ABSTRACT

Title of thesis: ROBOTIC TECHNOLOGIES FOR MINIMIZING CREW MAINTENANCE REQUIREMENTS IN SPACE HABITATS

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The International Space Station (ISS) is crewed continuously by astronauts conducting scientific research in microgravity. However, their work is not limited to scientific research alone; in fact, logistics, maintenance, and repair tasks on the ISS require more than 80% of available crew time, severely limiting opportunities for performing scientific experiments and technological development. NASA is planning a new project known as Gateway (also referred to as the Lunar Orbital Platform-Gateway). This station will orbit the Moon and be uncrewed for 11 months per year. Astronauts will only be present in the outpost for a limited period of time and will not always be available for continuous repairs and maintenance, as is required for Gateway to operate. Therefore, robotic system(s) are necessary to regularly accomplish these tasks both in the absence and presence of astronauts. Throughout this project, Team ASTRO (Assessment of Space Technologies for Robotic Operations) explored the feasibility of integrating dexterous robotic systems in space habitat architectures to perform routine and contingency operational and maintenance tasks. Ultimately, this allows for astronauts, when present, to focus on exploration and scientific discoveries. The team conducted this research through three approaches: Gateway component analog taskboard

development and end effector assessment, Cargo Transfer Bag (CTB) manipulation and logistics, and AprilTag situational awareness simulation development. Based on analyses and experimental results gained from this research, the team found that robotic systems are feasible alternatives for space habitat operation. Team ASTRO also determined that AprilTags can be used for optimization of the Gateway design to facilitate uncrewed operations and robotic servicing to improve crew productivity when present.

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Key Terms and Abbreviations

1) **Baxter**: Industrial robot design from Rethink Robotics with two manipulator arms and an animated face.
2) **Bi-TRRT**: Bi-directional Transition-based Rapidly-exploring Random Trees. Motion-planning algorithm.
3) **CTB (Cargo Transfer Bag)**: Foldable fabric containers used by NASA to send cargo to and from space stations.
4) **DOF**: Degree(s) of Freedom.
5) **ECLIPSE (Extensible Concept for Live-In Pressurized Sortie Elements)**: One of two space habitats owned by the University of Maryland's Space Systems Laboratory. ECLIPSE is the older of the two, and was motivated by applications of lunar exploration. ECLIPSE is a two-level habitat, 3.65 meters in diameter and 5.5 meters tall.
6) **ECLSS (Environmental Control and Life Support System)**: NASA regenerable life support system that generates clean water and air for astronauts on the ISS.
7) **End Effectors**: A collective term referring to the part of a robotic arm that interacts with its surroundings, mimicking the functionality of a human hand. Appearance-wise, an end effector could look and function very similar to a human hand, or it could be as simple as a two-pronged claw.
8) **EPM**: Electro Permanent Magnet.
9) **EVA (Extra-Vehicular Activity)**: An activity conducted by an astronaut outside of a spacecraft. These tasks are completed to maintain the spacecraft when they are too advanced or complicated for a robot to handle, or simply for research purposes.
10) **Gateway (Lunar Orbital Platform-Gateway/LOP-G)**: A space system similar to the International Space Station (ISS), currently being designed by NASA to orbit the moon. It would be used both for lunar research and as an entrance point for future lunar habitats. It would also serve as a place for preparation and storage for potential trips to Mars.
11) **GUI**: Graphical User Interface.
12) **HAVEN**: The second space habitat owned by the University of Maryland's Space Systems Laboratory. HAVEN has a larger interior space (5 meters in diameter), and is a single-level habitat.
13) **IEEE**: Institute of Electrical and Electronic Engineers.
14) **Intra-Vehicular Activity**: Activity conducted inside of a spacecraft or space habitat.
15) **ISPR**: International Standard Payload Rack.
16) **ISS (International Space Station)**: A space station in low earth orbit, operational since 2000, that serves as a laboratory in a microgravity environment. It is serviced by a crew of up to six astronauts and a set of extravehicular robots on the outside of the station.
17) **JAXA**: Japan Aerospace Exploration Agency.
18) **MDMs**: Multiplexer/DeMultiplexers.
19) **NASA**: National Aeronautics and Space Administration. Government agency responsible for US space exploration, space science, earth science and aeronautics

research.

20) **NIST**: National Institute of Standards and Technology.
21) **OMPL**: Open Motion Planning Library.
22) **ORUs (Orbital Repair Units)**: A form of space habitat design involving modular structures that can be removed and replaced whenever needed, rather than replacing individual parts in the system. A single system or a large combination of systems can all be replaced at once.
23) **PLA**: Polylactic Acid. Standard material used for 3D printing.
24) **Ranger NBV (Neutral Buoyancy Vehicle)**: Six degree-of-freedom single arm dexterous manipulator within the Space Systems Laboratory.
25) **Ranger TSX (Telerobotics Shuttle Experiment)**: Two arm dexterous manipulator within the Space Systems Laboratory.
26) **ROS**: Robot Operating System.
27) **SPHERES**: Synchronized Position Hold Engage Re-Orient Experiment Satellites.
28) **SSL (Space Systems Laboratory)**: A research facility at the University of Maryland, College Park dedicated to research on robotics and structures for use in outer space, as well as human factors in space exploration. SSL has a neutral buoyancy tank, which is 50 feet across, 25 feet deep and holds up to 367,000 gallons of water. It is used to simulate microgravity environments, like the ISS, and environments with different gravitational forces than Earth such as Mars and the moon.
29) **Team ASTRO**: Assessment of Space Technologies for Robotic Operations.

1. Introduction

1.1. Description of Problem

Ever since 1998, the International Space Station (ISS) has been in orbit around Earth and at no point since its launch has the ISS been uncrewed [1]. This is because the ISS requires constant maintenance in order to sustain a habitable environment and keep all systems running at peak efficiency. The main advantage of the ISS is that research can be conducted in microgravity to observe how variables change in a space environment. This research spans a wide variety of topics, ranging from astronomical research to medical and astrobiological studies [2], [3]. However, a large portion of astronauts' mission time on the ISS is spent performing maintenance work, rather than conducting ground-breaking research. This issue has the potential to be amplified in the future, with the launch of the lunar orbiter known as Gateway. The motivation behind Gateway is that it will allow for research in cislunar space and act as a 'pit stop' for astronauts embarking on long-duration space travel. Currently, it is planned that Gateway will be uncrewed for nearly 11 months out of the year [4]. Without a crew to maintain and operate the outpost, robotic systems become necessary. Therefore, finding a feasible methodology to maintain these habitats both in the absence and presence of humans would increase allocated time for research, as well as allowing Gateway to become a feasible mission concept. Robotic systems have the potential to complete the required tasks necessary for continued operation of Gateway because of their ability to mimic humanoid movements and adaptability for diverse applications. While multiple studies show the potential for utilizing robotic systems, decisive proof that a robot can complete space habitat maintenance tasks is necessary for it to be a suitable solution. Throughout this paper, Team ASTRO will explain what operational and maintenance tasks the team was able to complete using two robotic systems (Baxter and the Ranger NBV arm) and what simulations the team created to expand upon the team's experimental results. This will culminate in a proof-of-concept assessment on the feasibility of implementing robotic systems in space habitats.

1.2. Research Questions

When completing this research project, Team ASTRO sought to further investigate the usefulness of incorporating robotics in a microgravity habitat. The first question that the team addressed was: What specific logistics tasks could be performed by robots on Gateway? In order to conduct useful research, Team ASTRO needed a sufficient understanding of problem areas and common operational tasks on space stations so the team could select useful tasks to perform with robotic systems. Team ASTRO also addressed the question of how the team could use university resources such as the Neutral Buoyancy Research Facility, the Ranger Dexterous Manipulator robotic arm, and (to a lesser extent) the ECLIPSE and HAVEN habitats to assess robotic capabilities. Building an entire robot or mock-up of a habitat is an extremely expensive and time consuming endeavour, so the team wanted to utilize as many existing resources as possible. This would allow the focus of the project to be on data collection. Laboratory testing of current resources also helped the team determine what existing hardware is best suited for the identified tasks and what modifications are necessary to optimize the robotic system for use on the Lunar Gateway. Lastly, safety was an important concern with this project. Developing a highly capable maintenance and repair robotic system that was dangerous when interacting with humans would not be acceptable. Even if the robot could complete many types of tasks, it would never be approved for use by the National Aeronautics and Space Administration (NASA) if it posed a safety risk to astronauts or station hardware. Over the past three years, Team ASTRO focused on answering the following question: How can robotic systems be utilized to perform operational and maintenance tasks on the Lunar Gateway to upkeep the habitat while uncrewed and allow astronauts to focus on science and mission objectives when crewed?

2. Literature Review

2.1. Overview

Habitat design and robotics are two fields that have grown significantly in recent years due to the push to return humans to the Moon and send them on more complex long-duration missions. However, there have been very few instances in the aerospace industry in which the two fields have been successfully integrated. Therefore, it is important to thoroughly analyze the attempts that have been made and determine what could be improved in order to create a large-scale habitat maintenance robotic system that is reliably safe, efficient, and useful.

This literature review will begin by examining instances of robotic servicing in space, followed by an analysis of the tasks the human crew currently completes while onboard the International Space Station to determine opportunities for robotic assistance. In addition, existing literature on robotic taskboard testing will be analyzed to determine a basis for Team ASTRO's taskboard testing, which the team used to determine the capabilities and limitations of robotic arms within the Space Systems Laboratory and end effectors designed by the team. Robotic capabilities can also be extended beyond basic operational tasks to logistical and diagnostic tasks, which include visual inspection of equipment status for fault detection purposes, as well as logistical and organizational management of cargo transfer bags. These tasks are further described in this literature review.

This literature review will conclude by exploring the differences of the new NASA Lunar Gateway compared to previous space habitats. The proposed concept of operations has created a unique opportunity for robotic operational and maintenance systems to be necessary for the continued operation of the outpost, which gives this research a direct application and contribution to the near-term future of space exploration. In addition, this review will identify gaps in existing research to allow Team ASTRO to assess what aspects to focus their research on.

2.2. History of Robotic Servicing in Space

NASA has investigated and pursued various designs for a robot that could function while in microgravity to assist astronauts in maintenance tasks onboard the International Space Station. Explored designs include the two-armed humanoid robot, Robonaut; a modular robot that navigated via a web of cables, Charlotte; the Canadian Canadarm robotic arms, which were implemented on Space Shuttle Orbiters; and free-flying robots SPHERES and Astrobee. These robots all differed greatly in design, making each one more equip for a specific set of tasks.

2.2.1. Robonaut

The greatest amount of resources and time allocated to NASA's microgravity robots has been invested on Robonaut and Robonaut 2. These were humanoid robots built by NASA in the early 2010s with the goals of safely interacting with humans, tools, and interfaces on the ISS. Robonaut was ultimately designed to be an astronaut assistance and human spacecraft maintenance robot [5]. Robonaut 2 was the next iteration of the original robot that added two climbing manipulator legs (pictured in Figure 1) and upgraded processors and sensors [5]. Robonaut 2 possessed the capability of transporting payloads of 9 kg, minimizing the amount of manual labor astronauts were required to conduct. Robonaut 2 also was able to manipulate tether hooks via teleoperation and pull back protective jackets to look for damage on hoses [6]. To allow for crew interactions, the Robonaut systems attempted to implement a Natural Language Interface capability. The Natural Language Interface utilized Python PyAudio Library and Google Cloud Speech to detect voice commands and link them to a user specified command list. This allowed Robonaut to then carry out the command. This system was important because it would have enhanced the collaboration possible between robots and humans. During testing, however, the cognitive capabilities of the robot were found to be only limited to the Natural Language Interface and a vision processing system, which greatly restricted the robotic manipulation aspects of the system [7].

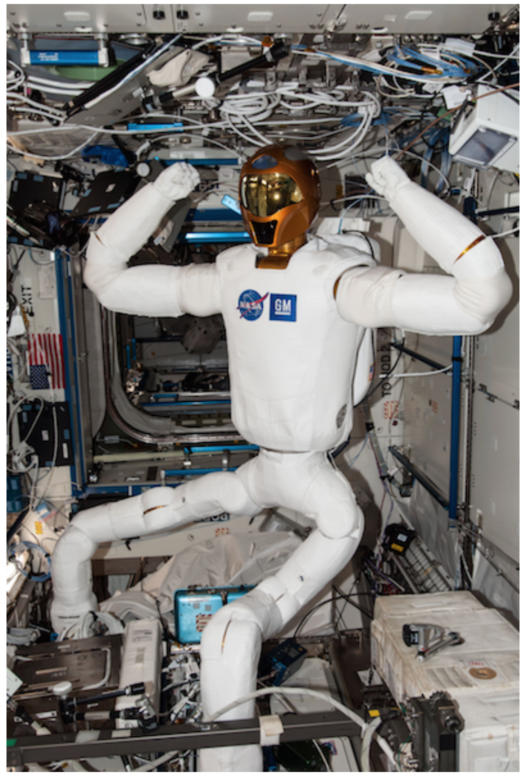

Fig. 1 Image of Robonaut 2 inside the ISS [5].

Robonaut 2's time on the ISS ended when it was returned to Earth in 2016 due to a failed upgrade made to the system back in 2014. Astronauts had spent approximately forty hours performing an upgrade on the system that would increase its mobility by attaching legs to the body of Robonaut [8]. In the process of completing this upgrade, there were multiple system-level failures, including an electronic sensor failure and communication and telemetry failure. Essentially, any attempt to engage the system would result in immediate failure. On the ground, it was determined that this failure stemmed from a lack of a ground path to allow the electric current to travel from the computer chassis to ground, which resulted in a slow deterioration of the robot [8].

The end of the Robonaut program on the ISS made it clear that Team ASTRO needs to work to mitigate potential problems and focus on consistency so that astronauts do not have to constantly repair the robotic system. The goal of the robotic system the team is developing is to reduce the time spent by astronauts doing simple maintenance tasks; the system needs to be robust and easily adaptable so that it, itself, does not require significant maintenance. During testing, it is important that Team ASTRO's system can complete trial runs repeatedly without issue. Ultimately, the development of Robonaut and Robonaut 2 emphasize the importance of implementing intelligent systems that can provide maintenance and logistical support in spacecraft concepts that are not always crewed, such as Gateway [7].

In addition, the leg mobility system of Robonaut emphasizes the necessity for a mobility system that would allow the robots to move around the space habitat. The robotic systems on Gateway will likely have to transport objects throughout different modules or perform complex dexterous manipulations tasks. Lessons learned from the Robonaut program are important in advancing the technology readiness levels of these complex systems, and these lessons can be applied to the team's robotic system [9].

