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Design and Development of On-orbit Servicing CubeSat-class Satellite

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ABSTRACT

The long term vision of the Naval Academy Satellite Team for Autonomous Robotics (NSTAR) is to lower both the risk and cost of on-orbit space system construction and repair through the use of a CubeSat robotic arm system. NSTAR developments will enable space agencies and private companies to construct large, complex structures in space at a reduced cost with greater diagnostic assessment ability. Robotic Experimental Construction Satellite (RECS) is designed as NSTAR's second project iteration and works to meet five different capabilities for semi-autonomous orbit assembly. RECS is a 3U CubeSat with two extendable robotic arms, each with six degrees of freedom. In coordination with the launch manifest, RECS has been designed, completed, and is awaiting launch to the ISS where it will conduct testing. This type of on-orbit demonstration has never been completed on CubeSat-scale systems. A successful mission will indicate entry into a new frontier of satellites, where space systems remain in operation longer, missions are of lower cost, and the ability to complete space-based scientific research is expanded. This paper provides the details of the design and capabilities of the NSTAR system.

INTRODUCTION

While previous space exploration missions have been short in nature, projects developed over the past decade now demand spacecraft with long-term capabilities. Contrasting the current practice of Earth-based assembly and testing, new designs call for a "born-in-space" architecture [1]. With the space industry developing increasingly longer missions, the need for on-orbit servicing has grown drastically. Launching larger, more complex spacecraft intended for lengthier missions has posed commercial and private space agencies with new, costly challenges associated with system up-keep, construction, and repair. The space industry now faces the need to more fully utilize and exploit flight systems already launched and to provide additional systems that cost-effectively and reliably support the pursuit of long-term missions [2].

Extended spaceflight missions, like those which will be planned in coordination with NASA's Artemis program for example, require cheaper, less risky alternatives to current repair and construction solutions. NASA's new lunar and space exploration project, the Artemis program will see astronauts prepare for missions to the moon and beyond on the Lunar Gateway, a small spaceship similar to the International Space Station (ISS) which will be built to orbit the moon [3][4]. To ensure the success of such long-term projects, there is now greater need for more advanced, adaptable space robotic systems.

Current robotic solutions for on-orbit construction and repair, although an upgrade from previously risky manned missions, are still large, bulky, and costly. The Canadarm2, for example, was installed by astronauts on the ISS in 2001 with the objective to aid astronauts in exterior construction and repair. Although the arm has seven degrees of freedom and thus the capability to move almost exactly like a human's, it weighs approximately 1,497 kg and stretches 17 m in length [5]. Furthermore, the project has unnecessarily cost NASA hundreds of millions of dollars in upkeep in recent decades and its size has limited its ability to attend to smaller scale projects.

Considering developments like the Artemis program and the shortcomings of previous solutions, there is a current need for smaller, cheaper, and more maneuverable repair systems for orbiting spacecraft, including the ISS. Because of this need, and to enable longer, more complex missions, the Naval Academy Satellite Team for Autonomous Robotics (NSTAR) is developing an autonomous CubeSat robotic arm system that will lower both the risk and cost of on-orbit space system construction and repair. Developments made by NSTAR will enable space agencies and private companies to construct large, complex structures in space at a reduced cost with increased diagnostic abilities. Unlike the Canadarm2 and other inadequate solutions, the developments of NSTAR will provide a small-scale satellite that can be implemented in swarms, providing constant and adaptable repair to orbiting or transiting spacecraft. Small, easily maneuverable satellites, such as those provided by NSTAR, will more effectively construct and repair spacecraft of all sizes.

This paper will discuss the mission objectives and design of NSTAR's current project iteration. The developments and knowledge gained from this iteration, a 3U CubeSat termed the Robotic Experimental Construction Satellite (RECS) to be tested on the ISS, will enable future NSTAR members to improve subsequent designs. With improvements, NSTAR will effectively contribute to solving the space industry's current on-orbit construction and repair challenges.

MISSION DESCRIPTION

The long term vision of NSTAR is to lower both the risk and cost of on-orbit space system construction and repair through the use of a CubeSat sized robotic arm system. So far, NSTAR has developed two project iterations which have both sought to achieve five key capabilities. To fulfill these capabilities, a number of functional requirements must be met. Among these, NSTAR seeks to first verify a designed system's ability to complete precision pointing and object tracking, manipulation, and inspection.

1. The repair satellite shall have the capability to manipulate and alter hardware, such as screws and bolts, in a space environment.

2. The repair satellite shall have the capability to move with ease in a space environment.

3. The repair satellite shall have the capability to operate autonomously.

4. The repair satellite shall have the capability to run diagnostics and identify issues of the hardware and systems it will be repairing.

5. The repair satellite shall have the capability to successfully process data and generate data reports to its user.

NSTAR's first iteration, a free-flyer satellite named RSAT, was designed as a 3U CubeSat and launched in 2018 [6] [7]. Its main goal was to test two robotic arms' ability to actuate and hold accurate orientations. Unfortunately, RSAT was dead-on-arrival and thus failed to reach its given objectives.

