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Design and Development of a CubeSat-scale Robotic Arm Test Bed to be Deployed to the International Space Station

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Abstract

The CubeSat-satellite scale Repair Satellite (RSat) system is a low cost, 3U CubeSat-class satellite intending to advance robotic assembly capabilities. Equipped with two, 60 cm, six-degree-of-freedom robotic arms and a 3-D camera system to perform various tasks analogous to common assembly and diagnostic tasks, RSat was launched to the International Space Station (ISS) as an internal payload in Fall 2022. The RSat system has been completed and delivered for integration and launch to the ISS. This paper will present an overview of the RSat system, detail design, operation, and demonstration modifications for the on orbit demonstrator, analyze the results from the ground test platform, and discuss the interfacing features for integration into the internal compartment of the ISS. The paper will also detail the robotic arm operating procedures and discuss any lessons learned.

Keywords: CubeSat, On-orbit Servicing, Robotic Satellite

Acronyms/Abbreviations

Command and Data Handling (C&DH)
Defense Advanced Research Projects Agency (DARPA)
European Robotic Arm (ERA)
Huntsville Operations Support Center (HOSC)
In-space Servicing, Assembly, and Manufacturing (ISAM)
International Space Station (ISS)
Marshall Space Flight Center (MSFC)
Material Science Glovebox (MSG)
National Science and Technology Council (NSTC)
On-orbit Servicing, Assembly, and Manufacturing (OSAM)
Robotic Experimental CubeSat (RECS)
Repair Satellite (RSat)
Shuttle Remote Manipulator System (SRMS)
Technology Satellites for Demonstration and Verification of Space Systems (TECSAS)
United States Naval Academy (USNA)

1. Introduction

Demand for more complex space systems is ever increasing, as the scale of the future missions expands to encompass ambitious missions such as asteroid mining and human space exploration. Accordingly, much focus has been given in recent years to innovations in on-orbit assembly and servicing to ensure those missions are executed in a time-efficient manner. Modular construction of large space projects and routine maintenance of crucial space infrastructure will be enabled by a new generation of In-Space Servicing, Assembly, and Manufacturing (ISAM) or On-orbit Servicing, Assembly, and Manufacturing (OSAM). These new ISAM capabilities have been the focus of much investment in the past few years, garnering broad support from the National Science and Technology Council (NSTC) and the White House [1]. Past on-orbit robotic servicing missions have involved large structures or systems designed to operate in very specific environments: generally aboard the ISS or the US Space Shuttle. In 1993, Rotex, the first remote controlled robot in space, was designed and launched to assist astronauts with basic tasks like opening and closing connector plugs and assembling basic structures [2]. Robonaut, a spiritual successor to Rotex in many ways, is an ongoing NASA project that put a humanoid robot aboard the ISS to work with astronauts, with the goal of future astronaut/robot integration during the Artemis missions [3]. In terms of strict ISAM capabilities, the Shuttle Remote Manipulator System (SRMS) commonly known as the Canadarm was famously used aboard the Space Shuttle to payload handling operations [4]. A brief review of the literature surrounding ISAM projects reveals vast and continued efforts that have been made in the field. From the Russian Space Agency's Technology Satellites for Demonstration and Verification of Space Systems (TECSAS) mission to demonstrate on-orbit satellite capture to the ongoing Defense Advanced Research Projects Agency (DARPA) project PHOENIX aimed at capture and removal of waste in GEO orbits, ISAM projects are the focus of public and private space organizations now more than ever [5]. However, each of these projects have carried high price points, prohibiting any notion of mass-production. For instance, the recently installed European Robotic Arm (ERA) cost over $360 million, and has already been reduced to limited use by the Russian Space Agency [6]. Most current ISAM projects carry a similar prohibitively high price and fail to leverage advancements in small satellite technology. While high cost projects are useful for high profile missions such as Gateway and the Orbital Express, lower profile missions such as university research satellites or generic telecommunications satellites would reap incredible benefits from a low-cost on-orbit servicing solution. With the recent boom in the CubeSat and nano-satellite fields, the small satellite capabilities have drastically increased to a point where many of these satellites are able to provide realistic augmentation, and sometimes replacement, to missions once only conceivable with multi-million dollar large satellites [7]. In addition, growing access to orbit and small satellite design standards have enabled delivery of greater payload volumes for research and commercial applications. This increased access to space allows for the potential construction of complex structures and remote servicing of existing assets in order to better support a variety of missions, including scientific research, commercial endeavours, and manned space exploration. To support these increasingly complex missions, capability to assemble mission hardware and diagnose problems on-orbit is essential. While these capabilities have historically been limited to space stations and programs with large budgets, the development of lower cost satellite form factors offer increased diagnostic capability with marginal impact on mission cost [7]. Development of remote orbital assembly and diagnostic techniques within the CubeSat standard could allow future missions access to these capabilities. This is the goal that RSat was designed to achieve: low-cost, multi-mission effective, highly reproducible ISAM capabilities in a CubeSat form factor satellite.