2.2.2. Charlotte

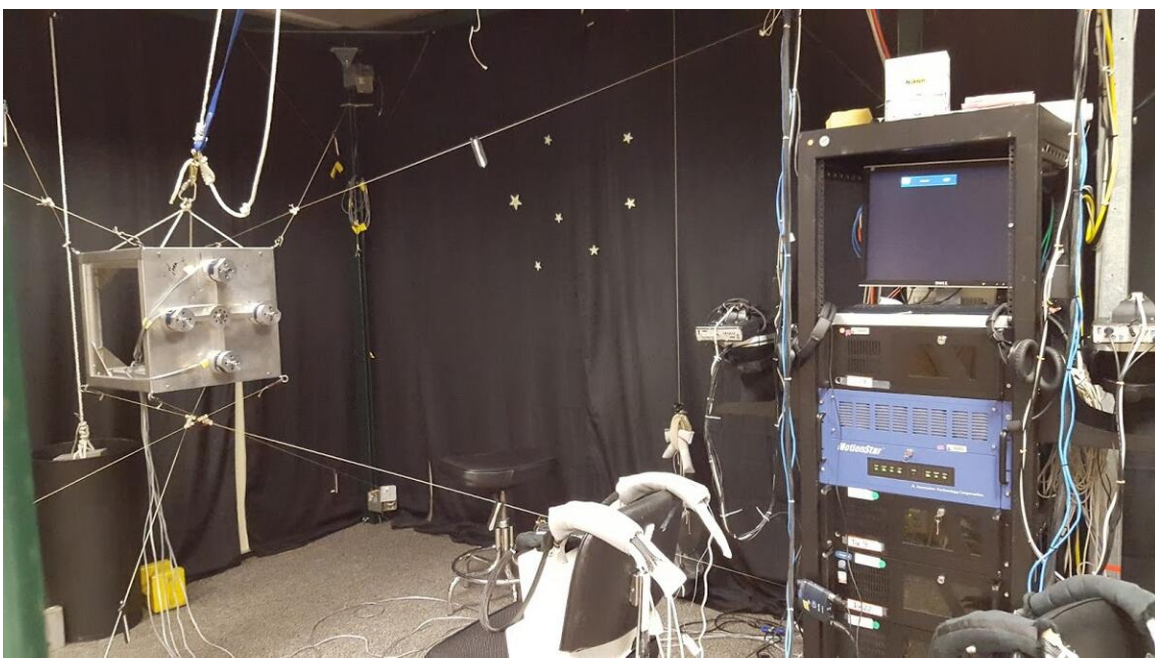

Fig. 2 Charlotte shown on the left now used by NASA for VR training completed on the ground [10].

The Charlotte™ Intra-Vehicular Robot was a robot used onboard the ISS back in the 1990s that was capable of operating switches, buttons, knobs, and dials, as well as performing video surveys of experiments and switch panels. The robot was teleoperated and had six degrees of freedom, meaning it could move via translation and rotation in three dimensions. Charlotte^{TM} was able to move around the Space Station via a system of eight cables, as depicted in Figure 2. The robotic system's spider-like resemblance resulted in its name [11].

Charlotte^{TM} Intra-Vehicular Robot was created with the intent to reduce the existing crew work load on the ISS and provide increased monitoring of experiments to aid in the earlier detection of problems. Financial constraints resulted in engineers not making modifications to crew interfaces to allow them to be more "robot friendly," driving the cable design of the system. It was also deemed essential that the flight robot could be easily programmed to complete a wide variety of tasks autonomously or via teleoperation. These requirements led to the final design and creation of the IVA (Intra-vehicular activity) robot Charlotte^{TM} [11].

According to a conversation with Dr. David Akin of the University of Maryland Space Systems Laboratory, the wire system used to control Charlotte proved to be problematic. The large volume required for the cables interfered with astronauts moving within the same space. In addition, the cable mobility system greatly limited the speed at which the robot could move, as well as the payload mass it could carry [12]. Charlotte has since been retired from spaceflight and modified by Johnson Space Center's Virtual Reality Lab to help train astronauts on the ground [10].

Charlotte is an excellent example of a system that was too difficult for astronauts to work and maneuver around to justify its continued operation on the Space Station. The objectives of the robot's capabilities, however, such as onboard vision recognition, automation and deduction of attachment geometry, and modification of user interfaces onboard the ISS would allow for operations and maintenance on the ISS to be done remotely and without astronauts [11]. Aiming to minimize the time astronauts spend maintaining the station and maximizing the amount of science being conducted were excellent objectives for the Charlotte program. However, it has been shown that the major drawback of this system's complex cable system, resulting in inhibiting the movement of astronauts, was enough to remove the robot from the ISS. This emphasizes the importance of developing a safe robotic system that interacts comfortably with astronauts and does not interfere with their work, when they are present. After Charlotte's first flight test on the ISS, it was noted that the, "high inherent safety [of a tendon suspended robot] is an invaluable quality," for the system to possess [13]. Although the bulk of Team ASTRO's research will be focused on the capability of a robotic system to maintain an environment in the absence of humans, the system still needs to be able to maneuver successfully around astronauts or even be stowed away safely when humans are present.

2.2.3. Canadarm

The Canadian Space Agency has contributed to the field of robotic servicing in micro-gravity with their Canadarm project, shown in Figure 3. The Canadarm was a series of robotic arms developed by the Agency, implemented on the Space Shuttle orbiters beginning in the early 1980s [14]. During its time in operation, the Canadarm was responsible for many aspects of external space operations, such as retrieving satellites for repair, sending satellites into orbit, and assisting astronauts during spacewalks [14].

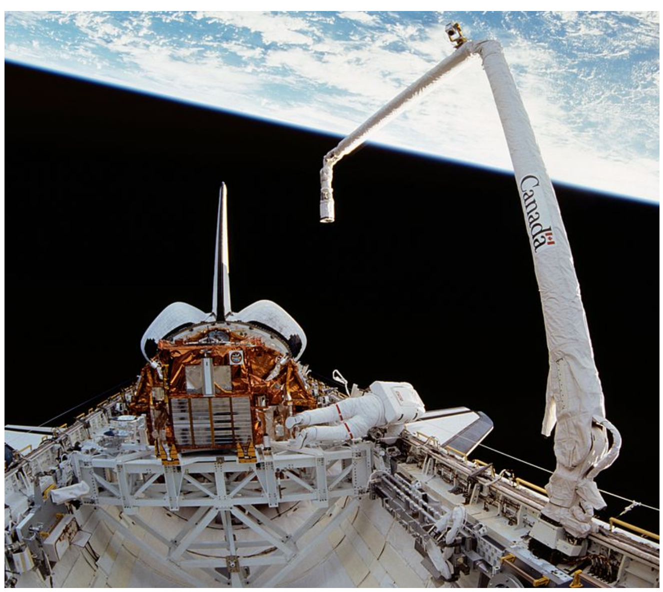

Fig. 3 Canadarm on orbit as a part of the Shuttle's Remote Manipulator System [15].

Canadarm was used for extravehicular actives and while the focus of this project is on creating a robotic system to perform intravehicular repairs and maintenance tasks, robotic systems initially intended for external use can still influence the team's choice of internal robotic system. It is important to note that the jointed arm design of Canadarm has always performed flawlessly on the missions it assisted with and that the elbow and wrist joint cameras proved especially useful in completing visual inspections of the shuttle and payloads [14]. This emphasizes how simple and elegant solutions have the potential for less mechanical or electrical failures. The success of the Canadarm also corroborates the team's choice of using existing robotic arm systems within the Space Systems Laboratory. Additionally, in the development of the project, Team ASTRO must keep in mind how the robotic system will transmit useful data back to ground control. Deliberate and movable camera placement would allow for video monitoring of an unoccupied space station, which would be useful in performing visual inspections of the station from the ground.

2.2.4. SPHERES & Astrobee

In addition to the aforementioned robots, there have also been a handful of free-flying robots onboard the ISS. SPHERES is made up of three satellites on the ISS, and has been in operation ever since 2006. Two SPHERES satellites can be seen in Figure 4. They have been used to test a variety of software and hardware systems, with an example being the "Tether Slosh" experiment conducted in December 2017 [16]. The purpose of this study was to investigate if tethering could be used to tug vehicles in a microgravity environment. This was done by using two SPHERES satellites to tug a liquid tank inside the ISS and evaluate the fluid dynamics of how liquid in the tank sloshes in microgravity [16]. This sort of investigation could easily be extended to moving other objects around a space habitat, such as cargo transfer bags.

Another free-flying robot found on the ISS is the Astrobee robot, also shown in Figure 4. This robot was designed specifically to assist astronauts with routine activities so they can focus on more advanced scientific tasks. They can be controlled autonomously or via teleoperation, and can perform tasks such as taking inventory and experiment documentation [17]. Although these robots can possibly be extended to assist with science experiments and space station monitoring, these robots are currently extremely limited in their overall functionality.

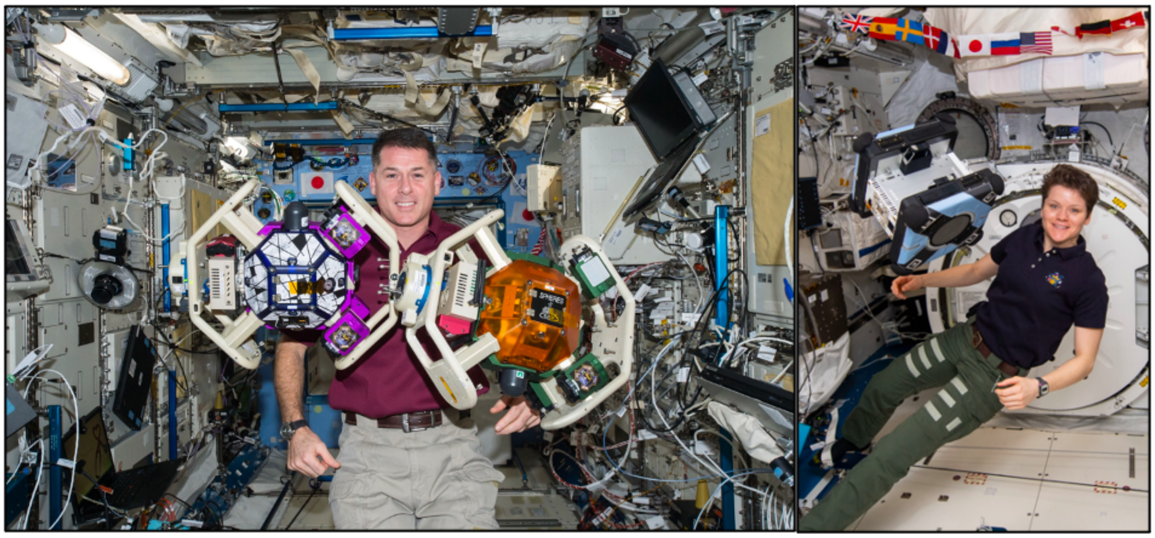

Fig. 4 Astronaut Shane Kimbrough with two SPHERES units on the ISS (left) [16] and astronaut Anne McClain unpacking the first Astrobee unit on the ISS (right) [17].

2.3. Autonomous vs. Teleoperated Robots

The method used to control the robotic system has significant implications on its safety and complexity. Teleoperation refers to a system that is being operated by a human at a distance. Autonomous operation of a robot describes a system that can function on its own without human input. The following section discusses the benefits and drawbacks of each form of control.

2.3.1. Safety for Robot and Human Interactions

The development of safety protocols for autonomous robots interacting with astronauts is vital for robot/human interactions. A teleoperated system is under the control of a human at all times. This creates a smaller risk of an incident occurring that would damage equipment or injure an astronaut. However, there is an opportunity for operator error with teleoperation. When a robot is able to operate autonomously, sufficient safety parameters and operational time much be present [18]. If the robot can "learn" from completing tasks and moving in its environment, the risk of damage decreases. Autonomous operation has higher costs on the front end, developing and testing the software, compared to the life long costs of using a human to operate the robot whenever a task needs to be completed [19].

When working on teleoperated or autonomous robots, the team needs to implement safety protocols as these will be vital to protect the operators and astronauts. With teleoperated robotics, the focus would be on developing safety protocols that the operator must follow. With autonomous robotics, safety measures would include extensive development and testing of required algorithms. Although autonomous and teleoperated robots can be extremely expensive during development and throughout the duration of operation, the cost of teleoperation is negligible for initial testing as these resources are readily available within the Space Systems Laboratory. Autonomous operation has many benefits, but initial development of these algorithms is time-consuming and increases the overall complexity of the system. Ultimately, team ASRTO's efforts will involve both teleoperated and autonomous elements. Initial data collection will be conducted via teleoperation in order to increase the amount of data able to be investigated, but the team will also investigate opportunities for autonomous algorithms to be implemented in future iterations of this project. Operator safety will be accounted for during testing, and human/robot interaction on a space habitat will be evaluated.

2.4. ISS Crew Task Designation

Crew tasks on the International Space Station are designated through the Operations Planning Timeline Integration system [20]. For each mission, crew and ground control review the daily schedules and tasks of short-term and long-term crew members. Scheduled work activities for crew members include logistics operations, upkeep operations, repair, scientific operations, extravehicular activities, medical tasks, exercise, work preparation, loading/unloading, conferences, public relations activities, and vehicle operations. Historically, crew time utilization on the International Space Station has prioritized routine operations, maintenance tasks, and repair tasks over the completion of experimentation and scientific discovery. Approximately 16 percent of crew work time is dedicated to maintenance and repair and 7 percent to operational tasks, as shown in Figure 5 [20].

Per week, approximately 12.8 hours of crew time are dedicated to routine operational tasks and 11.6 hours to routine logistical operations [21]. Logistical loading and unloading of CTBs requires approximately 10 minutes of crew time per CTB. This can easily add up and take away from valuable mission time, as astronauts have to unload tens of CTBs at a time. Preventative maintenance and corrective repair tasking duration is dependent on the respective mission architecture. Historically, an increase in crew maintenance operations by 0.5 hours corresponds to a 0.3 hour mission operation decrease per work week [21].

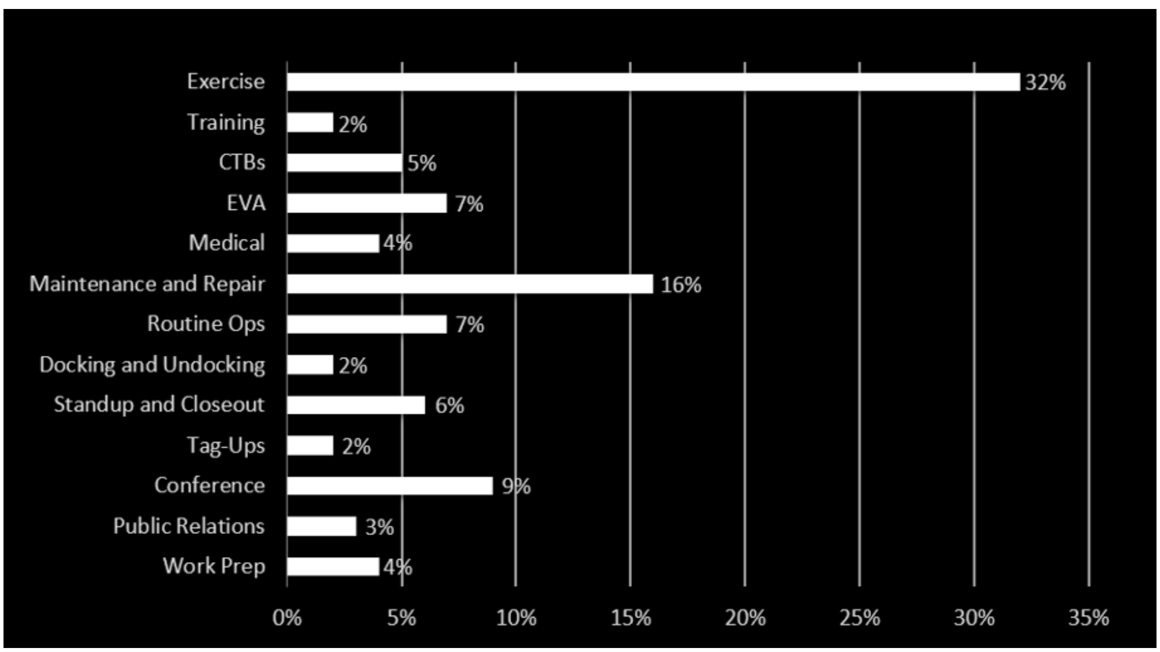

Fig. 5 International Space Station crew time allocation percentages on work activities. [20].