To prevent a similar power and communication failure, the current and second iteration of the robotic arm CubeSat, called Robotic Experimental Construction Satellite (RECS), was designed and developed for integration and testing aboard the ISS [8]. Mounted inside the Station, RECS will draw from the ISS' power and communication resources. By eliminating the communication and power issues that frequently challenge CubeSats in orbit, this configuration enables NSTAR to focus on demonstrating the first few rudimentary capabilities needed for achieving its vision with future iterations [9]. With arm capabilities already established from RSAT, RECS' main goal is to establish initial autonomous operation capabilities. Built with commercial off the shelf parts for streamlined production and controlled by a ground station, RECS is the next step in providing the space industry with a small, adaptable solution to on-orbit construction and repair.

NSTAR has defined three mission objectives for this iteration. Successful completion of these mission objectives will inform future designs of the RECS system.

1. RECS shall accurately and precisely hit a target repeatedly with its end effectors.

2. RECS shall have the ability to "hand off" an object from one arm to another.

3. RECS shall inspect 360° of an object by use of RECS' end effector cameras.

During its time on the ISS, RECS will run a series of tests designed to validate that these objectives are achieved. Its Concept of Operations (CONOPS) is outlined in Fig. 1.

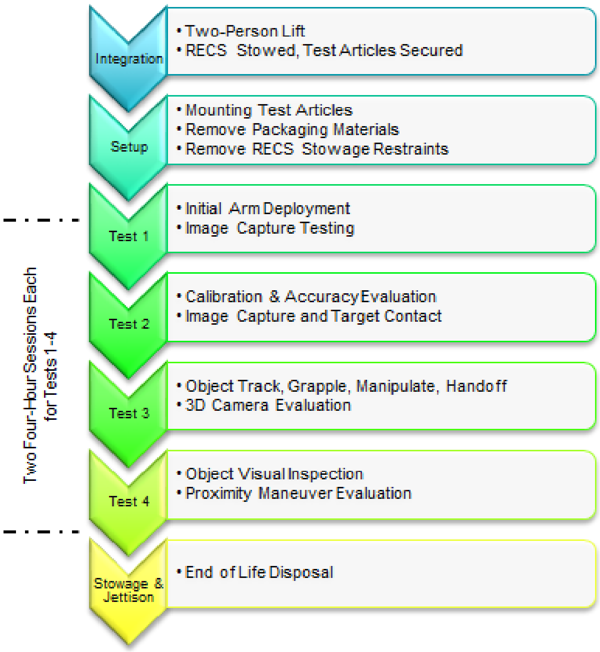

Figure 1: CONOPS of RECS aboard the ISS

To begin its integration period aboard the ISS, the system will initially be unloaded, stowed, and secured by astronauts within a scheduled period of 2.5 hrs. Over the course of approximately one week, depending on astronaut availability, RECS will complete a series of tests, each with two, 4 hr testing windows. The first test is the initial arm deployment and testing of the data link. From the stowed position, the arms will be deployed and diagnostics will be run. CubeSat Assessment Guarded Enclosure (CAGE) cameras will observe and downlink RECS arm movements. Upon completion of each test, the RECS will be powered down as needed. The second test works on calibration of the arms and a full evaluation of end effector pointing accuracy. The test consists of a series of move-to-point maneuvers, where the two arms will consecutively maneuver to a target and then away. The third test consists of object tracking, grappling, manipulation, and hand-off maneuvers. The two arms will hand off a “toy” from one end effector to the other. Both arms will be brought together to complete the handoff. The fourth and final test consists of a visual inspection of objects and a proximity maneuver evaluation. The arms will extend toward a designated object, with end effector cameras on and recording. The end effectors will be moved around the object and pictures and video will then be captured as needed.

Once testing is complete and all pertinent data is collected for the next RECS iteration, the system will be disposed of and jettisoned from the station.

SYSTEM OVERVIEW

RECS takes the form of a 3U CubeSat and contains two extendable robotic arms, each with six degrees of freedom. Each arm is outfitted with an end effector camera, and the “body” of RECS is outfitted with a 3D camera that generates a point cloud, enabling RECS to be aware of its surroundings. The flight load will include two duplicate RECS systems placed inside an enclosure known as the CubeSat Assessment Guarded Enclosure (CAGE). The CAGE has two corner-mounted cameras in opposing corners for ground-based monitoring purposes and two LED light strips located behind the RECS to supply lighting for all operational cameras. Power will be provided externally from the ISS and all data transfer will take place via I2C communication protocols through the ISS’ Ethernet network. An isometric view of the entire CAGE and RECS system is shown in Fig 2.

The CAGE houses all test apparatus, is built with 80/20 10 series aluminum beams connected with an off the shelf assembly package including nuts, screws, and corner pieces, and is surrounded by polycarbonate siding. The -Y face of the enclosure is a door, allowing astronaut access to the RECS systems.