2. RSat Vision

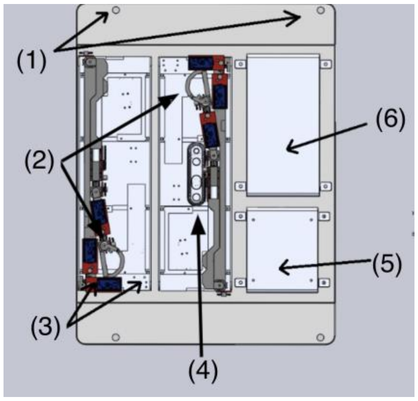
The U.S. Naval Academy (USNA) is contributing to advancing on-orbit servicing and assembly technology with a next-generation CubeSat-satellite scale Repair Satellite (RSat) system, which seeks to demonstrate semi-autonomous robotic assembly capabilities on-orbit on a nano-satellite scale. RSat is a low cost, 3U CubeSat-class satellite intending to advance robotic assembly capabilities. Equipped with two, 60 cm, six-degree-of-freedom robotic arms and a 3-D camera system to perform various tasks analogous to common assembly and diagnostic tasks, RSat was launched to the International Space Station (ISS) as an internal payload in Fall 2022. RSat will manipulate and reposition demonstration assembly hardware in a variety of tests designed to simulate assembly of an orbital structure. The structure of the RSat mission allows for various assembly techniques to be tested, modified, and evaluated for their viability in robotic assembly operations. Furthermore, the RSat system can be updated by research teams on the ground to test new arm and sensor operation algorithms. Data from robotic arm stepper motor encoders will be collected for each test and compared with visual and timing data to evaluate internal algorithm performance. These data will be used to determine which techniques can be successfully completed using our hardware and algorithms in a microgravity environment. Through evaluating algorithms and techniques from a variety of sources and determining which tasks may be performed with high levels of accuracy, standard procedures and techniques may be developed to assemble a variety of modular structures in future orbital missions using commercial-off-the-shelf components housed in a CubeSat form factor.

The Naval Academy student engineering team originally conceptualized an ultra low-cost, off-the-shelf component driven autonomous repair satellite, capable of being mass produced and involved in any number of on-orbit construction, maintenance, or deactivation missions where only a human operator could function in the past. The idea of a constellation of these low-cost devices repairing, refueling, and rebuilding previously unreachable satellites already in orbit would change the way the engineering community perceived space engineering and end-of-life functionality calculations. To this end, a proof-of-concept platform had to be designed, flown, and tested in the space environment to provide functionality. RSat was designed as this proof-of-concept: a technology testbed to carry out a series of experiments proving that small scale, ultra low-cost ISAM capabilities were within grasp. After much collaboration with NASA, the US Space Force, as well as a number of civilian contracting agencies, the RSat testbed was slated to be installed aboard the ISS in order to carry out robotic arm movement experiments in a controlled, micro-G environment. Key to the success of the RSat test was the development of an arm-control algorithm and software behind RSat, as well as the assembly of the physical hardware enabling such low cost, small-scale, and highly precise performance. If the RSat is successful in completing the series of tests outlined later in this paper, it will mark a major step forward in accessible ISAM capabilities, and bring the astronautical engineering community one step closer to a revolution in the reusability of space infrastructure.