Crew task allocation on the Lunar Gateway will vary from that utilized for crew members on the ISS. Logistics operations are anticipated to take approximately 3 hours per day, or 21 hours per week, with a crew of three people [22]. Outfitting operation time is expected to decrease, along with CTB unloading and loading and work preparation time. Preventative maintenance and corrective repair remains dependent on the mission architecture. Only four crew members are intended to inhabit the Lunar Gateway at any given time [23], with crew members on a 30 day time model for crew time allocation. Since more than half of a standard work week is going to be dedicated to routine operations, this emphasizes the need for robotic systems to be implemented in the Lunar Gateway. In addition, the short crewed mission duration only leaves a small window for scientific opportunity. This time must be as optimized whenever an opportunity presents itself to complete as many scientific objectives as possible.

2.5. ISS Crew Task Categories

The types of operational and maintenance tasks that Team ASTRO is cataloging for this concept are based off of the common internal in-flight maintenance tasks performed on the the International Space Station. The three categories of in-flight maintenance on the ISS include Preventative Maintenance (routine cleanings/inspections), Corrective Maintenance (repairing/replacing faulty hardware), and Diagnostic Maintenance (determination of fault location) [24]. Specific task examples regarding Preventative and Corrective Maintenance that could be explored include the following:

- "Remove and Replace" tasks
- Disassembly/reassembly of malfunctioning life support systems
- End-to-end repair of an oxygen generator assembly

These tasks will help determine the varying complexity of assignments that a robotic system can handle. Starting with simple remove and replace tasks, such as replacing electrical connectors, can help determine the dexterity and accuracy of the robot. Later transitioning to a full-scale repair of different systems can demonstrate the feasibility of performing a sequence of commands and movements. Diagnostic maintenance is discussed further in section 2.7.

2.6. Taskboard Testing

Robots often have significant issues manipulating objects with complex geometry. As a result, robotic systems often utilize some form of an end-effector, a specialized fixture mounted on the end of a robotic arm to perform a task. In order to test how a robot performs during different tasks, a certain standard must be set to compare performances. The Institute of Electrical and Electronic Engineers (IEEE) has defined an extensive set of metrics under their Robotic Hand Grasping and Manipulation Technical Committee [25]. The metrics for grasping and manipulation of objects is broken down into two categories, kinematics and kinetics. The former describes the shape of the motion, being described using position or velocity. The latter describes the forces or effort imparted by the robot, often testing loads, torques, or electrical current. Effort exerted by a robot arm is usually monitored with a load cell. This can include measurements for strength of a certain finger/appendage and see what the maximum force imparted is. Alternatively, load cells can assist with touch sensitivity tests to determine the maximum impact force after colliding with an object. In regards to kinematics, robot arms can be benchmarked with their ability to move an object into a desired orientation. In order to catalog a variety of tasks which could be performed by an end-effector, in-hand manipulation is the primary benchmark to be studied. In-hand manipulation involves tracking the relative position of an object after interaction from a robot arm. This could be as complex as using tracking systems to monitor the relative motion of an object, or as straightforward as using simple mechanisms to confirm manipulation. Some examples include buttons, switches, knobs, and other similar components. A taskboard uses a variety of these components to not only test a robot arm's dexterity and flexibility, but also test their precision and accuracy. Many studies of robotic systems employ taskboard tests tailored to a specific robot arm to test the capabilities of its motion. A few examples of these taskboards are shown below in Figure 6.

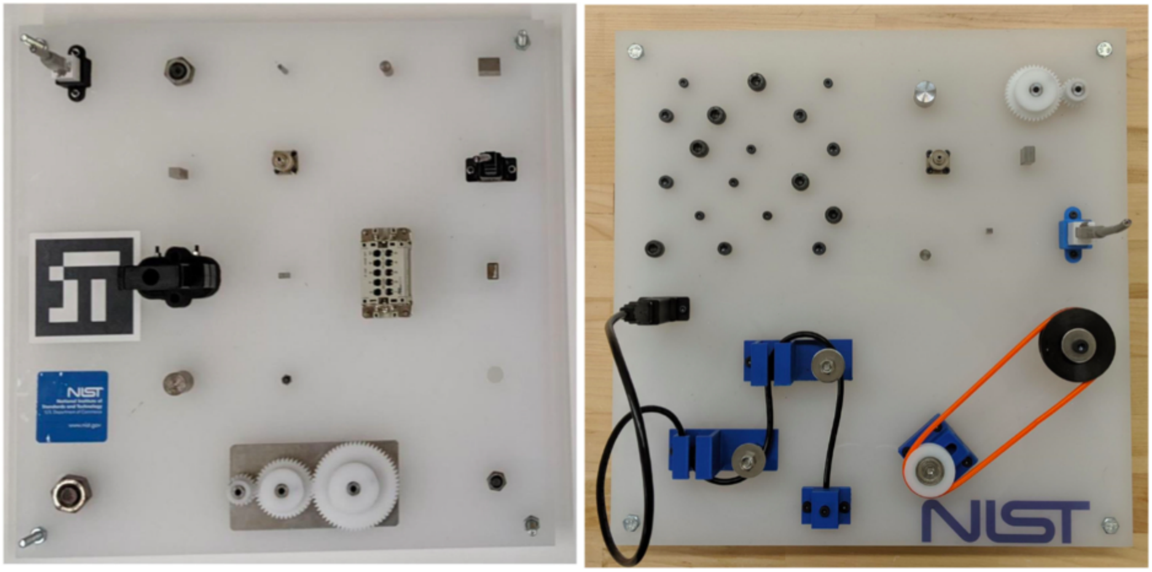

Fig. 6 NIST robotic taskboard examples from [26]. The taskboard on the left was designed to assess a robot's ability to perform peg insertion, mesh gears, thread nuts, and insert electrical connections. The taskboard on the right possesses similar tasks, and was used to look at flexible gripper system.

While bench-marking is the primary method to research robotics, taskboard layouts are not uniform, and are usually designed specifically for the robot being tested. The National Institute of Standards and Technology (NIST) lays out sets of test methods and metrics to be used during testing [25]. Some of the taskboard components are described in great detail in this document to provide insight into valid taskboard metrics. For example, one task is described as inserting pegs. By using sets of different sized pegs in different orientations, one can test a broader range of motions from the robot arm. A similar example includes threading nuts, where the position and orientation of the nuts need to be precise before performing any rotational motion. Some of these taskboard tasks overlap with benchmarks for finding forces imparted by a robot arm. Any tasks that involve applying a force to insert a part such as inserting a connector, or tasks that require pushing a button or switch can produce results on both the sensitivity of a robot arm as well its strength. Team ASTRO will take previous taskboard iterations, as well as NIST standards, into consideration when designing their taskboard for robotic system and end effector assessment.

2.7. Inspection of Equipment

In order to effectively fix faulty pieces of hardware, the robotic system must first be able to detect and identify faults. This is done on the ISS by using Diagnostic Maintenance, which is the process of detecting where faults occur [24]. One piece of technology used for this is the Centerline Berthing Camera System on the ISS. This system includes cameras mounted in hatch openings that are used to verify alignment of docking spacecraft. Since ground control continuously has eyes on the ISS (and will also be monitoring Gateway), camera systems will serve as an important aspect of equipment inspection and monitoring.

Another technology on the ISS that is used for diagnostic maintenance are Command and Control Multiplexer/DeMultiplexers (MDMs), which stream data about all electronics components and report any anomalies [24]. The function of MDMs are split into three tiers in order of how critical the function is. Tier 1 MDMs allow ground control to send commands and receive telemetry data from the ISS, as well as allowing ground control to take necessary action in cases of emergency. Tier 2 MDMs control overall spacecraft functionality, such as the regenerative life support systems, ventilation and temperature control. Finally, tier 3 MDMs receive data from sensors and control firmware, allowing it to monitor smoke detectors, control heating, monitor cabin pressure, etc. In order for a robotic system to detect problems, it would need to receive information from the tier 2 and 3 MDMs. This would allow for a robot to detect and fix leaks, as well as repair a faulty life support system, if provided with the correct tools.

An example of a maintenance robot is a robotic system known as SmartGaurd, pictured in the left image of Figure 7 which was able to autonomously detect visual anomalies and hot spots inside of electrical power substations [27]. This was accomplished with a visible light and infrared camera along with a data center for a reference of what should be called an anomaly. Similar infrared and thermal technology can also be observed on the 2020

Electrical Substation Inspection Robot, depicted in the right image of Figure 7, indicating that this methodology in fault detection is feasible and could be further explored for the Gateway maintenance system [28].

Fig. 7 Examples of maintenance inspection robots: SmartGuard Robot (left) [27] and Electrical Substation Inspection Robot (right) [28].

This same process can be followed on the ISS to detect issues like leaks. On the International Space Station, once a problem is detected astronauts can make appropriate repairs, however, on Gateway anomalies will need to be detected by and appropriately dealt with using robotic systems if crew members are not present on the station. Therefore any robotic system will need to be able to empirically detect problems, whether that be trough the use of cameras or sensors.

2.8. Cargo Transfer Bags

In order to get necessary tools and supplies into space, they are loaded into Cargo Transfer Bags (CTBs) and then launched onboard a spacecraft during a resupply mission.

CTBs are made of a flexible Nomex cloth material and are available in four different sizes: half, single, double and triple [29]. The dimensions of each size CTB are listed in Table 1, below.

CTB Size	External Dimensions (inches)
Half-Size	9.75 x 16.75 x 9.25
Single-Size	19.75 x 16.75 x 9.75
Double-Size	19.75 x 16.75 x 19.75
Triple-Size	29.5 x 16.75 x 19.75

Table 1 Cargo transfer bag external dimensions (half, single, double, and triple) [29].

Figure 8 shows an example of what a crowded resupply module looks like. Each module can hold hundreds of CTBs, significantly adding to the amount of time required to unload all of the bags. The materials that are eventually to be used by astronauts are kept in the CTBs until required for use. As seen in both Figures 8 and 9, CTB storage essentially consists of securing CTBs with cables in any available space, and full CTBs can take up a large volume of living space [29].

Fig. 8 JAXA H-II Transfer vehicle docked to ISS Harmony module showing vast number of CTBs [30].

Even when CTBs are unloaded, it is difficult to keep track of the contents within each bag, and it is initially unknown what is inside each bag, causing the unloading process to take unnecessarily long. In order to improve this disorganized situation, there have been groups that have tried to test the feasibility of a robot manipulating and organizing CTBs. In a study done in 2017, Robonaut 2 was used to remove a CTB from a simulated logistics resupply vehicle, all with only one operator command [31]. In this study, Robonaut 2 was able to autonomously remove the CTBs with an 80% success rate and a 95% success rate with limited human interference. Robonaut 2 has a five-fingered hand that it can use to grab the CTBs at the handles. However, this is extremely limited by location of the handle and if it is in an easy-to-grab area. Robotic interaction with flexible material proves to be extremely challenging, indicating that a redesign of CTBs may be necessary to improve robot/CTB interaction. In addition, future work regarding this challenge will undoubtedly require specialized end effectors for the CTBs to effectively be picked up and transported.

Fig. 9 NASA astronauts Chris Cassidy (left) and Cady Coleman (right) managing and unpacking CTBs [32], [33] .

2.9. NASA Lunar Gateway

A direct application of robotic operation and maintenance in space can be found in NASA's Lunar Gateway, pictured in Figure 10.

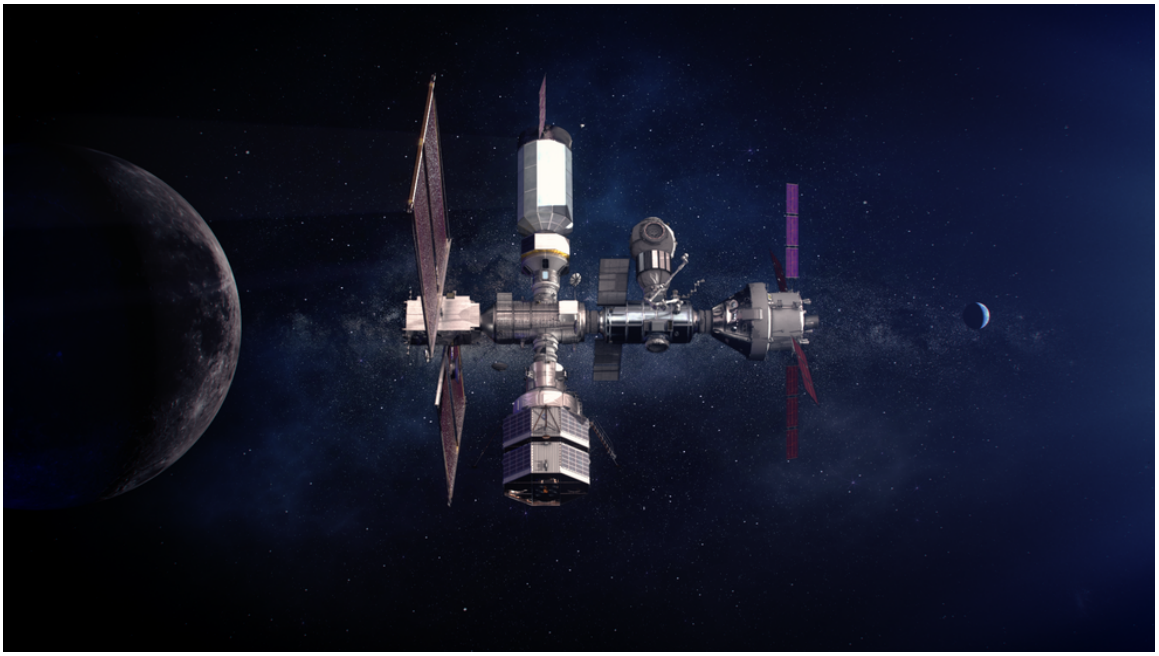

Fig. 10 Artist rendering of the NASA Lunar Gateway [34].

With its first components (Power and Propulsion Element and Habitation and Logistics Outpost) scheduled to launch in 2024, the Lunar Orbital Platform-Gateway will serve as an outpost orbiting the moon and will directly contribute to the NASA Artemis program with the goal of returning humans to the surface of the Moon [4], [34]. This habitat will be utilized not only as a base for operations on the lunar surface, but it will also enable international collaboration in cislunar space, as well as future missions to Mars and beyond [4], [35].

2.9.1. Concept of Operations for Gateway

Unlike the International Space Station, which is continuously crewed by three to six astronauts [36], the Lunar Gateway is designed to support 4 crew members for a minimum mission duration of 30 days [4]. This means that at a maximum, the lunar outpost would be completely uncrewed for 11 months at a time. Since astronauts living onboard the ISS are a critical component for ensuring the continued operation of the station, other means, such as robotic systems, must be implemented during the uncrewed portions of Gateway to allow for the outpost to be maintained. To understand the importance of crew presence for operating the ISS, in August 2011, the ISS was almost faced with being wholly unoccupied for the first time in it's mission life because of a resupply vehicle being lost due to an issue with an engine of the Soyuz U rocket [24]. This led to an indefinite inspection of Soyuz rockets, resulting in the possibility of the crew on the ISS having to return to Earth before they can be replaced by a new crew. Although this forced NASA to develop de-crewing operations of the ISS (and the fact that the ISS was designed to be remote controlled), the protocols do not specify how long the ISS could safely operate without a crew [24], [37]. Crew members are also extremely important for emergency task response. Due to the current lack in knowledge of how to operate an uncrewed space habitat for long duration, this further justifies Team ASTRO's research topic in that this issue must be addressed for future space exploration.

2.10. Gaps in Existing Research

Team ASTRO was able to identify a few areas of interest that have not been greatly expanded upon. While there have been studies to observe how robots can interact with CTBs, no studies have proposed alternative designs to make CTBs better suited to be handled by robots. Redesigning CTBs will allow the team to be more creative with their proposed solutions and explore different options for manipulating the bags. In addition, little research exists on assessing systems that would allow individual CTBs to be identified. This thesis will explore a method to do so using an AprilTag system, described later in this paper.