The CAGE houses two electronics clusters on aluminum plates mounted on the internal -Z face. These plates host a master Raspberry Pi 3, two Raspberry Pi 3s which control the corner-mounted cameras, a switch box, and a LAN. The duplicate RECS systems are mounted on the same wall. Close up images of the electronics clusters and the RECS systems are shown in Fig. 3. The project’s final design allows for all mission objectives to be performed within the confines of the CAGE, which will protect the system from unintentional astronaut-induced disturbance. As it completes its four tests, the system will communicate with and receive updates from a Ground Station via the ISS’ Ethernet network. The following sections will explore the final design of each subsystem, proving the system’s ability to fulfill this iteration’s mission objectives.

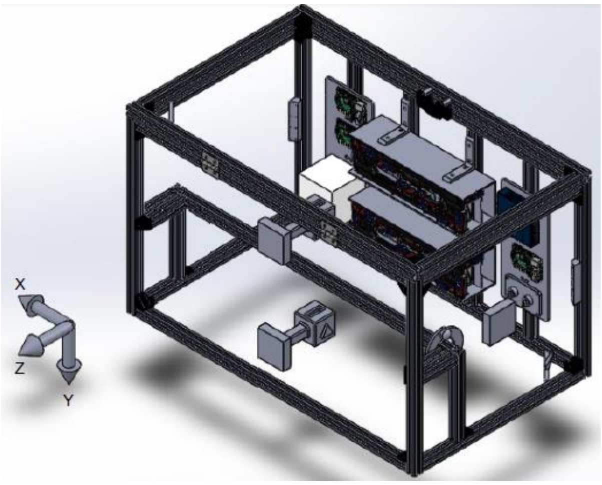

Figure 2: Isometric view of the entire CAGE and RECS system

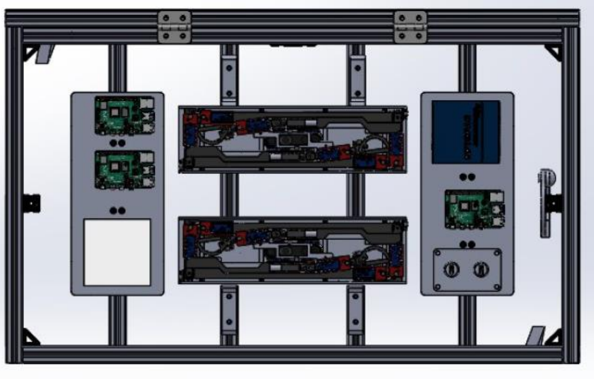

Figure 3: RECS systems and enclosed electronic clusters

RECS Hardware

RECS' arms are constructed with 3D printed parts made from ABS Ultimaker plastic. The United States Naval Academy's (USNA) Additive Manufacturing MakerSpace, which houses Ultimaker S5 printers, has been utilized to manufacture these parts. Where necessary, the arm parts are connected with 3M Scotch-Weld epoxy. Each arm has six degrees of freedom from seven motors. The end effector has an additional motor to accomplish a simple pinching motion. Faulhaber 2-Phase DC stepper motors were selected for flight. Each of these motors is controlled by an Arduino Pro Mini computer and an EasyDriver stepper motor driver, as shown in Fig. 4. These motor controllers are used to direct precision movements and are linked in series with a computer that houses the decision-making algorithm for that arm. Due to current and power restrictions, RECS is limited to running only two motors at a time, one motor per arm. A CAD representation of one RECS arm and its associated computers and controllers is shown in Fig. 5.