3. RSat Design

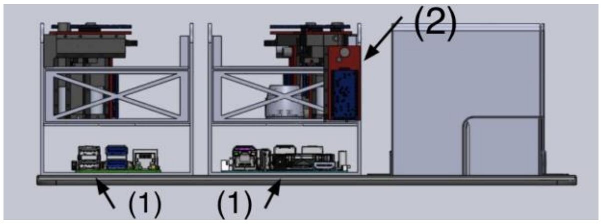
3.1 Design Overview

In early 2022, RSat was delivered to Marshall Space Flight Center (MSFC) for flight-readiness testing and verification. The full RSat structure consists of a power control box, a network and computing box, and two Robotic Experimental CubeSat (RECS) units. Figure 1 depicts a labeled CAD model of the final RSat design and critical components. Figure 2 depicts the same model from a longitudinal viewpoint, with the inner composition of both RECS units more clearly visible. Figure 3 depicts an isometric view of RSat in both a 'stowed' position–the delivery orientation and the position RSat was launched in–and a 'deployed' position with both arms extended fully out and each joint visible. Each RECS unit houses a Raspberry Pi microprocessor for sending arm movement commands and a 6 degree-of-freedom (DOF) robotic arm and end-effector camera.



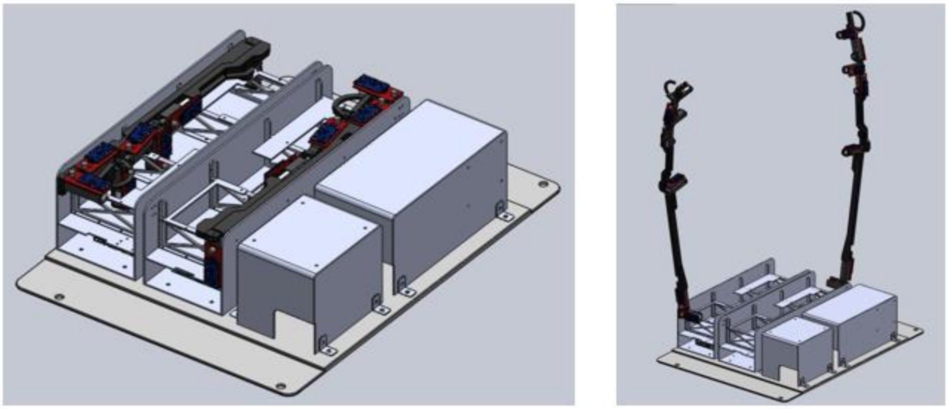
1. *Material Science Glovebox (MSG) mounting points*
2. *Arm end effectors and fiducial recognition cameras*
3. *Robotic Experimental CubeSat (RECS) unit mounting points*
4. *Intel RealSense 3D Depth Camera*
5. *Power control housing*
6. *'Master' Raspberry Pi and Network box*

Fig. 1. RSat payload and stand configuration - arms stowed, top-down view



1. *'Arm Pi' 1&2–arm control microprocessors*
2. *Faulhaber arm motors and Arduino motor boards*

Fig. 2. RSat payload and stand configuration - arms stowed, side-on view



RSat - Stowed Position RSat - Deployed Position

Fig. 3. RSat in both ‘stowed’ and ‘deployed’ positions

One of the RECS units is equipped with an Intel RealSense Depth Camera for determining target position and orientation. Each RECS unit was initially designed to individually house two robotic arms and a dedicated depth camera, but due to acquisitions problems regarding the motors and motor control boards used on the arms, each RECS unit was reduced to a single arm and only one depth camera between the two. While removing redundancy, this change did not affect mission capabilities. Onboard the ISS, RSat will be mounted inside a Material Science Glovebox (MSG) for the duration of the testing. Figures 4, 5, and 6 depict the physical flight configuration of RSat during flight-readiness testing at MSFC, and serve to help visualize both the RSat system as a whole and its positioning inside the MSG, which has been replicated on the ground at MSFC.