The team also found there was not much information available about autonomous operation of robots in microgravity. The ISS is an important international resource and NASA does not complete missions with high levels of unnecessary risk. Neither the ISS nor other space habitats have been left for robots to independently maintain. NASA's robotic testing has been largely teleoperated and heavily supervised.

Finally, a majority of research investigating the use of intra-vehicular robots for space habitats involves highly complex end effectors, such as the Robonaut hand system. However, this level of complexity may or may not actually be required. The team will explore a variety of end effector options to determine the actual complexity requirements to perform the required tasks.

2.11. Conclusion

As seen in this literature review, astronauts onboard the ISS spend a large portion of their time working on the operation and maintenance of the space station. With the launch of the Lunar Gateway and future space habitats where crew presence will already be limited, it is vital to use other means to address operation and maintenance tasks to maximize the amount of time astronauts can dedicate to performing valuable science experiments. Additionally, since the U.S. space program has never experienced uncrewed operation of the ISS, robotic systems must be further assessed for long-term upkeep of crewless space habitats.

Although there have been multiple attempts to integrate robotic systems with the interior of the ISS, it has been shown that overly complex systems such as Charlotte and Robonaut can be more problematic than useful. Free-flying robots such as SPHERES and Astrobee can also be rather complex and add a degree of difficulty since they are not constrained to a single location. The simpler design of the Canadarm has demonstrated continued success for extravehicular operations on the ISS, which supports Team ASTRO's choice of investigating the feasibility of various robot arms within the Space Systems Laboratory for operation assistance.

Team ASTRO will use sections 2.5, 2.6, and 2.8 of this literature review to determine what tasks to evaluate and what methods to use for assessing the feasibility of robotic systems with applications to space habitat operation, maintenance, and repair. Section 2.6, in particular, will help the team standardize their taskboard for robotic assessment. Section 2.8 emphasizes the difficulty of CTB manipulation and management, as well as the time-consuming task of actually unloading hundreds of CTBs, resulting in this task being a major focus of work for this project as well. In addition, although this literature review discusses the importance of fault detection, the team has deemed this outside the scope of the project and that is left for future work. Also, based on complexity and time constraints, the majority of tests conducted will be teleoperated. Autonomy will be included for simulations, but other opportunities for integration of autonomous algorithms in future work will be identified. For immediate relevance and the ability to make a direct impact in near-term space exploration, Team ASTRO will be targeting this research project with applications to NASA's Lunar Gateway.

3. Experimental Testing & Validation of Common Operational & Maintenance Task Movements

3.1. Overview & Motivation

As mentioned in the literature review, operational and maintenance tasks on the ISS can be divided into several categories, with the two most relevant for this project being preventative and corrective maintenance. While tasks within these maintenance categories can include complex, large scale disassembly and reassembly of systems, there are also smaller scale tasks that can be addressed. Although one of the end goals of this research is to have robotic systems fully capable of performing end-to-end assembly and repair of larger systems, a natural starting point is "remove and replace" tasks. By looking at relatively simple tasks and common operational movements, such as pushing specific buttons and turning knobs, the team was able to assess the overall dexterity capabilities of the robot. This assessment shows which movements are relatively easy to perform and which are more difficult or even impossible to complete. To test if a robotic system is able to complete the selected tasks quickly, precisely, and repeatedly, the team created a taskboard with a multitude of possible tasks and common ISS operational hardware. In this section, Team ASTRO will also identify the selected robotic systems used for testing, as well as present end effectors designed and optimized for certain tasks. Throughout this chapter, testing results are discussed, with key findings pertaining to success rates and tasks completion times. By knowing which movements the robotic system is able to perform, this knowledge can be used to predict how capable a robot would be at applying these movements to a larger scale system.

3.2. Robotic Systems Utilized for Testing

Over the course of the project, the team has used various robotic arms to conduct a variety of tests. The choice of arm used for testing was highly dependent on arm availability, functionality status, and overall system capabilities. The three different robotic systems, Baxter, Ranger NBV, and Ranger TSX, that the team used are detailed in the following subsections.

3.2.1. Baxter

Baxter is the name given to a commercially available robot that was built by Rethink Robotics to serve as an industrial robotic system. Baxter has two arms and a display that serves as an animated face, as shown in Figure 11. The robot stands 1.9 meters tall including its mounting pedestal, and weighs 75 kg excluding its pedestal. Baxter has both passive and active safety systems and can be controlled through a vision and force sensing system. There is a camera located in each of the robot's forearms, two in its chest and one in its head, for a total of five cameras. The head of the robot also has a sonar system allowing for the detection of passing objects. Baxter requires a 110-V power supply to power its series elastic actuators with brushless DC motors and computer system, which can be controlled with the Robot Operating System (ROS). Baxter has a total of sixteen degrees of freedom, seven in each arm and two in the head. With a maximum reach of 1210 mm and a maximum 2.2 kg payload per arm, one unit costs approximately 22,000 dollars [38].

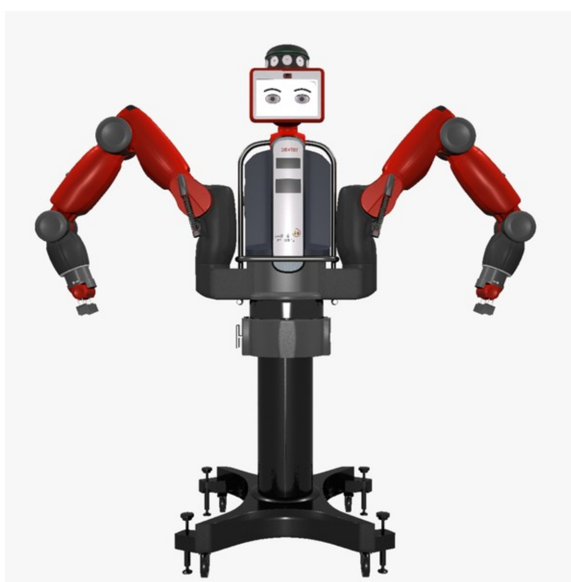

Fig. 11 A Baxter robot, as available for purchase from the manufacturer, Rethink Robotics [39].

At the University of Maryland, the Robotics Realization Laboratory has a Baxter robot that the team was allowed to use. At this time, the robotic arms from SSL the team had intended to utilize for experimentation were out of operation. Initial testing at the Robotics Realization Laboratory lab allowed Team ASTRO to perform preliminary testing before data collection. Baxter was an ideal robot to use in the early stages of this project because it had two arms and built in safety features. Some tasks on the team's taskboard, such as closing a buckle, would be far easier to complete with two independent manipulators. Using Baxter would allow for these tasks to be completed without advanced operator skill or complicated end effector design. The safety features built into Baxter's system were also a reminder of the safety requirements that would be required by NASA on any robotic system that would be integrated into a space where human astronauts would be working alongside of or in the same area as the robot. However, the accuracy of the Baxter robot was far from sufficient for actual data collection. The arm would not go precisely where directed by the operator when using joint control, making it difficult to orient the end effector directly over the desired tasks. Therefore, Baxter was used for preliminary testing only.

3.2.2. Ranger NBV

Ranger NBV, or Neutral Buoyancy Vehicle, is a single arm robotic system built by the University of Maryland's Space Systems Laboratory. Ranger NBV, shown in Figure 12 has a free flying base when operating in the Neutral Buoyancy Tank, which acts as a simulated microgravity environment. This, along with more precise actuators and a specifically designed sensor and computer system, allowed for more accurate neutral buoyancy simulation. Additionally, the robot's subsystems were designed to be more robust, specifically the power and pressurization system, so that less time was required for robot repairs and maintenance [40].

Ranger NBV was designed to mimic the reach and force capabilities of an astronaut in a spacesuit, and in total has 6 degrees of freedom with a maximum 5 kg payload in Earth's gravity. The mobility of the robotic arm was also designed to be analogous to that of an astronaut so that operating Ranger NBV would allow for the completion of tasks an astronaut could perform while on an EVA. The 6 DOF enables the robot to be potentially capable of performing large scale assemblies [40].

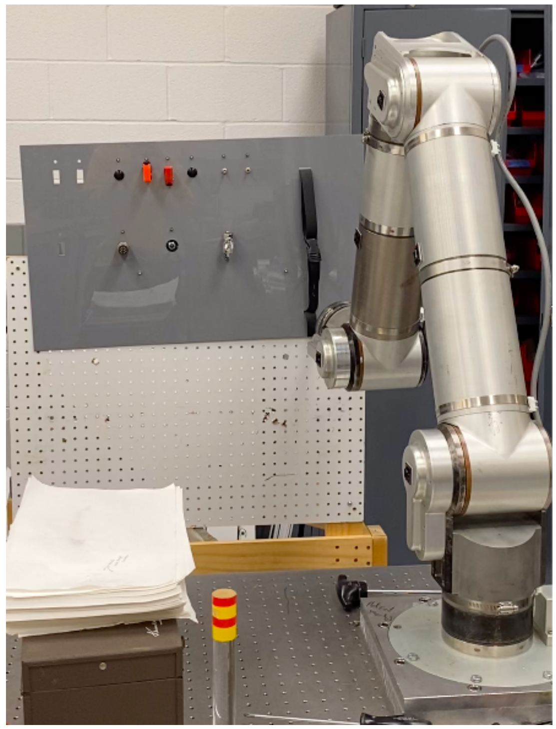

Fig. 12 Ranger NBV arm interacting with Team ASTRO's updated taskboard.

Team ASTRO would use Ranger NBV to execute various types of tests because the robotic system was created to be able to perform similarly to an astronaut. Since the team was investigating how robotics can be used to maintain or repair a space habitat while uncrewed, the robotic system would need to complete tasks traditionally carried out by astronauts. Ranger NBV's arm could also be adapted by mounting different end effectors onto it. Over the course of the project, the team designed and tested a number of end effectors to determine which designs were best suited to complete various types of tasks on a taskboard.

3.2.3. Ranger TSX

Ranger Telerobotics Shuttle Experiment, or Ranger TSX, is flight-qualified robotic system designed by the Space Systems Laboratory at the University of Maryland and consists of two robotic arms mounted to a positionable base. This system, shown in Figure 13, was designed to operate unassisted in either a 1G environment or in SSL's neutral buoyancy tank. The robot had originally been built for a Space Shuttle mission, but due to a limited number of Shuttle flight opportunities after the Columbia accident, Ranger TSX was re-adapted for use in the Space Systems Laboratory to determine how robots can best be used in space.

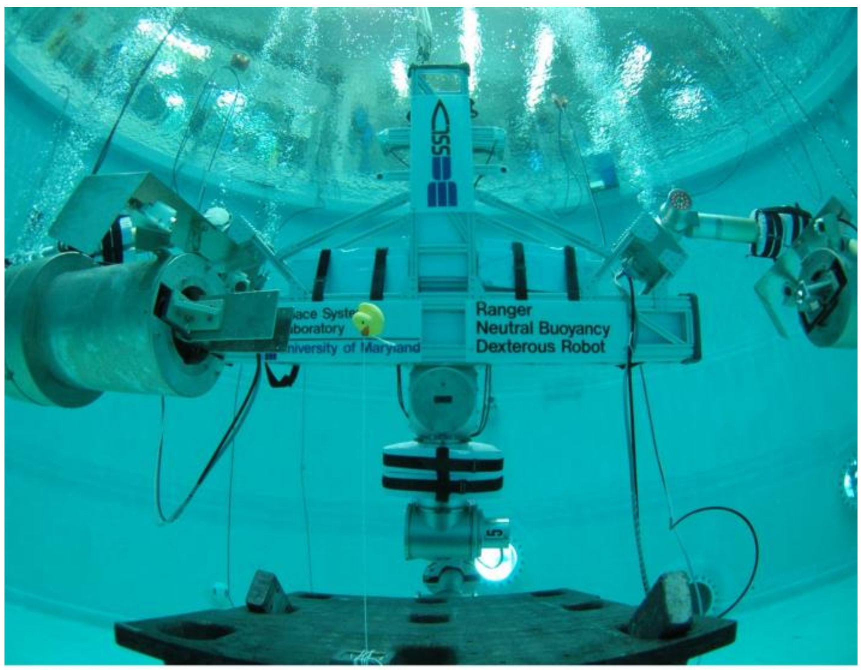

Fig. 13 Ranger TSX operating in SSL's Neutral Buoyancy Tank [40].

Ranger has three dexterous robotic manipulators, providing the system with both positional and manipulative abilities. The robot rests on a six degree of freedom leg, that along with an active breaking system, allows for the system to be positioned. The leg joint is also extremely stiff, ensuring that the robot remains in the desired position. Ranger's two dexterous manipulator arms were of interest to Team ASTRO, as the arms allow Ranger to interact with the surrounding environment. The left and right arms are identical, with each having 8 degrees of freedom and the ability to mount an end effector to each arm. Ranger TSX can hold a maximum earth payload of 10 kg. In the design of Ranger TSX, consideration of the system's kinematics allowed for a design with minimal joint offset to be selected [40].

Team ASTRO selected Ranger TSX for its dexterous manipulation capabilities; the team could use the robot to perform common movements that would be needed to complete operational and maintenance tasks in a space station or habitat. Additionally, the team could design customized end effectors for the robot's arms to enable a greater range of tasks to be completed. However, due to testing and time limitations, Ranger TSX was never used for physical taskboard testing. It was however, the robot modeled and used for the simulations described in Chapter Five of this thesis.

3.3. Taskboard Testing Apparatus

In order to assess the capabilities of both the SSL robotic arm systems and the end effectors developed by the team, Team ASTRO developed two iterations of a taskboard. Both taskboards contained a variety of tasks and required movements analogous to those astronauts on the ISS regularly perform. The taskboard ultimately served as a way to assess what types of movements are difficult for a robot to achieve, what tasks are easily repeatable, what tasks are achievable but require excessive time compared to a human performing the task, and what types of movements are too difficult for a robot to complete. The preliminary and updated taskboards created by the team are further described in the following subsections.

3.3.1. Preliminary Taskboard Design

The team constructed a preliminary taskboard using foamcore to mount various types of hardware. As shown in Figure 14, the taskboard consists of push buttons, a keypad, rotary knobs, switches (both with and without switch guards), a lever, an electrical connector, a valve, and a buckle. These specific items were included on the taskboard, as they are representative of frequently manipulated items or common movements performed daily by astronauts. All hardware was arranged such that the chosen robotic arm could successfully interface with each item. Each individual item was also connected to an LED and powered by an Aruidno Uno to indicate successful completion of the task. The electrical connector, valve, and buckle were later additions to the taskboard, which served to function as higher fidelity tasks that a robotic system would have to be able to accomplish on a space station. Some of these tasks, such as detaching and refastening a buckle, would commonly be completed with two hands. This is challenging for a robot to carry out, as calculations and control over two end effectors moving through space is required. This preliminary taskboard worked satisfactorily for most of the team's initial testing with the Baxter robot. During testing with Baxter, the taskboard placed on top of a table facing up in front of the robot. However, foamcore is a weak material and cannot retain its structural integrity when moderate stresses act upon it. In order to complete tasks that involved pushing or pulling with any reasonable force without breaking the taskboard, the team needed to create another board that could withstand more significant forces and stresses.