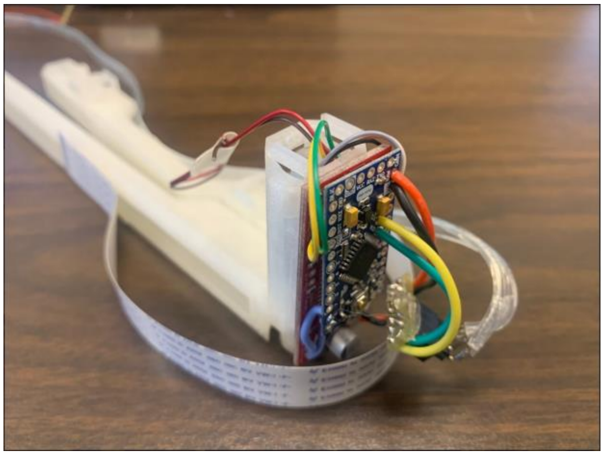

Figure 4: Arduino Pro Mini computer that controls arm motors

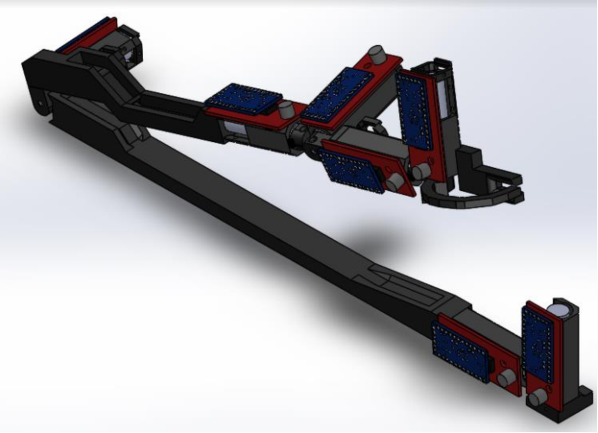

Figure 5: One of RECS' two autonomous arms

In addition to a claw-like apparatus designed to grasp test objects within the CAGE, each arm's end effector is equipped with a Raspberry Pi Spy Camera, as shown in Fig. 6. These Spy Cameras are connected to the RECS' main arm computers and are responsible for aiding the arms in completing the four prescribed tests. Close up images of an arm end effector are shown in Fig. 7.

Figure 6: Raspberry Pi Spy Camera located on arm end effectors [10]

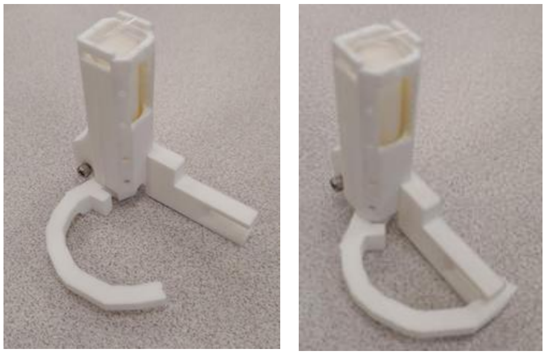

Figure 7: Prototype prints of the RECS arm end effectors without Raspberry Pi Spy Camera

The RECS arms are housed inside a 6060-T6 aluminum body, as shown in Fig. 8. This body takes the dimensions of a 3U CubeSat, to simulate the desired size of future RECS iterations that will be launched into space as free-flyer satellites.

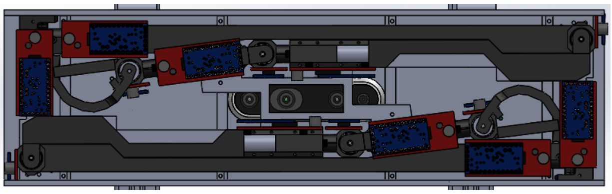

Figure 8: Close up view of enclosed RECS

Within the CAGE, the duplicate RECS systems are attached to 80/20 10 series posts on the -Z face of the enclosure with 80/20 corner brackets. Inside each RECS body is a 3D camera which enables the robot to visually detect targets and obstacles. The Intel RealSense D435 camera was selected for flight, as shown in Fig. 9. The camera is used to generate a point vector field, which senses targets, any obstacles, and the arms themselves.

Figure 9: Selected Intel RealSense D435 camera for RECS body

These coordinates, as depicted in Fig. 10 are fed into the arm computers, where they are turned into movement orders for the motors. Each RECS system houses two arm computers, the first an ODROID-XU4 and the second a Raspberry Pi 3. The ODROID, which has greater processing power, receives inputs from the D435 camera and sends commands to its own arm as well as to the partner arm via the Raspberry Pi 3.

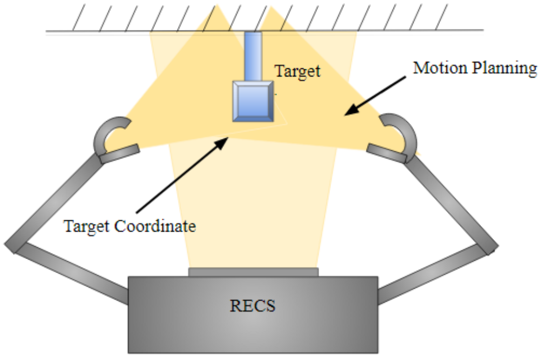

Figure 10: RECS body and arm camera views

Using the developed control algorithm, the four tests will collectively show that each arm is able to precisely touch a point within a 1/4” diameter circle, grasp a designed test object, maneuver into a position in which the other RECS arm can reach it, and point its Spy Camera at a designed test object for observation.

To demonstrate that the arms are able to precisely touch a point within a 1/4" diameter circle, two target pads have been attached to the CAGE walls. A rudimentary representation of a target pad is shown in Fig. 11. During Test II, using the end effector cameras and the developed control algorithm, the arm end effectors will maneuver to the known location of a target circle on these pads.