Fig. 4. RSat flight hardware at NASA Marshall Space Flight Center

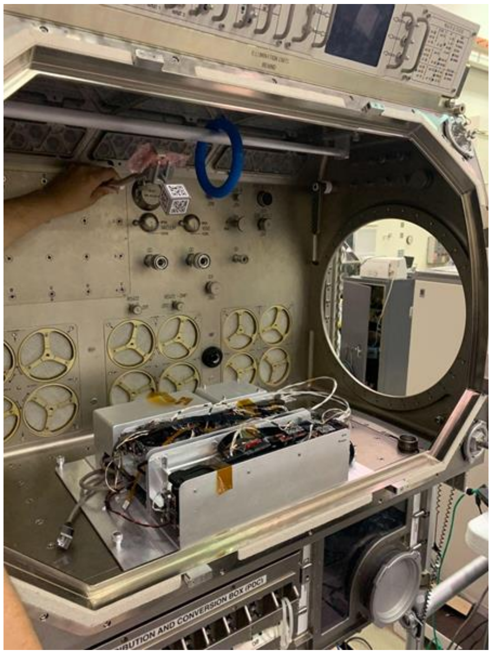


Fig. 5. RSat flight hardware in mock MSG at MSFC, corner-view

Fig. 6. RSat flight hardware in mock MSG at MSFC, head-on view

3.2 Key Features

RSat serves as a testbed for two autonomous 6 DOF robotic arms, pictured in Figures 1-6. The arms are controlled by a set of two Raspberry Pi microprocessors, which are in turn controlled by a single microprocessor–the ‘Master Pi.’ This connection diagram is examined in greater detail in Figure 13. A depth camera powered by an ODROID single board computer provides depth imaging and position reconciliation of targets in the view of RSat. Each of the end effectors on the two arms are equipped with a curved ‘claw’ end-effector capable of gripping everything from large objects to wires, as well as a camera for translating fiducials installed on satellites to aid in RSat orientation determination. The current iteration of RSat was designed to complete a series of tests aboard the ISS, not as a freeflying satellite (as the name ‘satellite’ may imply). As a result, there is no attitude control, propulsion, or external power generation capability on the current testbed. A dedicated propulsion unit is in development for future iterations of RSat, with a focus on the intricacy of orbital rendezvous required to deliver freeflying RSat units to their required destination.

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3.2 Design Iterations

RSat was first designed as a fully freeflying satellite and a version of this was flown in 2018 as depicted in Figure 7. Unfortunately, this satellite was dead on arrival after launch, and no useful data or experiments could be conducted. After the failure of the original RSat, a new design was introduced that would mount RSat internally in a 'cage' that would serve as a testbed for experiments in orbit, as depicted in Figure 8.

Fig. 7. 2018 RSat free flyer

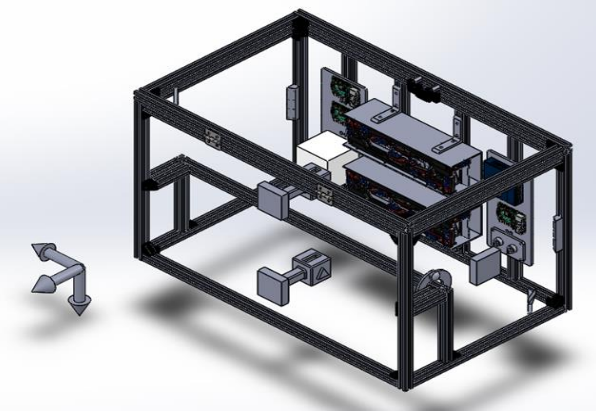
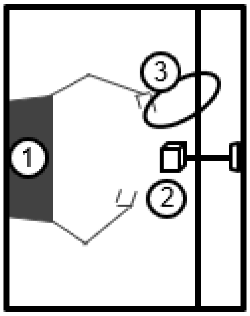


Fig. 8. RSat 'Cage' concept design

However, after an agreement with NASA was reached to test RSat aboard the ISS, a new RSat design concept was created that took advantage of the opportunity offered by being inside the ISS, where power and communications are provided through the ISS/NASA framework. Designed for compatibility with the ISS power supply system, rigorous testing was conducted at both NASA Johnson Space Center and Marshall Space Flight Center to ensure power, computing, and network compatibility between the RSat system and the ISS.