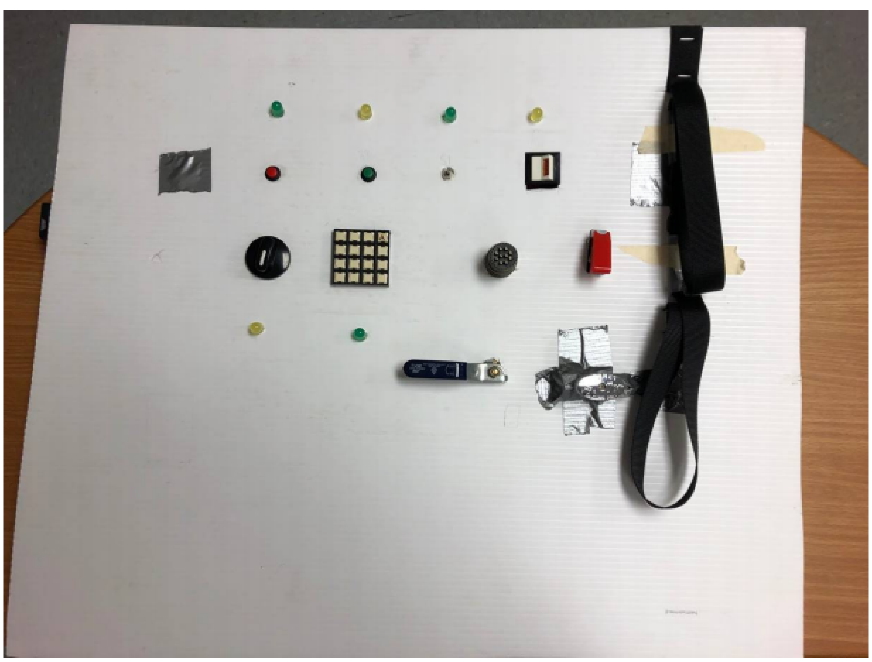

Fig. 14 Preliminary taskboard with low fidelity and high fidelity tasks, such as switches, knobs, and buckles, wired to LEDs.

3.3.2. Updated Taskboard Design

Team ASTRO found that the preliminary foamcore taskboard lacked sufficient rigidity, as foamcore is merely a thin piece of foam covered on either side by a sheet of thick paper. When testing with the robotic arm, the preliminary taskboard could not withstand the force that the end effector and Ranger NBV exerted on it for higher level tasks, i.e. turning the knob and disconnecting the electrical connector. The team decided to manufacture a new taskboard which would be able to withstand these forces, which is depicted in Figure 15. The new taskboard was constructed out of an acrylic back-plate to ensure that the taskboard would be sturdy enough to interface with the robot. Team ASTRO laser cut customized holes in the taskboard to mount the push buttons, switches, switch guards, knobs, and electrical connectors originally used on the first board. Applicable hardware was again wired to LEDs that would light up when the task was successfully completed. The team wanted to create a taskboard that was able to withstand the completion of all of the tasks by the robot. This would show that any limitations in the team's results were due to Team ASTRO being unable to complete the task, rather than the taskboard limiting what was able to be done.

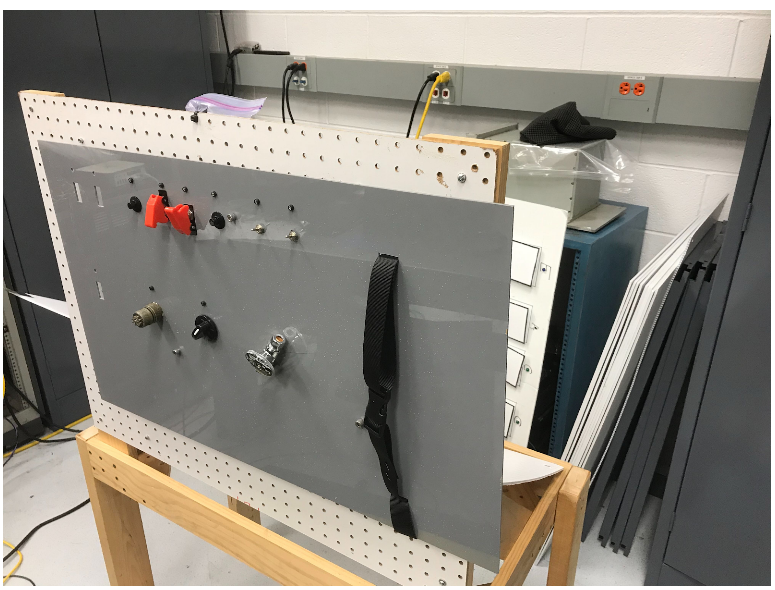

Fig. 15 Updated taskboard design. Top row, from left to right: push button, switch with switch guard (flip up), switch with switch guard (flip down), push button, switch without switch guard (x2). Bottom row from left to right: electrical connector, knob, buckle.

3.3.3. Updated Taskboard Set-Up

In order to test the different tasks on the taskboard, it was set up in proximity to Ranger NBV. The first step in the set-up was to have three wooden blocks attached with bolts to the back of the taskboard. Then, the bolts were put into the blocks through an already existing vertically mounted board, shown in Figure 15. The placement of the wooden blocks allowed for spacing between the LED wiring on the back of the taskboard and the mounted board. However, due to the placement of the blocks, there was a lack of support in the center of the taskboard. This caused issues when a task required pulling on or pushing into the board, as the board would flex in or out and tasks would have to be stopped before risking breaking the taskboard. To rectify this design flaw, additional wood beams were attached along the back side of the taskboard to provide added support. This modification, shown in Figure 16, was a success: the board components were still accessible to the arm, and the acrylic board remained steady and level for all subsequent testing.

Fig. 16 Additional wooden supports added to the updated taskboard to prevent flexing during testing.

This set-up was placed approximately two feet from the robot. The taskboard and human operator were located on either side of the robot, with the taskboard facing the operator. This apparatus worked well for the majority of tests, however some issues did arise when the operator was unable to see the exact placement of the end effector. This was solved by either having an additional team member guide the operator, or by having the operator move to a better vantage point and then return to the joystick controls of NBV. Both of these methods worked for testing, however they increased individual task time.

3.4. Taskboard End Effector Designs

In order to complete the most tasks with a single end effector, the team performed taskboard testing using various two-pronged grippers. The grippers incorporated both electromechanical and pneumatic actuation. These methods are described further in the following subsections.

3.4.1. Electromechanical Gripper

Preliminary testing with Baxter and Ranger NBV was conducted with a 3D printed, two-pronged rack & pinion gripper jaw end effector designed by [41] and pictured in Figure 17. The material used for 3D printing was standard PLA, and the jaws can open to a maximum gripping distance of approximately 70 mm. 3D printing was selected as the method of fabrication for the team's end effectors due to its rapid prototyping ability. The gripper was actuated by a Tower Pro MG995 servo motor with a stall torque of 13 kg-cm at 4.8 V [42].

This end effector allowed the robot to grab parts on the taskboard, such as the switches and electrical connector, while also making it easy to push a button when the grippers were in the closed position. However, a large disadvantage of this end effector was the lack of grip force it could apply, indicating the necessity for a pneumatically actuated end effector. Additionally, the gripper prongs would often flex and fail to properly grasp items such as the knob. This indicates the need for a sturdier gripper with wider prongs.

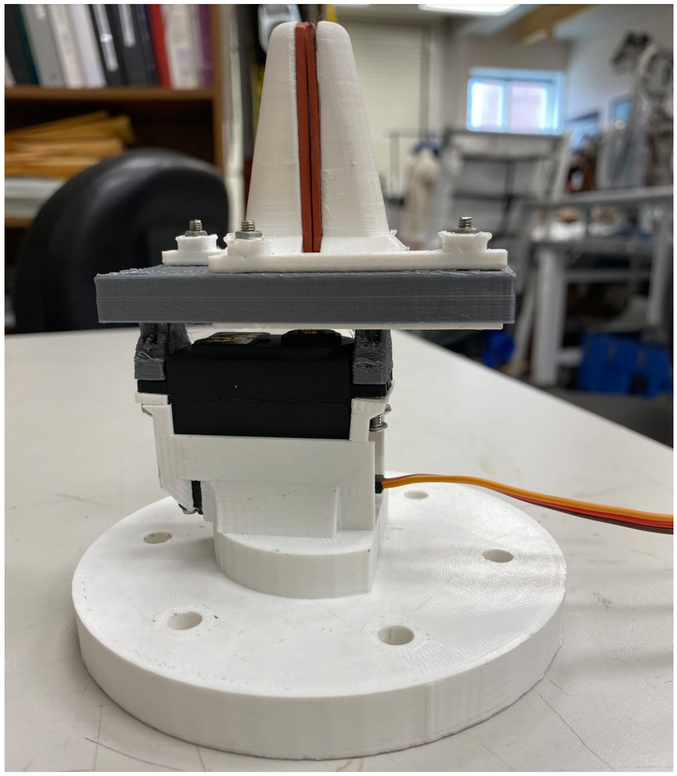

Fig. 17 3D printed two pronged gripper end effector designed by [41]. The two prongs would move laterally, when in this orientation, to open and close. Each pronged has had gripper tape applied to it to increase the friction between it and the object being manipulated.

3.4.2. Pneumatic Grippers

The taskboard included several tasks that required additional grip and dexterity to complete, as the electromechanical gripper failed to apply enough torque to complete the tasks. For example, removing electrical connectors required a significant amount of gripping force that the servo could not apply and turning knobs or unbuckling belts required dexterity beyond what the initial servo-powered gripper could offer. The end effector was improved upon by using pneumatic systems as a source of gripping force. Pneumatic based grippers proved to significantly increase the ability to complete taskboard tasks, as the actuation system was able to apply a larger gripping force that was able to be more effectively sustained throughout the task.

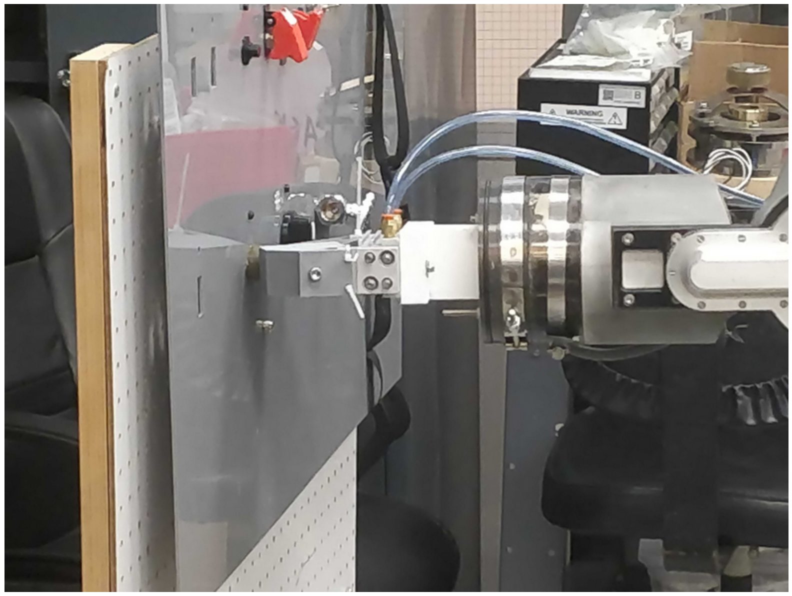

Fig. 18 Original pneumatic gripper mounted on Ranger NBV, interacting with the taskboard.

Team ASTRO utilized two different pneumatic actuators during the final rounds of taskboard testing with Ranger NBV. The first system, pictured in Figure 18, was a Fabco-Air FKHL-10D1 Wide Parallel Pneumatic Gripper [43]. This specific gripper had a total stroke of 40 mm, and could apply 3.1 lbf of effective gripping force. The gripper also used 3D printed PLA prongs, which were bolted on to the moving plates of the end effector and made thick enough to prevent the deformation experienced by the electromechanical gripper and wide enough to effectively grasp the buckle. However, the first pneumatic gripper still struggled with being able to output enough force to consistently grip the more secure components, such as the electrical connector. Thus, a second pneumatic actuator was purchased.

The second pneumatic actuator used by the team was the Fabco-Air FKHL-16D2 Wide Parallel Pneumatic Gripper [44]. This second gripper, depicted in Figure 19, used the same 3D printed prongs used by the original pneumatic gripper. However, the second gripper improved greatly upon the first pneumatic gripper, as it had a total stroke of 80 mm and could apply 10.1 lbf of effective gripping force. By having the ability to open wider and apply more grip force, the team used this end effector for the majority of taskboard testing with Ranger NBV as it was able to complete every possible task.

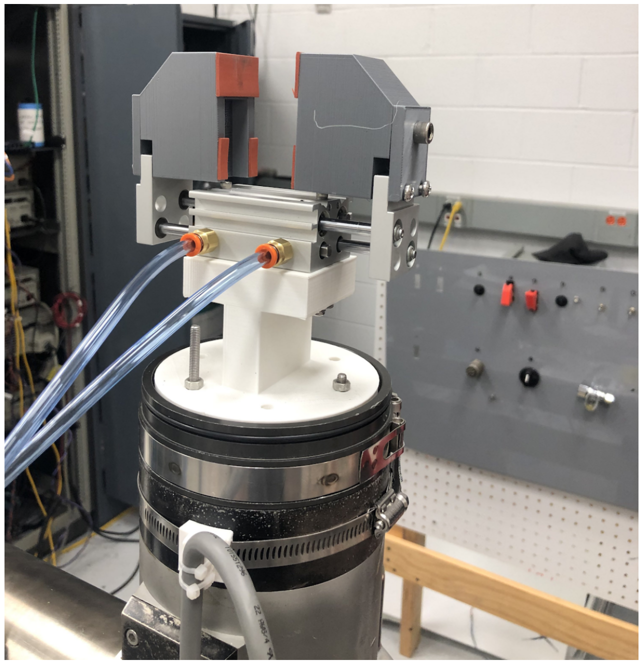

Fig. 19 The NBV arm with a second type of pneumatic end effector, aimed at increasing grip strength.

3.4.3. Pneumatic System Components

The system for operating the pneumatic gripper involved a complex setup. The components included a pressure regulator, solenoid, and a control box for toggling the solenoid. The pressure regulator was set to 80 psi for all tests, since that is close to the maximum of 87 psi for the pneumatic grippers the team worked with. If the pressure was set too low, then the pneumatic would not actuate due to the internal friction of the mechanism. The control box has an Arduino Uno that read the state of a three-position switch. Position one was to open the gripper, position two was an override state in which a computer connected to the Arduino could toggle the state, and position three was to close the gripper. The pneumatic end effector itself was connected to the robot's final joint via a 3D printed mount and bolts.

3.5. End Effector Modifications

Team ASTRO's research involved the use of a few end effectors that had to be adjusted to truly complete the tasks the team set out to complete. The most significant modification made to the 3D printed end effectors was the addition of grip tape, shown in Figure 20.

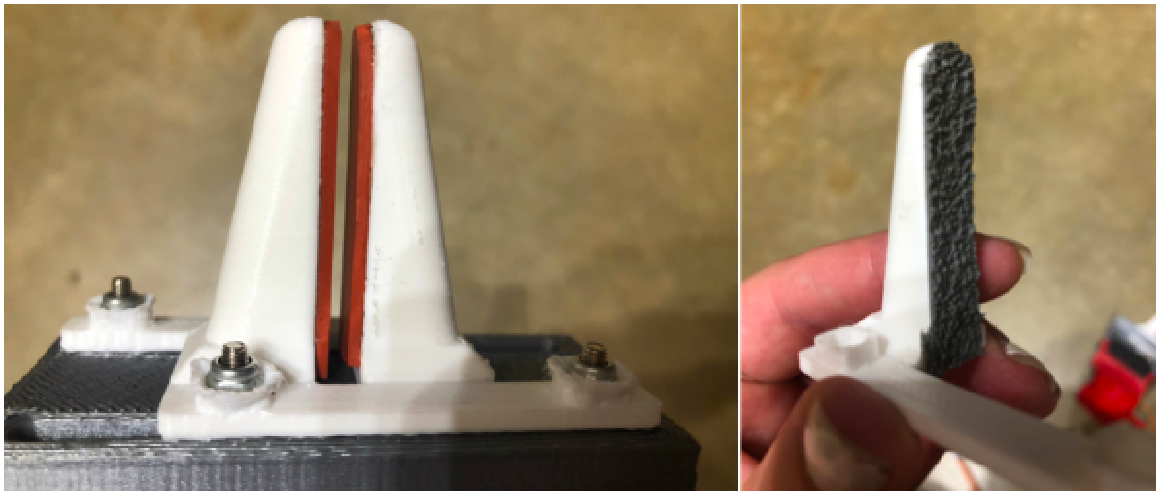

Fig. 20 Electromechanical gripper end effector modifications. The left image shows rubber gripper modifications and the right image shows sandpaper-like gripper modifications.