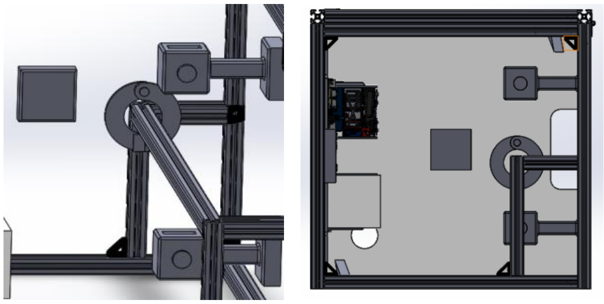

Figure 11: CAD image of CAGE and RECS system and Test II target pad

To demonstrate that a RECS arm can grasp an object and maneuver into a position in which the partner RECS arm can reach it, during Test III, one arm will grasp a designed test ring, mounted on an 80/20 10 series beam, and move the ring within reach of the other arm. A CAD representation of the designed test ring and set up is shown in Fig. 12. Like the RECS arm parts, the test ring was printed from the Ultimaker S5 printers in USNA’s MakerSpace.

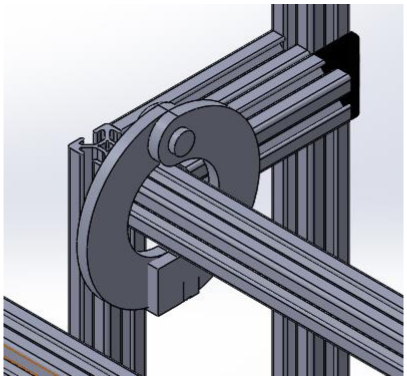

Figure 12: CAD images of Test III ring and 80/20 mounting beam

Finally, during Test IV, the Raspberry Pi Spy Cameras mounted on the arm end effectors will be used to inspect a designed test article. A close up view of the designed article is shown in Fig. 13. The Test IV inspection article is a 3D printed part using Ultimaker S5 printers in USNA’s MakerSpace. Two copies of the Test IV article, one for each RECS, will be mounted with epoxy within the CAGE on the +Z wall. Furthermore, each face of the test article will be colored differently to demonstrate the Spy Camera’s ability to detect color. This ability will prove useful within future testing of RECS systems. For example, subsequent iterations may be launched with a “bin of parts” and be required to assemble those parts in space. The ability to detect color will support such efforts.

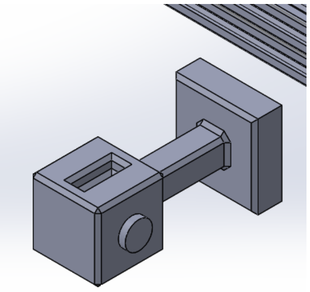

Figure 13: CAD image of Test IV inspection article

RECS Command and Data Handling

RECS communications will take place through the organic ISS network. The ground portion of communications will employ the Telescience Resource Kit (TReK) software, which allows NSTAR to monitor and control each RECS. Using this software, NSTAR will be able to upload commands, downlink position data and video feed, and operate a secure shell (SSH). The SSH capability will be used to make updates to the software and allow for the tuning of coefficients to refine the precision of the arms' movement. The SSH allows the ground controllers to command both the master Raspberry Pi 3 and its subordinates, enabling the update of every program onboard.

The designed control algorithm is housed in each arms' computer, is supported by inputs from the body-mounted 3D camera, and allows for the successful completion of all four tests. The D435 camera can assign a vector from an arm to a target, detect when an arm is in close proximity of a target, and can coordinate with the Spy Cameras to ensure they are pointing at a target in a specific configuration. By calculating a series of individual motor movements, the algorithm will direct the arms to follow vectors assigned by the D435 camera, coordinate the arms to grasp and ungrasp the Test III ring, and place the arms in a position to visually inspect the Test IV object from multiple angles. After calculation, these motor movements are sent to the motor controllers through lines using I2C communication protocols. All of the arm computers are connected via an Ethernet switch to a master Raspberry Pi 3 computer. This master computer is the central communication hub for the entire system, as shown in Fig. 14.

