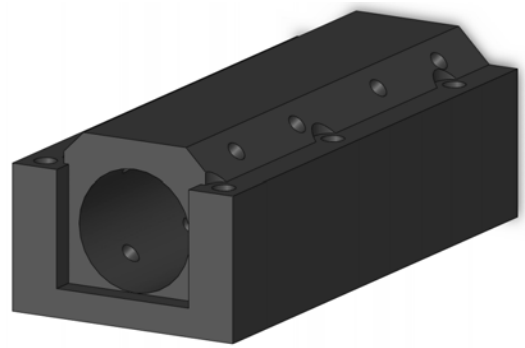

Figure 21: Motor Casing for BRICSat-D Mission

The results of this test will allow for the further development of the motor control operations for the integration of these motors on future RSat missions. Once the motor is observed in the space environment, a manual for space operations can be developed using the information gained from the test.

CONCLUSION

The AMODS program is the development of a system of spacecraft that have the ability to provide up close diagnostics of failed satellites. This ability is made possible by the RSat spacecraft which is two robotic arms within a 3U CubeSat which have an arm span of 1.5 m and seven degrees of freedom. The first prototype of the arms will be launched in early 2017 and will demonstrate the ability of the arms to perform basic maneuvers. Through thorough ground testing of environmental factors as well as motor accuracy the AMODS program was able to demonstrate that the technology onboard the RSat-P spacecraft will be able to withstand the conditions of space and continue to operate effectively. The results of the RSat-P flight will help in the redesign process of the spacecraft leading up to the MBSE flight which will demonstrate the ability for each spacecraft to work together in order to carry out the AMODS mission. Because of its low cost and diagnostic capabilities, the AMODS program has the potential to revolutionize satellite diagnostics in order to increase the lifespan and decrease the risk of mission failure in spacecraft.

Acknowledgments

The authors gratefully acknowledge the generosity of Penny and Roe Stamps and the Stamps Family Charitable Foundation. Additional support has been provided by DARPA, PEO-IWS, AFOSR/AFRL (UNP).

The team would also like to acknowledge with appreciation the contributions of CDR Robert Bruninga, USN (ret), Lt. Col. John Varljen, USAF (ret), Dr. Bradley Bishop, and CAPT Shorr, USAF.

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