The grip tape was added after testing with the initial electromechanical gripper proved to be problematic. When attempting to grip items, the PLA material failed to generate enough friction to securely grab a piece of hardware. Therefore, two different types of grip tapes were explored, with the rubber grip tape proving to be the most effective at creating friction. Due to the experienced success with this modification, the rubber grip tape was used on all future 3D printed grippers for the pneumatic end effectors.

Another modification made to the end effectors was the addition of screws during pneumatic testing. This modification was due to the fact that the wide, flat 3D printed prongs of the pneumatic end effector were unable to effectively grasp the curved shape of the buckle. Thus, screws were attached to the inside of the prongs to provide a more concentrated area for gripping the buckle. Although this ad hoc method proved successful for unbuckling the buckle, future end effector iterations should include smaller fingers to complete this task.

3.6. Taskboard Testing Rounds

Although preliminary taskboard testing was conducted using the Baxter robot and initial foamcore taskboard, primary data collection was done using the Ranger NBV robotic arm and updated taskboard design. The following subsections report on the procedures used during each round of testing, observations made during testing, and gathered results. Each subsequent round of testing also explains how the data gathered expands upon the results of the previous round.

3.6.1. Round 1 of Testing

During the team's first round of testing, Ranger NBV was disassembled for maintenance for a portion of testing. Therefore, the first objective of testing was to have a human hold the pneumatic end effector to qualitatively evaluate ease of task completion. Following that assessment, a sequence of tasks was determined and completed by a human to establish a baseline for human performance. When Ranger NBV was fixed, the robot was then used to complete the same task sequence in order to compare the robot's performance levels to that of a human.

While the NBV arm was disassembled, the team chose to test the new pneumatic end effector on six taskboard tests, ranking their ease of use when the end effector is being held by a human. A ranking of one on the scale would indicate the task was very easy, a seven would correspond to a task that was very difficult. The results are presented in Table 2 below. It is important to note that a human operator was standing in front of the taskboard holding the end effector, so this is a qualitative assessment of only the end effector's aptitude for these tasks; it will not account for any challenges in alignment and remote operation of a robotic arm.

Task	1 (Very Easy)	2	3	4	5	6	7 (Very Difficult)
Button	X						
Switch			X				
Switch w/ Guard			X				
Knob		X					
Electrical Connector		X					
Buckle							X
Buckle (new approach)				X			

Table 2 Human operator's qualitative difficulty ratings for performing taskboard tasks while holding this end effector. Testing performed while the robotic arm was out of service.

As shown by the above results, the button, knob, and electrical connector proved to be relatively easy. The switch (both with and without the switch guard), as well as the buckle with the screw modifications, were slightly more challenging. The buckle without the gripper modification was deemed near impossible.

After the qualitative analysis of the tasks, the next objective was evaluating a sequence of tasks. To simulate interaction with a control panel onboard a space station, the optimal preliminary test procedure involved the operator attempting to complete a specific sequence of tasks as quickly and efficiently as possible. For these trials, the robot started approximately two feet away from the taskboard. The procedure for operating Ranger NBV for this test is as follows:

1) Align the robot arm such that the front face of the fingers on the gripper is parallel to the taskboard. This initial position did not have to be directly adjacent to the first task in the sequence, although pre-positioning beforehand resulted in an overall quicker completion time.
2) Begin timing the task sequence, indicating to the operator when to begin. As the

operator completed each task, the timer's stopwatch would be used to mark a "lap," so that the time required to for each task could be easily recorded and referenced after testing was completed.

3) Complete each task in the sequence without pausing. The test sequence is as follows:
   - Press the small button on the taskboard.
   - Open the switch guard, and flip the switch within.
   - Disconnect the electrical component from the connector, then re-attach the electrical component.
   - Flip a secondary switch.
   - Rotate a rotary knob by one notch in the counterclockwise direction.
   - Return to the switch guard from step 2 and close the guard, flipping the switch with it.
4) Once each task has been completed, record the times needed for each step in the sequence and the total time in the test log. Once the times have been recorded, return the robot arm to a rest state. Once secured, the operator and timer can move to the taskboard and note any potential damages caused or reset the taskboard for the next test sequence.

Note that this same test procedure was followed for the human performance portion of this round of testing, omitting step one as the robot arm was not used for those trials.

First, the times of a human operator using their hand on the above series of tasks was taken as a benchmark. Then the same series of tasks with a human holding the pneumatic end effector was performed. Lastly, the tasks were performed using the Ranger NBV with the gripper attached. The results (in seconds) are presented in Table 3 below.

Trial	Button (s)	Open Switch Guard (s)	Electrical Connector (s)	Switch (s)	Knob (s)	Close Switch Guard (s)	Total (s)
Human 1	0.81	1.78	4.06	1.77	1.78	0.90	11.10
Human 2	0.85	1.34	3.85	1.47	1.83	1.00	10.34
Human 3	1.16	1.70	3.62	1.73	1.14	1.16	10.51
Held Gripper 1	1.51	2.02	5.67	3.00	3.16	4.22	19.58
Held Gripper 2	1.31	2.01	6.27	2.75	2.72	2.66	17.72
Held Gripper 3	1.18	1.91	5.35	2.23	3.78	1.70	16.15
Arm with Gripper (Practice Run)	8.66	57.6	141.26	42.23	116.58	13.76	380.12
Arm with Gripper 1	9.82	57.46	64.61	46.20	148.03	23.00	349.15
Arm with Gripper 2	11.22	34.23	40.63	40.70	79.68	10.78	217.26
Arm with Gripper 3	6.29	29.16	27.71	25.18	70.93	29.08	188.37
Arm with Gripper 4	6.35	31.70	21.36	27.13	82.33	12.09	181.00
Human Avg	0.94	1.61	3.84	1.66	1.58	1.02	10.65
Held Gripper Avg	1.33	1.98	5.76	2.66	3.22	2.86	17.82
Arm with Gripper Avg	8.42	38.14	38.58	34.80	95.24	18.73	233.95

Table 3 Times of a series of taskboard tests, comparing a human using their fingers, a human holding this end effector, and the robotic arm using this end effector. The bottom three rows are the average times for each method.

As expected, the trials with a human holding the end effector were slower than the benchmark, but not significantly; the time to complete the full series of tasks only averaged about seven seconds slower than a human using their hand. Most of this time would have been added due to needing to open and close the pneumatic gripper during operation. This indicates that, independent of the alignment and remote operation of a robotic arm, this end effector in and of itself is well-suited to every task on the team's taskboard. The one exception is the buckle, which was impossible to manipulate with the current setup.

Lastly, once Ranger NBV was fixed, the same series of tasks was performed with the end effector on the robotic arm. These trials were performed with the operator looking at the taskboard directly, with occasional assistance from another spectator for guidance. These times were much longer, due to the movement of the arm being much slower than a human's arm. However, after experiencing an operator learning curve, the times were lowered significantly (on average). This was due to a few factors. First, the operator was relearning the controls, and thus sometimes had unwanted inputs that slowed movement down. To build on this, the movements in between tasks were also optimized, with multiple inputs being utilized at once (i.e. up, to the right, and into the board all at once). Lastly, the execution of the tasks themselves were improved each time, on account of improved speed, accuracy and spacing. This can especially be seen in the reduction of time in each individual task from the first trial compared to the last few.

Overall, Ranger NBV took longer to complete the sequence of tasks. However, this difference was only on the order of minutes. Therefore, this round of testing shows that a robotic arm can feasibly and successfully complete movements analogous to tasks found on the ISS.

3.6.2. Round 2 of Testing

Round two of testing was done using the pneumatic end effector and the updated acrylic taskboard. This round of testing further investigated the electrical connector, unbuckling, and knob turning, as these were deemed higher fidelity tasks as they required additional dexterity to be completed. The robot operator received verbal guidance when attempting a task from another person who was also looking at the robotic system and taskboard. For each task, NBV was started directly in front of the task, and timing began once the operator began moving the robot. Once the operator performed a task, the success or failure of each task was recorded. The detailed test procedures are listed below:

1) Align robot with the selected task. Alignment implies the axis of the end effector is coincident with the central axis of the component. The distance from the component was approximately 10 centimeters, however this was not measurable because it is unsafe to approach the robot during operation. Variance in the starting distance will be considered in the results analysis, but based on the nature of the task, the approach did not take a considerable amount of time. In the future, to ensure repeatability, the taskboards location relative to the base of the robot could be calculated and then taking the robot to the exact same spot in Cartesian space.
2) Begin recording of task.
3) Operator attempts to complete task by approaching the taskboard, opening the gripper if necessary, and rotating the end effector.
4) Assistant provides verbal guidance in the form of directions from the list: up/down, left/right, forwards/backwards, rotate clockwise/counterclockwise.
5) Once the task is completed, failed (e.g., slipped off), or it is deemed impossible in the current configuration, the recording is stopped and the robot is reset to the original position for a new trial.

The results from this round of testing are listed in Table 4:

Task	Average Time (min:sec)
Electrical Connector Removal	0:21
Electrical Connector Insertion	0:11
Unbuckling	0:25
Knob Turning (Alignment)	1:14
Knob Turning (Per Click)	0:14

Table 4 Average times for completing a series of taskboard tests by an experienced robot operator.

Observations that the operator made during this round of testing are listed below:

1) For the electrical connector task, the axis of the end effector was not aligned with that of the connector, then it was impossible to remove because the gripper would slide off when attempting to pull it. The suspected reason was that an insufficient amount of gripping force was being applied.
2) For the knob task, while rotating the knob it was very difficult to tell how far it was turned aside from the auditory cue - clicking - when it reaches set positions. Without this, it would be impossible to determine how far it has turned. An indicator light or other electronic feedback could help in this regard.
3) Unbuckling was the easiest task with no failures recorded, even if the alignment was not perfect.

3.6.3. Round 3 of Testing

The third round of testing used the same testing procedure as round two with one major difference. Instead of verbal guidance by an assistant, the operator would rely on a camera for guiding their control of the robot, shown in Figure 21. This was an important change in procedure, as it better representative of an actual teleoperation situation if the space habitat containing the robot is uncrewed, such as the Lunar Gateway. In this case, no astronaut would be present to provide guidance for an operator at ground control, and they must solely rely on camera visuals. The camera was positioned at the base of the robot and rotated to face the taskboard. During this round of testing, one thing that was attempted was mounting the camera parallel to the tool of the robot. This proved inefficient because the gripper jaws would obscure the taskboard component from the operator's view, making it impossible to effectively control the robot. The same tasks assessed in round two were also investigated in this round, excluding the buckle.

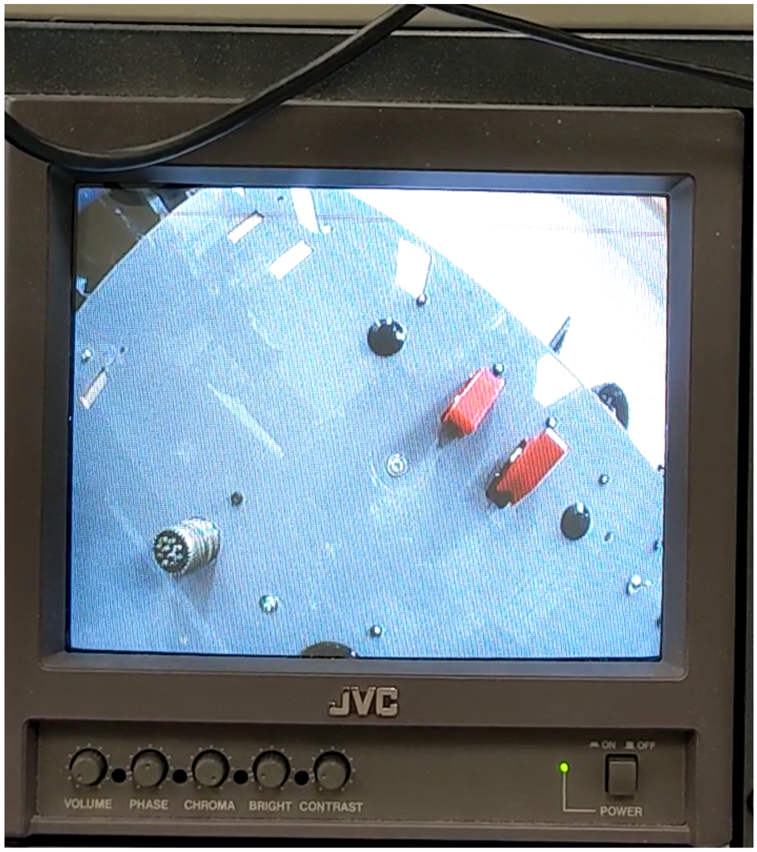

Fig. 21 Camera view for teleoperated control. The updated taskboard is in the camera's focus.

The results from this round of testing are presented in Table 5:

Task	Average Time (min:sec)
Electrical Connector Removal	0:26
Electrical Connector Insertion	0:06
Knob Turning (Alignment)	0:27
Knob Turning (Per Click)	0:13

Table 5 Completion times for taskboard tests using camera as guide.

Observations that the operator made during this round of testing:

1) Initially, it was difficult to gauge the distance through the camera view, as it was not the highest quality, but after getting used to it most tasks became doable.

2) While the operator had not previously attempted to remove the electrical connector with verbal assistance, they had served as the assistant. The operator felt that it was more difficult to extract meaningful information from the screen and took longer to get into position for grabbing.
3) For the knob turning task it was actually significantly easier because the perspective offered by the camera made it easy to gauge the relative orientation of the gripper to the knob. Since the operator was in the same room as the robot, the clicks from the knob turning were audible. This cue was crucial for being certain that the robot had successfully turned the knob.

3.7. Discussion of Taskboard Testing Results

Team ASTRO began taskboard testing using a 3D printed electromechanical end effector. Due to the relatively weak nature of the end effector, only basic tasks such as pushing a button or flipping a switch guard were able to be tested. Pulling out an electrical connector, turning valves, and buckling a buckle were all attempted and failed.

With the pneumatic gripper, more advanced tasks such as pulling out an electrical connector were able to be completed in addition to the preliminary basic tasks. The pneumatic gripper performed better than the servo-powered end effector when turning a knob. Additional testing resulted in the completion of unbuckling a buckle. However, a secondary arm with gripper would be necessary to emulate both human hands used when completing a buckling task. To replicate this, a clamp was used to keep one end of the buckle in place, while the secondary part of the buckle was maneuvered by the gripper. The buckle was able to be closed in this fashion, making it a feasible task for a two armed robotic system to perform on the Lunar Gateway.

The task completion of the robots significantly improved after the taskboard was redesigned to mitigate the bending of the acrylic board. The foamcore taskboard was deformed significantly during the performance of tasks, which hindered the ability of the robots to complete them.

Once provided with the sufficient end effectors and taskboard set-up, the team's testing showed that operators were easily able to perform most tests after a brief learning curve. As shown in round 1 of testing, the completion time of the task sequence significantly decreased on the order of minutes as the operator became more accustomed to controlling Ranger NBV. This means that if a robotic system has the ability to be positioned within a set distance of a desired task, an operator can rapidly complete the task. The better the feedback the operator receives, the more quickly they were able to complete the task. Additionally, it was crucial that the operator had some way of indicating that the task was completed, whether through visual, verbal, or auditory cues. The manner of feedback did not drastically affect the results of testing, as shown by the consistent average times of rounds two and three of testing. The fact that the test was teleoperated did not make it impossible, although it was clear that this is not a one-size fits all solution for all possible operational tasks. In order to achieve that, operators would need additional feedback and the ability to switch out end effectors in order to match their needs under different circumstances.