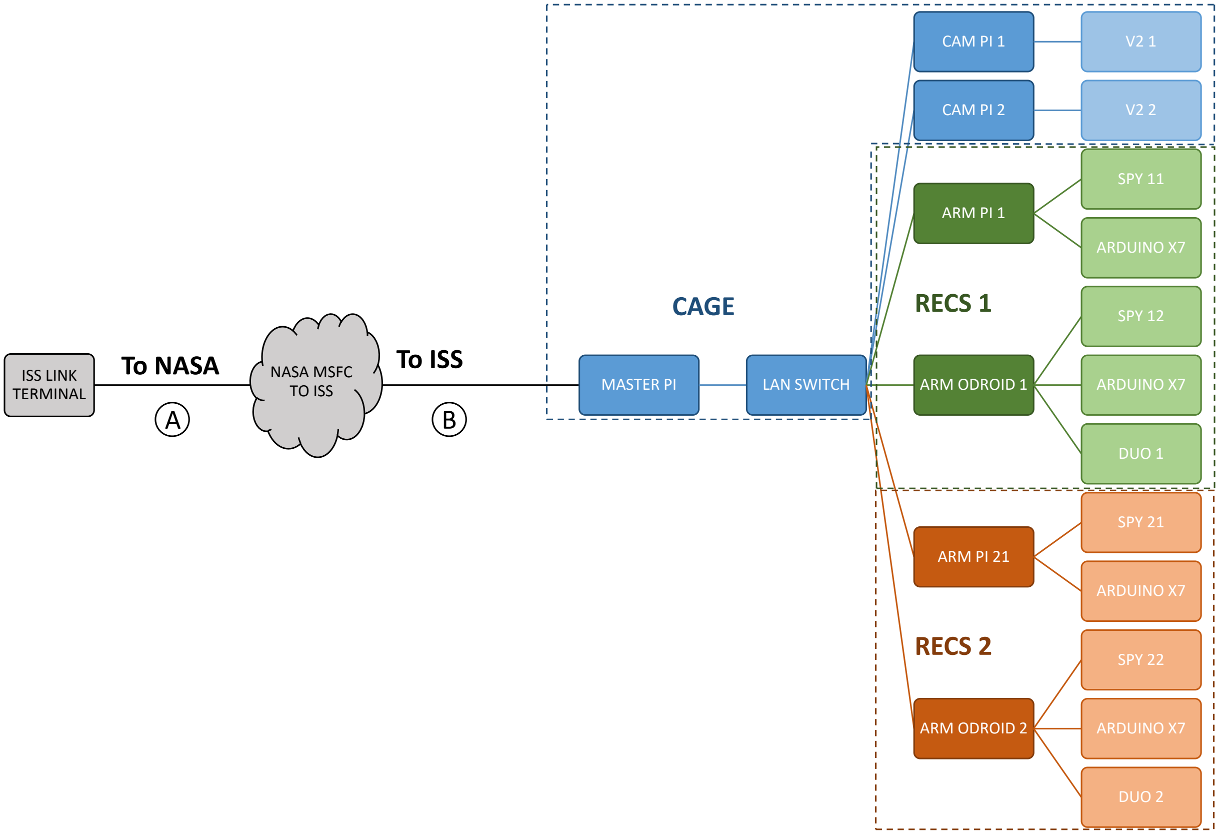

Figure 14: C&DH Block Diagram for CAGE and RECS systems

CAGE

The CAGE, built as a protective measure and to contain all necessary test apparatus, houses two RECS systems, two corner-mounted cameras in opposing corners, and two LED light strips on the enclosure’s -Z face to supply ample lighting for the cameras. The CAGE is a 34” x 20.86” x 20.86” rectangular frame made from 1” x 1” 80/20 10 series aluminum beams. The chosen CAGE dimensions fulfill NASA’s given requirements. With these dimensions, the entire system will fit inside the ISS cargo hold entry, which has a 30” diameter, and can be easily transported to its final location. The first prototype of the CAGE is shown in Fig. 15, though the design has since been scaled to accommodate ISS restrictions.

Figure 15: The first iteration of the CAGE made of 1.5” x 1.5” 80/20 aluminum beams

As shown in Fig. 16, polycarbonate walls surround the CAGE frame. This clear siding will allow astronauts to observe testing and will protect the system from external debris and disturbance. McMaster-Carr clear static-dissipative, impact-resistant polycarbonate with 3/16” thickness was selected for the flight load. Per NASA requirements, the frame can sustain a theoretical 250 lbf “kick load” and the walls a 125 lbf dissipated load over a 4” x 4” square in the center of its largest face. These requirements were established to protect the system should astronauts accidently disturb the payload while roaming about the ISS.

For the ground station team to monitor RECS testing, two Raspberry Pi V2 cameras are mounted in the CAGE in opposing corners. These cameras are run by one Raspberry Pi 3 computer each, which are both connected to a master system computer via an Ethernet switch. The designed mounts are made from ABS Ultimaker plastic and were printed using USNA’s MakerSpace.

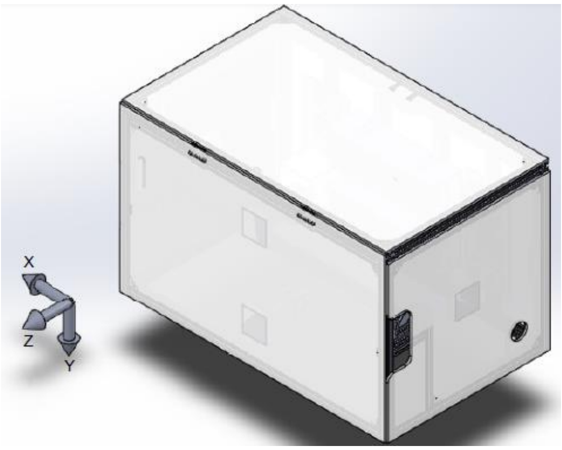

Figure 16: Polycarbonate layer over the CAGE

To allow astronaute access to the system, the CAGE features a door on the -Y face with hinges located on the top corner of the +Z face and a latch on the top corner of the -Z face. Off the shelf parts from 80/20 were selected for the door’s hinge and the latch. While the latch resides inside the CAGE above the top RECS on the -Z face, users can disengage the latch by simply lifting up on the door frame.