3.4 Mission Profile

When launched to the ISS, RSat will be installed by NASA Astronauts into the Microgravity Science Glovebox (MSG), matching the orientation of Figure 9 showing a top-down view of it mounted in the MSG. After it is secured to the RSat baseplate in the MSG, RSat will be powered through the internal 120V supply interface stepped down to just above 5V. A series of diagnostic tests will be run from the ground station at the United States Naval Academy to ensure that all computing, networking, and motorized components are powered and functioning as expected. This is achieved by networking the USNA ground station computers directly to RSat onboard the ISS via connections established through NASA Marshall Space Flight Center. Following these initial tests, three tasks will be completed to demonstrate mission functionality: imaging fiducials on all sides of a static cube target using the arm end effector cameras, maneuvering to and gripping the static cube target with the arm end effector, and finally the passing off of a ring target suspended on a mounted bar from one end effector to the other one.



1. *RSat frame & arms*
2. *Cube Target*
3. *Bar and Ring Target*

Fig. 9. Experiment concept-of-operations diagram

The first and simplest test will involve imaging the mounted cube from all five visible sides using the end effector camera on one of the arms of RSat. As seen in Figure 10, each side of the cube target will have been fitted with fiducials which, when read by the code onboard RSat, will determine the side of the cube that is in view. This test simulates the use of fiducial markers that could be installed in critical areas of future satellites and demonstrates how effectively adding something as simple and inexpensive as an external QR code could prove in enabling future RSat-like satellites to recognize, orient to, and make repairs on space structures.

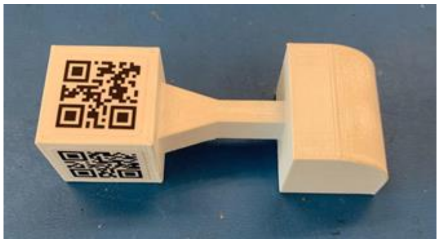


Fig. 10. Mounted Cube Target and fiducials

The second test is to use the same arm of RSat to move towards, grip, and maintain positive control of the mounted cube target. This test takes the first proof of concept a step further–using the fiducial information as well as the onboard camera suite to enable RSat to maneuver to and make useful contact with a target. The essence of on-orbit servicing and repair capabilities relies on this seemingly simple task repeated in extended and complex sequences. The third test acts as an extension of this idea of grasping and controlling a target. If RSat is capable of moving to and maintaining positive control with a target, it should be able to complete a more complex task like passing a ring target from one arm to the other through compounding sequences. After the tests with the mounted cube target are complete, the cube target will be removed and a bar target with an attached ring will be mounted in its place. From here, the depth camera suite aboard RSat will image the ring target to ascertain the XYZ coordinate of its centroid and move the closer arm to rendezvous with the ring target. Both the bar and the ring target are shown in Figure 11.

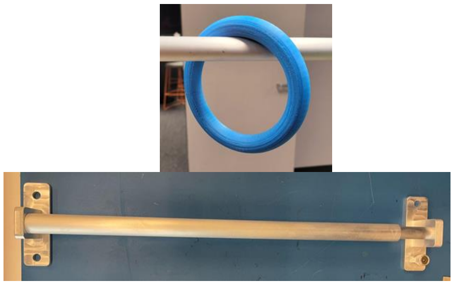


Fig. 11. Ring Target and mounted bar

After successfully gripping the ring target, the arm will move the ring along the bar towards the opposite end where the other arm will be waiting to complete the 'handoff'. Once close enough, the second arm will move to grip the ring target at which point the first arm will release and move away. Once the second arm has full and independent control of the ring target, it will move the ring to the other end of the bar target, completing the test and demonstrating the capability of an RSat-like satellite to complete complex tasks based on simple directives.