Aside from the lessons learned regarding robotic teleoperation, Team ASTRO also made valuable observations about the robotic systems themselves. Although some modifications were required, the team was successfully able to complete every task on the taskboard. Even though the robotic trials on average took longer than a human attempting the same task, the time difference is not significant enough to completely rule out the usage of robots. The robotic arm proved to be extremely adaptable for all tasks due to its high number of degrees-of-freedom, and with the correct end effector it can be applied to a variety of operational and maintenance tasks.

A key limitation of this testing procedure is the lack of force feedback technologies on the robotic arms. Operators used visual observations to simulate a teleoperated environment, which may not be as complete or intuitive from a camera in a space station scenario. A valuable area of future research would be to incorporate force feedback technologies to improve the performance of the robots when completing tasks and ensure no hardware is accidentally broken during operation. This could also offset the limitations of the robot that will inevitably come when time latency is introduced.

Beyond in-lab limitations, there would be real-world limitation of time delay that would occur due to the nature of teleoperation between the ground station and space habitat. The team attempted to simulate robotic handling with a time delay between the operator and robotic arm by moving in small increments rather than large motions. These small incremental movements would be similar to what an operator would have to do in an actual teleoperation situation, since there would be latency between sending the command and actually having the robot move. Otherwise, a larger motion could move the robot into a dangerous position before the operator even becomes aware of what they have done.

3.8. Malfunctions

Fig. 22 The pneumatic gripper mount broke, as it sheared along the bottom of the mounting, between the circular plate and the shaft. A redesign of the mounting system to be mechanically stronger was needed.

Throughout testing, in addition to new designs, 3D printed mounts and grippers had to be reprinted multiple times due to breaking during testing. The destruction of the end effector was a combination of operator error and the weaker design of the end effector fingers. In one case, when trying to flip a switch guard up, the arm was tilted up just slightly past where the switch guard stopped, and thus the finger bent backwards and cracked. This would have been solved by either more precise operation of the robot, or stiffer gripper fingers via higher printing infill. Although the team had originally planned to use 3D printed end effectors for preliminary testing only, time and research restrictions prevented the team from machining more robust aluminum end effectors. Sturdier end effectors can be developed for future tests.

Other cases of end effector destruction included the mount used to connect the end effector to the robot, which had thin connective elements that snapped after flexing too many times. During one of the preliminary tests with the rotating knob, the operator noted that the end effector was struggling to maintain a hold on the knob while rotating. Testing was briefly paused to inspect the taskboard and gripper. When no problems were identified testing then resumed. After resuming, a loud cracking sound was heard during the subsequent test, at which point the operator stopped said test, returned the robot to a rest state, and inspected the system. Initially, the sound was assumed to be related to the knob damaging the taskboard, but upon closer inspection the cause was revealed to be the mount having sheared almost completely evenly across its base, as can be seen in Figure 22. When reprinting, the mount was made more robust in order to prevent this same flexure in the gripper, as well as being more structurally sound itself.

In addition to issues with the end effector mount, the Arduino powered electromechanical gripper and the two pronged RC motor utilized resulted in insufficient stiffness to flip the taskboard switches. The gripper had an inherently large moment arm, impeding its ability to effectively flip the switches. A solution to this issue may have been to replace the gripper fingers with a single shaft end effector to accurately flip the switch. The electromechanical gripper design also prolonged malfunctions with the end effector mount. The gripper fingertips flexed, and a new end effector design was printed. Despite the reprinting, the end effector required threading leads to accurately mount it to the robot arm and was ineffective. The electromechanical gripper fingers suffered from malfunctioning pins, intended to ensure that the fingers remained in place and did not snap off. Zip-ties were used in an attempt to solve the issue, however one side of the gripper consistently deformed. The gripper deformation lead to an insufficient grip force, hindering further testing.

3.9. Conclusion

Team ASTRO completed taskboard testing utilizing the dexterous robots Baxter and Ranger NBV. This testing provided valuable data on the feasibility of completing tasks similar to those undertaken by crew members on the ISS or Lunar Gateway. Buttons, switch guards, electrical connectors, and knobs were included on the designed taskboard to accurately emulate operational activities, with LED lights to indicate whether the task was successfully completed. A 3D printed end electromechanical effector was initially designed for testing, however it was only capable of tasks such as pushing a button or flipping a switch guard. Tasks that required sufficient torque, such as turning valves or pulling out an electrical connector were unsuccessful. Utilizing the pneumatic gripper allowed for the success of the more advanced tasks. Human operators also conducted the various tasks using the pneumatic gripper end effector in order to provide adequate comparison between a crew member and possible robotic system. The designed gripper and robotic arm delayed the completion of tasks, however the time delay was on the order of minutes and proved to be insignificant. Overall, the pneumatic end effector was well suited for the majority of maintenance tasks tested.

Taskboard testing successfully proved the capabilities of dexterous robotic systems to complete maintenance tasks analogous to those on the ISS and Lunar Gateway, however there were contributing sources of error. There was a significant testing learning curve, contributing to increased time duration for the preliminary teleoperated Ranger NBV end effector trials. Another source of error was the numerous malfunctions, including issues with the end effector mount and the deformation of the gripper fingers. More durable materials will be required to ensure adequate grip strength and minimized deformations for future implementation of the end effector design.

4. Cargo Transfer Bag Logistics Management

4.1. Overview & Motivation

As discussed in the literature review, Cargo Transfer Bags are frequently used to store items and deliver cargo during resupply missions. In the present day, CTBs are sent to the ISS where they are only unpacked and managed by human astronauts. In space habitats where humans will not be available, robots need to be able to successfully interact with these objects. However, the cloth material of CTBs is difficult for a robot to interact with, so Team ASTRO sought to redesign these bags to make robot interaction with them more efficient. This section discusses the redesign of the CTB, the electromagnetic end effector utilized to interact with the CTBs, and the results and conclusions gathered from testing.

4.2. Cargo Transfer Bag Redesign

As mentioned previously, astronauts spend an inordinate amount of time on maintenance work and a large portion of that time is for the management and organization of CTBs. There are a few approaches that can be used to address this issue. For example, the team could develop complex software algorithms and design an advanced, highly dexterous gripper to be able to hold a flexible material like the cloth of a CTB. A second, more feasible option, is to modify the current design of CTBs to allow for more efficient interaction with a robotic system. Team ASTRO decided to redesign the CTBs and use more simplified end effectors rather than design a hand-like gripper due to cost, complexity and time.

In order to avoid the problem of having a robot trying to grab the CTB, the team decided to use the concept of a magnetic end effector to interface with the bag. This eliminates the need for locating an ideal gripping point, as the only addition that would be required is a metallic plate for the end effector to connect with. This addition of the plate then forces a flat surface onto the CTB where a electromagnetic end effector could easily attach and manipulate the CTB. This first aspect of the team's redesign allows a robot to interact with CTBs, but the robotic system needs to have the capability to locate the magnetic plate. This problem can be solved with an AprilTag. An AprilTag looks similar to a QR code, but also transmits information about its orientation and distance from the camera observing it. The exact details of the AprilTags will be described further in the AprilTag Situational Awareness section (section 5). However, the AprilTags will appear in figures throughout this section, so it is importance to introduce the concept as the addition of the AprilTags was a part of the redesign process.

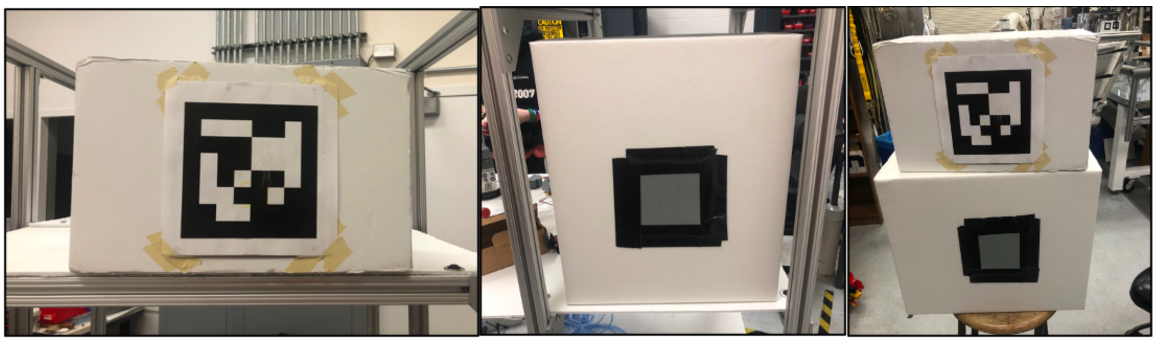

Fig. 23 Cargo Transfer Bag mock-ups: half-size with AprilTag marker (left), single-size with cloth covering and visible metal plate (center), and both half- and single-size stacked on top of each other (right).

The team created two different CTB mock-ups for testing: one half-size CTB of dimensions 9.75" x 16.75" x 9.25" and one single-size CTB of dimensions 19.75" x 16.75" x 9.75" [29]. Both CTBs were made of foam core, a lightweight material that allows the total mock-up mass to be under the maximum payload mass of the robotic system(s) being used. The half-size CTB, pictured on the left in Figure 23, has the metal plate required for the magnetic end effector attached on the outside of one face. The mock-up also has an AprilTag covering the metal plate, so the plate is not visible in the image. By using this set-up, this ensures that once the robotic system detects and aligns itself with the AprilTag, it will also be properly aligned with the metal plate. On the single-size CTB mock-up, pictured in the center image of Figure 23, there are two faces with cloth on them to mimic the flexible Nomex materials of actual CTBs. In order to investigate the level of rigidity required for the magnetic end effector to effectively interface with the CTB, one face covered with cloth is backed with foam core, while the other face covered with cloth is not. Similarly to the half-size CTB, there is a metal plate attached to one face of the single-size CTB. This metal plate can be moved depending on which face of the CTB the team wanted to experiment with. With both a new method to grip the CTB and a way to detect the gripping location, the last item required for testing was an electromagnetic end effector.

The addition of a magnetic plate deviates from the standard NASA-designed CTB. The metal plate provided by NicaDrone that matches the dimensions of the EPM interface (described in the following sub-section) has a mass of 8 grams. Adding one (or possibly more) metal plates to hundreds of CTBs would be less than 5 kg total, which is a negligible amount of mass when compared to the mass of Ranger NBV or other robotic systems which would be interfacing with the CTBs. While this additional mass should not trouble a robotic system moving them around, the additional mass of 8 grams per CTB would have to be taken into account when drafting a cost analysis as well as mass breakdown. This metal plate would have to be implemented in a redesign of the CTB if NASA were to utilize this technology. An alternative that the team considered using was a metal mesh instead of a solid plate, which would be able to interface directly onto the mesh of a CTB. A problem with this solution is that the NicaDrone must interface with a flat surface, and the metal mesh may not be suitable for that. Further testing should be done in this area if a metal mesh were to be implemented.

4.3. NicaDrone: Electro Permanent Magnet End Effector

The OpenGrab EPM V3 is an electropermanent magnet developed by NicaDrone that can toggle the polarity of its magnetism at the push of a button, allowing for the magnet to be turned on and off with ease. The switch in magnetism is activated by a brief 300 A pulse that lasts only 20 μs, so the device does not have to be continuously powered in order keep its magnetism on [45]. This device was turned into an end effector by the team to pick up and manipulate the redesigned CTB, as shown in Figure 24.

Although the EPM is relatively strong when it is activated, with a maximum holding force of 300 N [45], the team found that its strength is highly dependent on the quality of the connection between the EPM and the metal plate. This means that the magnetism isn't significantly affected if there is a piece of paper between the EPM and metal plate, but a thick piece of cloth can drastically affect the strength of the EPM's connection to the metal. Therefore, all CTB tests were conducted using either an exposed piece of metal or by having the metal covered only with an AprilTag. The NicaDrone EPM operates under a 5.0 V nominal voltage and can be driven by an Arduino Uno, and is only 65 grams in mass [45]. This ensures that when combined with the mass of any 3D printed mount and a CTB mock-up, the overall testing mass is less than the 2.2 kg and 5 kg maximum payloads of the Baxter robot and SSL's Ranger NBV, respectively, which were the two robotic arms used for CTB testing. In addition, the EPM is quite small with a 40 mm x 40 mm interface [45].

Fig. 24 NicaDrone EPM end effector in a 3D printed mount for the Baxter robot.

4.4. Logistics Management Testing Apparatus

The test set-up used for investigating the electropermanent magnet as a means of maneuvering CTBs consisted solely of a robotic arm with the NicaDrone EPM end effector, the CTB(s) being utilized, and a mock-up of an International Standard Payload Rack (ISPR). Preliminary, proof-of-concept testing was conducted using the Baxter robot, while the SSL Ranger NBV arm was used for actual data collection. The incorporation of the ISPR into the team's test apparatus was inspired by the common usage of these racks on the ISS. By assuming similar hardware would be installed on the Lunar Gateway, using the ISPR gave the team a constrained space to use during testing and allowed the team to explore multiple avenues of storing CTBs. The design and manufacturing of the ISPR mock-up is further detailed in the following section.

4.4.1. International Standard Payload Rack Mock-Up

In order to properly test the AprilTag identification system for the purpose of CTB management, a mock-up of an International Standard Payload Rack (ISPR) commonly used on the ISS was constructed. These racks are roughly the size of a large refrigerator (2 m x 1.05 m x 0.86 m), and offer immense versatility in what they can accommodate [46], [47]. Using the dimensions of an ISPR provided the team with a baseline volume that a robotic system would have to maneuver about.

Fig. 25 ISPR being installed in the ISS Destiny Module (left) [46], CAD model of rack mock-up (center), constructed mock-up of ISPR used for testing (right).

The mock-up, pictured in the right image of Figure 25, was built using an aluminum 80/20 frame with three rows of foam core shelves to be used in a 1G environment. The rack was intended for two main purposes: (1) to test the feasibility of the robotic arm to maneuver a CTB between shelves via teleoperation, and (2) to test the autonomous operation of the team's AprilTag identification system to locate and move a CTB to a pre-selected location.

However, due to time constraints and testing limitations brought on by the COVID-19 pandemic, only the first objective was tested.

4.4.2. Procedures

Testing was conducted by transferring a singular CTB from one shelf on the ISPR to another using the electropermanent magnetic end effector. This testing was done using the Ranger NBV arm operated in real-time by a team member. All tests were performed in a 1G laboratory environment. For each individual trial, the CTB would start on the same shelf in the same orientation, and the robotic arm would engage with and transport the CTB horizontally one shelf to the left. Multiple trials were conducted using either a half-size or single-size CTB, and recorded data included time to task completion and indication as to whether the CTB transfer was successful. The same task was repeated until the spread of the time data was minimal in order to minimize any bias due to operator learning curve. All results are reported and discussed in the following section.

4.5. Discussion of Logistics Management Testing Results

The two metrics used to quantify the feasibility of utilizing a robotic arm as a means of transporting CTBs on the Lunar Gateway and other future space habitats were task completion time and success rate. Figures 26 and 27 depict the elapsed time of the half-size and single-size CTB testing trials, respectively. Figure 28 combines both sets of data to illustrate the continuation of the consistent single-size CTB data past the learning curve. Since single-size CTB testing immediately followed the half-size testing, the operator was already accustomed to the robot and an adjustment time was not experienced. The graphs also indicate failed trials with an orange marker, where test failure is defined as the CTB mock-up falling off of the rack or prematurely disengaging from the electropermanent magnetic end effector. All failed trials occurred prior to the operator learning curve cut-off, for this reason they are automatically omitted from the average time calculation presented in Table 6.