Additionally, within the enclosure are two LED light strips which provide sufficient lighting for all of the system’s camera operations. These strips are located on the vertical beams of the enclosure’s -Z face and are mounted on 3D printed parts produced by the Ultimaker S5 printers in USNA’s MakerSpace.

Power System

RECS will be powered externally from the ISS. All power components will be conditioned and regulated through a common switch box capable of supporting a minimum of six independent power lines with minimal power delivery of 5 W per line. The final switch box design supplies nine power lines, of which six will have a nominal voltage of 5 V and a maximum current of 2 A and three will have a nominal voltage of 12 V and a maximum current of 0.86 A. The 5 V lines will supply all processors within the system, to include: the master Raspberry Pi 3, the two CAGE Raspberry Pis, and the RECS systems’ Raspberry Pi 3s and ODROIDs. The 12 V power lines will supply the LED light strips inside the CAGE as well as the RECS arm motors. The power system lines are shown in the system block diagram in Fig. 17.

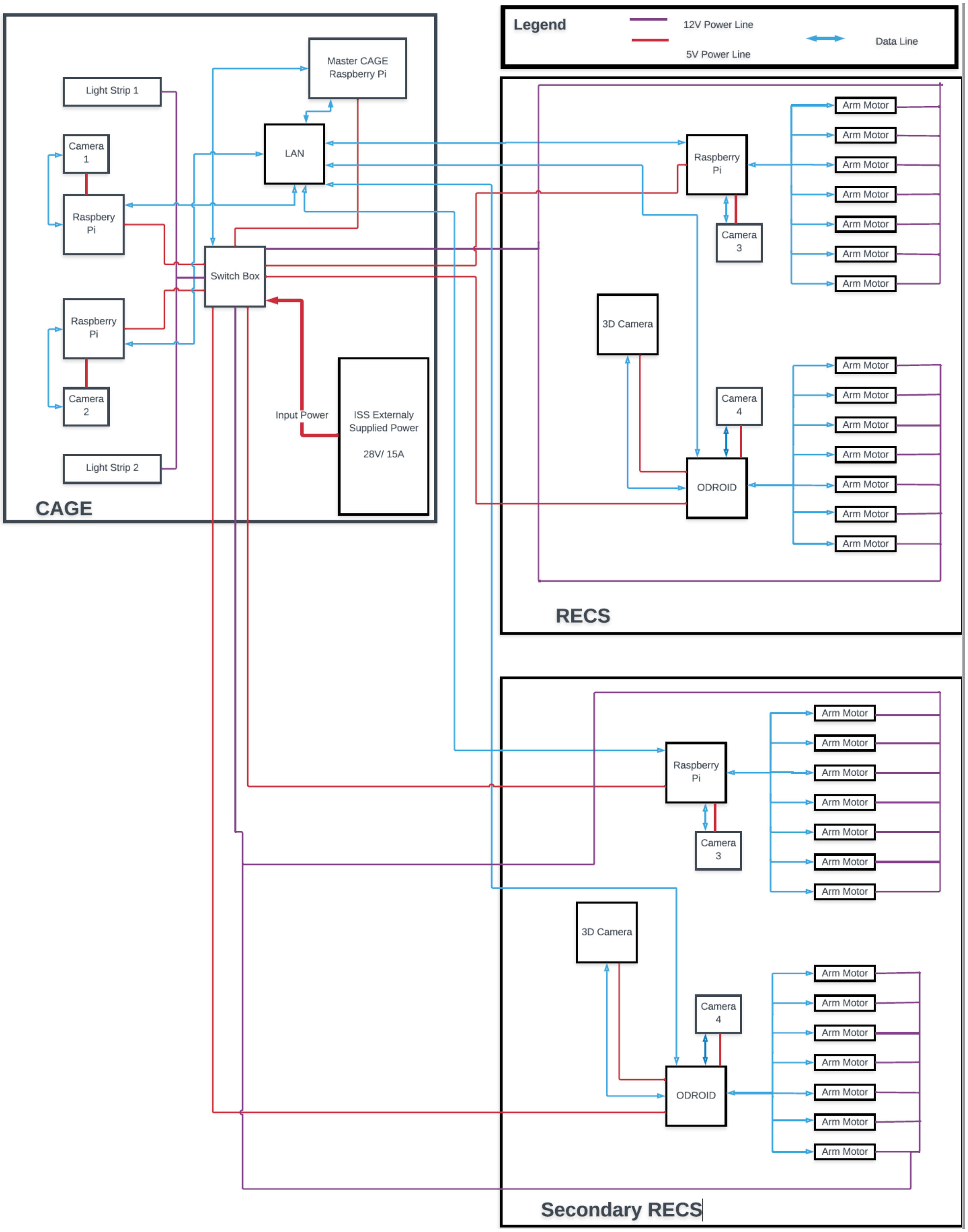

Figure 17: System block diagram including power and data transfer lines

The master Raspberry Pi 3 will be powered on at all times as long as power is supplied to the system. All power lines aside from that of the master Pi will include a CUI Inc. PYB20 DC-DC converter, a Linear Technology LTC1478 signal selector switch, and a Panasonic TX dual coil latching solenoid. The master Pi line will only have a DC-DC converter. The DC-DC converters will serve as power conditioners, taking the raw power supplied from the ISS at 28 V and 15 A and stepping it down to either 5 V/2 A or 12 V/1.6 A, depending on the component. Next, the signal selector switch will carry the conditioned power through the switch, while accepting a signal from the master Pi. The signal from the master Pi will transfer through the switch to activate the dual coil solenoid in an on or off position, depending on the received signal. If an on signal is sent, the conditioned power from the DC-DC converter that was carried through the switch will be output across the solenoid in order to properly power the respective component.

Per NASA requirements, it was necessary to ensure that RECS' internal components will produce heat within the allowable sensible heat limit of 250W. The power budget analysis reveals that at maximum power, RECS will draw 36.84 W, therefore inputting a maximum of 36.8 J/s into the system. Thus, NASA requirements are satisfied.

ON-ORBIT TESTING AND VALIDATION

While RECS and the CAGE will ultimately be jettisoned after completing its integration period, NSTAR, in conjunction with the USNA Small Satellite Program, is already in the early phases of designing its successor. In addition to considering lessons learned from RECS, NSTAR hopes to implement advancements made within specific independent student research.

For instance, one student research project being conducted within the USNA Small Satellite Program seeks to implement machine learning-based monocular pose estimation into the satellite's vision sensor. Pose estimation is an integral process for autonomous satellite servicing to guide the servicing satellite for rendezvous and capture of the satellite to be serviced. However, existing methods employed for this purpose require 3D imagery, and rely heavily on an accurate geometrical model of any given target satellite. This results in high