These RSat tests will be conducted over multiple sessions spanning four hours each on the ISS, after which the satellite will be removed from the MSG and disposed of. If successful in completing these tests, RSat will have demonstrated the capability of ultra-low cost on-orbit repair technology that relies on as little external input as QR code fiducials, opening the door to the creation of a fleet of RSat-like satellites to be launched alongside future projects such as the Nancy Grace Roman Space Telescope to ensure functionality through scheduled or unscheduled maintenance in the absence of manned missions [8].

3.5 Detailed Hardware Description

Each of the arms on RSat are housed within an aluminum Robotic Experimental Construction Satellite (RECS) unit. Designed to eventually be equipped with two arms each but modified to carry only one for the purposes of the ISS tests, each RECS was also designed to house the Raspberry Pi microprocessor controlling the arms, the Intel RealSense depth cameras enabling system perception, and the wiring harness connecting the seven motors on each arm to power and data inputs. Separate power and data boxes were designed to house the power converter and internal server connections that allowed each of the four computers (ArmPi1, ArmPi2, MasterPi, and ODROID) to communicate over ethernet. The power schematic for the RSat testbed, as pictured in Figure 12, had to be designed to the strict standards of operation aboard the ISS, and metrics such as maximum inrush current, maximum operating current, and exposed surface temperature were tested and verified rigorously to ensure that RSat would pose no threat to either ISS infrastructure or the astronauts setting up the tests. Though each of the components operated ideally at the available ISS input of 5V, there were unavoidable losses within the wiring system which meant having to use the 120V input and a step-down converter to properly power the system.

Structurally, the two RECS units mounted on RSat are 3U CubeSat dimensions (10cm x 10cm x 30 cm). Each of these two RECS units is mounted to a single aluminum stand, which also serves as the mounting point for both the power and network boxes, as previously depicted in Figure 1. The stand and all structural components except the arms themselves were machined in the USNA machine shop in strict compliance with the dimensions of the MSG testing mount received from NASA. The precision required from these MSG dimensions proved to be one of the major challenges during assembly.

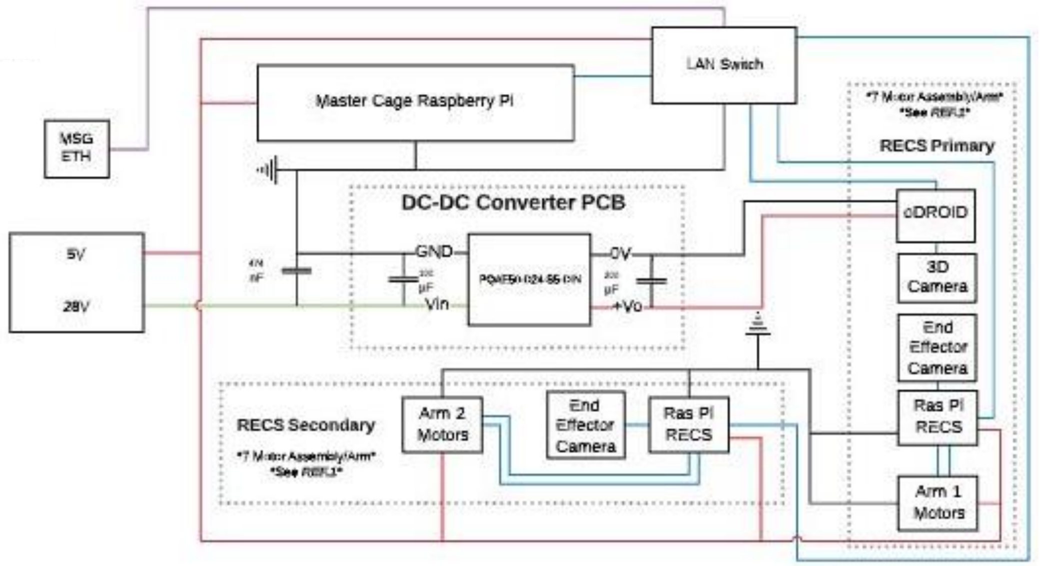


Fig. 12. RSat wiring diagram

The Commands and Data Handling (C&DH) system aboard ISS had to be designed to communicate data from the onboard computers through to the ISS communications relay, then down to Huntsville Operations Support Center

(HOSC) at NASA Marshall Space Flight Center. Once there, it was sent to the ground station at USNA with the return process used to send commands to RSat. The diagram in Figure 13 presents a simplified snapshot of each of the network connections required for RSat to function properly.