computational load and high sensitivity to environmental and sensor noise. The use of machine learning via Convolutional Neural Networks (CNNs) for this task is promising as CNNs can be trained to be resilient to noise and to provide pose estimates from 2D imagery. Trained CNNs incur low computational demand, which enables real-time pose estimation capability in small form-factors. However, the greatest weakness to the real-world use of pose estimation CNNs is generally the lack of real imagery that is labelled with detailed pose data in order to train the networks prior to implementation, forcing the use of computer-generated imagery for this purpose; this in turn leads to high magnitudes of error when the CNN is exposed to real-world data. This research centers on the use of Generative Adversarial Network (GAN) architectures to modify a set of computer-generated imagery based on the characteristics of a sparse set of real data, which would enable the creation of a photorealistic training set of sufficient size and diversity in order to train CNNs for robust, real-world pose estimation. The photorealistically-trained pose estimator CNN would then be uploaded to the ODROID-XU4 and employed real-time using the monocular RGB sensor integrated in the D435 camera.

Considering this and other research, in future iterations, NSTAR hopes to return to a free-flyer model capable of performing an on-orbit self-diagnostics demonstration. Ideally, this model would launch into orbit with a "bin of parts" and assemble something from those parts in space. With research collected from RECS, NSTAR will be able to further develop and improve upon a capable, on-orbit repair CubeSat.

CONCLUSION

As both private and commercial space agencies develop increasingly longer and more complex projects, more robust on-orbit assembly and diagnostic systems have become essential for mission success. Existing solutions have thus far proven to be both risky and expensive. NSTAR seeks to enable the construction of large, complex structures with a "born-in-space" architecture at a reduced cost and with a greater ability to run diagnostic assessments in flight. The long-term NSTAR vision is a fleet of highly capable, autonomous CubeSats equipped with robotic arms. This solution will more adequately meet the space industry's current need for functional on-orbit assembly and repair technologies.

In coordination with the Space Test Program (STP), RECS was developed as the project's second iteration. In order to avoid the power and communication failures faced by its predecessor RSAT, RECS will complete testing aboard the ISS as an internal payload. Should the system face issues during testing, astronauts will attend to and repair malfunctioning equipment. In this way, the NSTAR ground team will acquire accurate, usable data to inform future project iterations.

Built in the form of a 3U CubeSat, RECS is a robotic arm system housed inside a guarded enclosure known as the CAGE. Within the CAGE and aboard the ISS, RECS will complete three mission objectives. RECS will fulfill the initial, necessary capabilities of an autonomous construction and repair robotic satellite such as pointing accuracy and object tracking, manipulation, and inspection. A successful mission will indicate further entry into a new field of space robotics, allowing space systems to remain in operation longer, reduced mission costs, and the expansion of space-based scientific research.

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