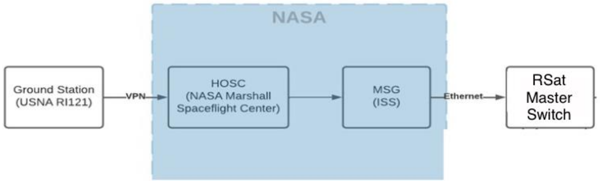


Fig. 13. RSat C&DH network route diagram, showing up link path

The arms of RSat were additively manufactured using a common carbon fiber composite and designed for testing in a zero-G environment, see Figure 14. The joints of the arm were designed with space to insert the Faulhaber stepper motors driving the arms, which were in turn controlled by software installed on Arduino processors as shown in Figure 15. While lightweight and cost-effective, the zero-G structural condition meant that the arms could not be tested with full range of movement in the lab. To circumvent this problem during testing, movements of the arms were tested in two dimensions at a time, so that the structures and the motors were not working directly against gravity at any point in the tests.

Fig. 14. Single RSat arm model, only structure shown

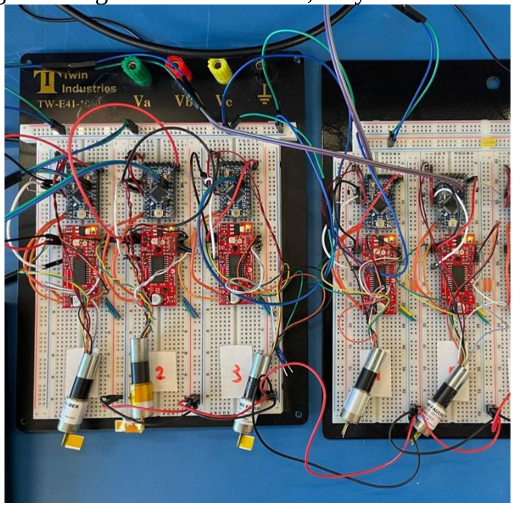


Fig. 15. Faulhaber motor test environment and prototype arm integration

Lastly, a ground station was designed at USNA specifically to interface with RSat during the course of the experiment. An arm movement simulation was created in Simulink in order to verify each of RSat's moments before execution, ensuring that, should a problem or faulty command arise, it could be prevented from becoming a mission critical failure. The connection between the ground station at USNA and RSat (through NASA and the ISS) also serves to create the potential for software updates, in the event that there is an error found within the code governing

RSat during the experiments. With this design and connectivity with the USNA ground station via NASA, the RSat will be evaluated and tested based on the three major tests described to prove the technology and proof of concept.

4. Conclusion

RSat marks a tangible shift towards accessibility and reusability in the space industry as one of the most cost effective small-scale solutions to ISAM requirements The concepts, hardware, software, structures behind RSat are the product of over five years of effort from students and faculty of the US Naval Academy. RSat represents more than just the efforts of this group, however; it represents a bold step towards an emerging philosophy of on-orbit maintenance or assembly in space engineering. After the completion of this testbed mission, future iterations of RSat will step closer to full functionality as a free-flying and highly adaptable ISAM option available at a fraction of the cost of current solutions. It would not be an exaggeration to state that the ultimate success of RSat has the potential to revolutionize satellite engineering through low cost planned maintenance missions capable of refueling, repairing, and increasing satellite lifespans to enable much longer mission lengths. Future ISAM projects have the potential to lower the financial barrier of entry into space engineering and enable large-scale on-orbit construction projects. It is clear that the future of space travel will rely on enhancing and revolutionizing modern ISAM capabilities, and the RSat experiment aboard the ISS is a bold step towards this goal.

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