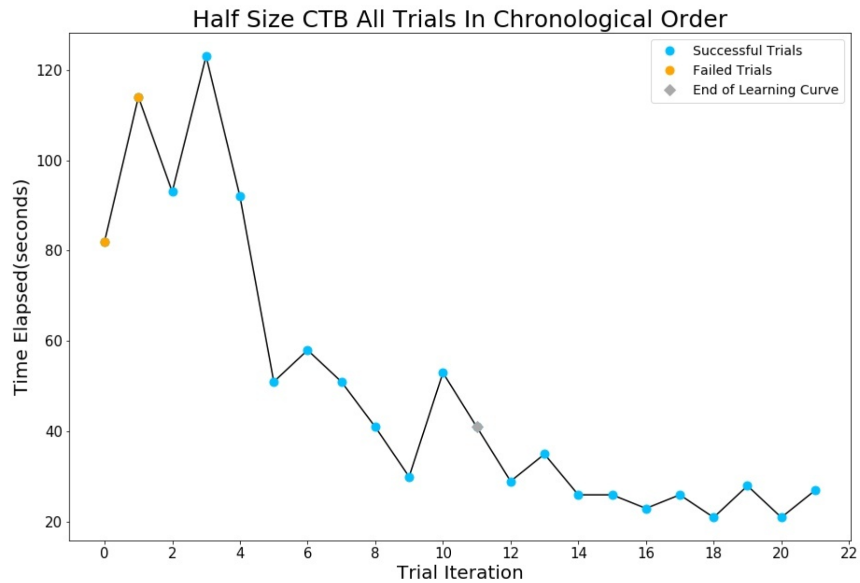

Fig. 26 Task time to completion for all half-size CTB trials. Successful trials are indicated with blue circles, failed trials are indicated with orange circles, and the end of the operator learning curve period is marked with a grey diamond.

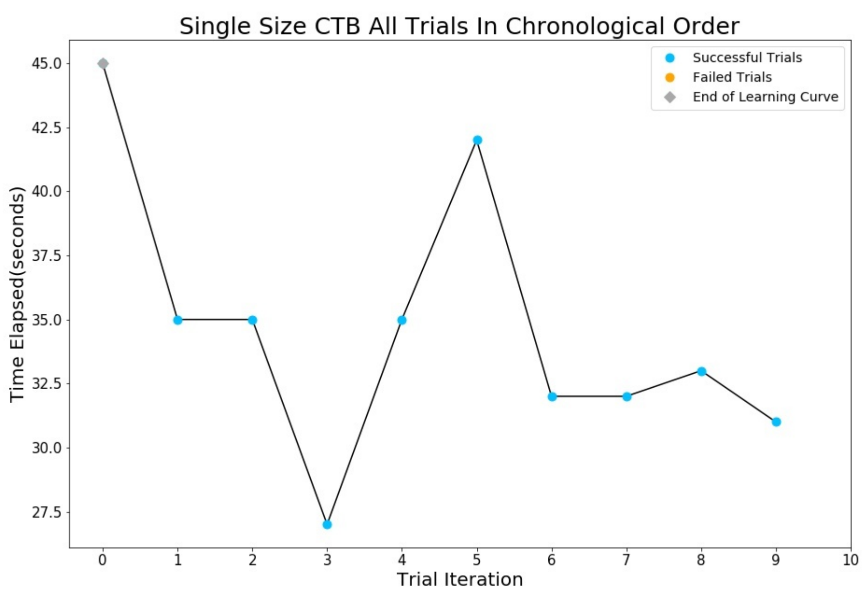

Fig. 27 Task time to completion for all single-size CTB trials. Successful trials are indicated with blue circles, failed trials are indicated with orange circles, and the end of the operator learning curve period is marked with a grey diamond.

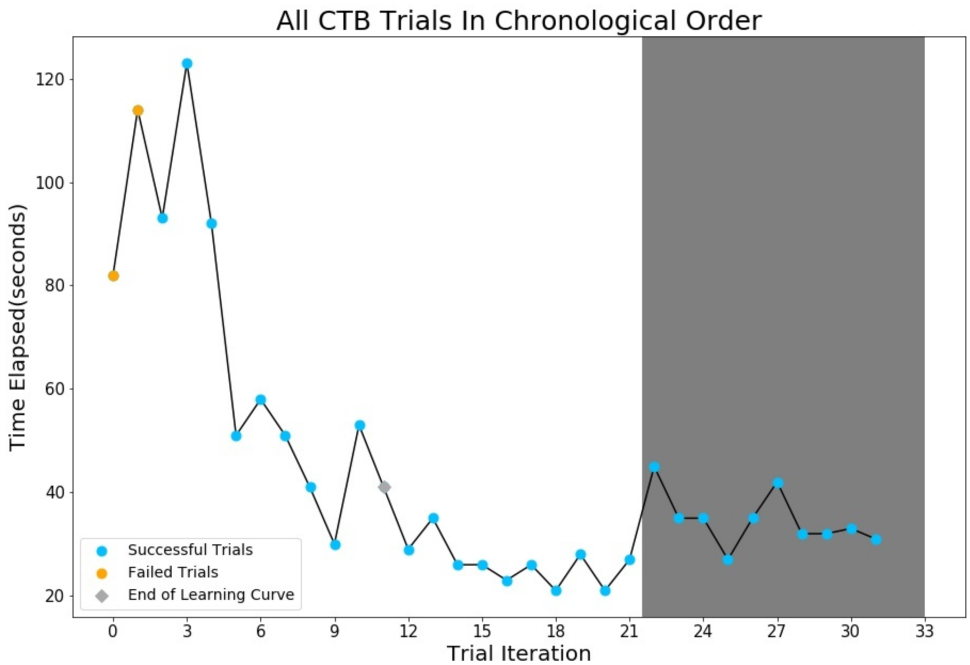

Fig. 28 Task time to completion for all CTB trials. Successful trials are indicated with blue circles, failed trials are indicated with orange circles, and the end of the operator learning curve period is marked with a grey diamond. The shaded grey region on the graph marks the transition from half-size CTB data to single-size CTB data.

As mentioned previously and observed by the grey diamond marker in all of the graphs, a learning curve was calculated in order to reduce bias introduced into the data by the robot operator. It can be seen by the trend in the data in Figure 28 that the operator experienced an initial adjustment period in completing the task. This is shown by the spike of high time values ranging from 90 to 120 second in the first 5 trials before the slope levels out at approximately 40 seconds. By setting a constraint that the standard deviation in time values must not exceed 20% of the average time, a cut-off indicating the end of the operator learning curve was calculated. All recorded trials prior to this cut-off were deemed insignificant and were ignored in further data analysis.

Table 6 presents the average times and standard deviations pertaining to task completion, along with corresponding success rates following the end of the learning curve cut-off. The single-size CTB took slightly longer on average (34.7 seconds) than the half-size CTB sorting (27.5), with a difference of 7.2 seconds. Since the single-size CTB sorting happened immediately after half-size testing, this increase in time to task completion is likely not attributed to the learning curve of the operator. Instead, it was likely due to having to maneuver a CTB with larger dimensions and heavier mass within the same space. However, the high end of the half-size CTB standard deviation overlaps with the low end of the single-size CTB standard deviation, so this observed time difference is not significant.

Trial Type	Average Elapsed Time (sec)	Success Rate
Half-Size CTB	27.5 ± 5.7	100%
Single-Size CTB	34.7 ± 5.0	100%
All CTBs	31.0 ± 6.4	100%

Table 6 Average elapsed time until task completion with corresponding success rates. The last row (All CTBs) combines both half-size and single-size CTB data.

In total, only two failed trails were experienced while testing, both during the half-size CTB trials. The specific reasoning for these failures is further discussed in section 4.6, but they were failures that could easily be avoided in future trials. In addition, these failures occurred prior to the end of the operator learning curve, therefore operators experienced a 100% success rate after adjusting to the controls for all trials.

4.6. Lessons Learned

It was observed during multiple iterations of testing that the effectiveness of the electropermanent magnetic end effector was rather sensitive to positioning, requiring extra precision during testing to effectively engage with the CTB. In order to ensure a strong connection between the magnet and the CTB, the magnet must be aligned with the center portion of the metal plate attached to the CTB. This location was marked to allow for consistency across all tests, and helped to prevent the magnet from sliding off the edge of the metal plate during transfer of the CTB. In addition, the electropermanent magnet was not activated until the magnet was in full contact with metal plate. Following this procedure, rather than just having the magnet be in close proximity of the metal plate, allowed for the end effector to exert maximum grip force on the CTB.

Another observation during testing was that the flexible cloth wrapping of the full-size CTB was easier to interact with than the foam core backed, cloth-covered face of the single-size CTB, as well as the exposed rigid foam core of the half-size CTB. A negative attribute of the Ranger NBV arm was that is often exhibited high frequency vibrational movements when transporting the CTB between shelves. Unlike the foam core, the cloth was more efficient at absorbing the vibrations and was overall less impacted by this occurrence.

4.7. Conclusion

Overall, Team ASTRO experienced high success with the implementation of the NicaDrone EPM end effector. After surpassing the operator learning curve, the teleoperated Ranger NBV arm was able to repeatedly pick-up and transport CTBs, indicating a robotic arm system is feasible to use for this purpose on future space habitats. The robotic arm was also able to interact with varying levels of rigidity in the CTB mock-ups, including the face on the single-size CTB that was only cloth. This indicates that as along as there is a small metal plate attached to the traditionally flexible CTB, an EPM end effector should not have an issue picking up the CTB. However, the focus of this portion of the research was only centered on the logistics surrounding CTB transportation. The team did not investigate a robot's ability to actually open and remove the contents within a CTB, so this leaves in important area of research that must be further explored in the future. Current CTB designs use zippers to keep the bags closed, and this interface has a history of proving difficult for a robot to interact with, especially in microgravity [29]. Devising a method to pack and unpack CTBs will save the astronauts hundreds of minutes, as each CTB takes approximately

10 minutes to unload [20], allowing them to allocate that time to scientific research.

However, the usage of an electromagnetic system introduces possible concerns. It is possible that the magnet could interfere with either the contents with the CTB, equipment in the space habitat, or sensitive experiments within the habitat. The nature of the specific NicaDrone magnet is such that the device does not have to be continuously powered to operate, as its magnetism is able to be switched on and off with a single pulse. While there are possibilities that this pulse and resulting magnetic field could affect surrounding hardware, electromagnetism has been used on the ISS before and has not been completely ruled out as useful tool. For example, the Controlled Dynamics Locker on the ISS operates off of small magnetic forces to isolate an experiment from the space station's movement [48]. Ultimately, the EPM technological concept possesses great potential and is something that should be further explored for future space applications. The use of the NicaDrone magnet would simply need to be accounted for in a space station's magnetic control plan. However, the team does recognize that there is a possibility that NASA would not want to pursue a redesign of CTBs, even though the changes are virtually negligible in mass. Even if the CTBs remain the same, the robotic systems could instead be adapted and alternate end effectors could be explored.

5. AprilTag Situational Awareness

5.1. Overview & Motivation

The last area of research explored in this project is the implementation of an AprilTag situational awareness system. This system can be used for a variety of purposes, but the main focus Team ASTRO explored was using them for CTB identification and manipulation. In application, a singular AprilTag would be attached to a CTB acting as that CTB's own unique identifier. The only additional hardware required to make this system functional is a camera mounted on the robotic system to allow the robot to visually detect the tag. Although AprilTags can easily be scanned by a human operating the robot, this system also opens the door for future incorporation of autonomy into CTB logistics management.

COVID-19 related research restrictions in the Spring of 2020 initially led to the simulation of CTB logistics management being developed. A graphical user interface was created to emulate an operator commanding a mobile Ranger TSX arm to CTB retrieval and delivery locations within an analogous Lunar Gateway environment. Since the simulation required a method for moving the robotic system throughout the space habitat, Team ASTRO also explored different mobility systems that could be incorporated into the Gateway architecture. The simulation and accompanying GUI, as well as the selected mobility method, are further described throughout this section.

5.1.1. Anomaly Detection

An important aspect of situational awareness is anomaly detection. Future habitats such as the Lunar Gateway could easily take advantage of existing technologies, such as using cameras to monitor operations and detect any faults that occur in large-scale mechanical systems. While diagnostic maintenance can be performed by humans as well as cameras, robotic systems must account for this fault detection in an uncrewed situation. The anomaly detection method would ideally be integrated with the robotic system through a suite of autonomous servicing algorithms. These pre-programmed algorithms would include known and forecasted failures based on common faults that are reported on the ISS. Utilizing these algorithms would completely eliminate the need for human-in-the-loop involvement. However, aside from time-critical events, human approval will be required before responding to each failure so mission control can properly assess the situation and determine the most effective response. Unexpected failures are also guaranteed to occur, so these will require external human operation to mitigate the failures. Although the team was unable to develop these algorithms during this project, this leaves an interesting area of future work.

5.1.2. AprilTag Description

The team's CTB logistics management system is centered around the incorporation of AprilTag markers. AprilTags are a fiducial marker system that can be used to provide identification and position data of objects. They essentially function like a QR code, and once scanned provide 6 DOF position data (x, y, z, roll, pitch, yaw) of the AprilTag [49]. Unlike QR codes however, AprilTags have the ability to automatically provide localization data in non-ideal situations, such as low lighting conditions or imperfect alignment [50]. This is due to the fact that they contain smaller data payloads ranging from only 4 to 12 bits [51]. Another advantage of AprilTags is that there are six families of AprilTags, with the standard Tag36h11 family alone possessing 586 unique tags [51].

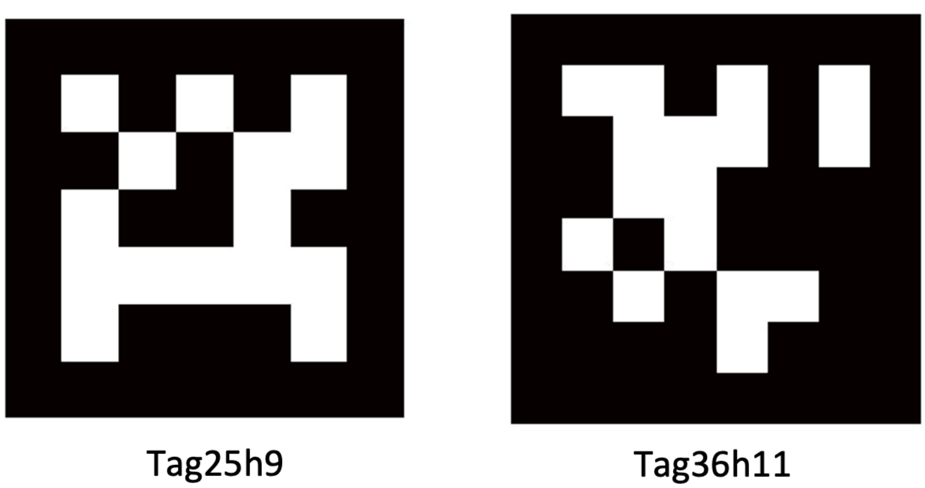

Fig. 29 Example of two unique AprilTag identifiers within two families: Tag25h9 (left) and Tag36h11 (right) [52].

With the high quantity of existing tags and the capability of developing additional families of AprilTags, this makes the system ideal for identification of tens to hundreds of CTBs. An example of two different AprilTag markers is pictured in Figure 29.

In addition, the APRIL Robotics Laboratory at the University of Michigan has already conducted tests incorporating AprilTags into a virtual reality environment for astronaut crew cabin training [53]. Therefore, the fact that NASA and other universities have already started using AprilTags for training purposes corroborates the team's choice of this marker system for CTB applications.

5.2. Simulation Details

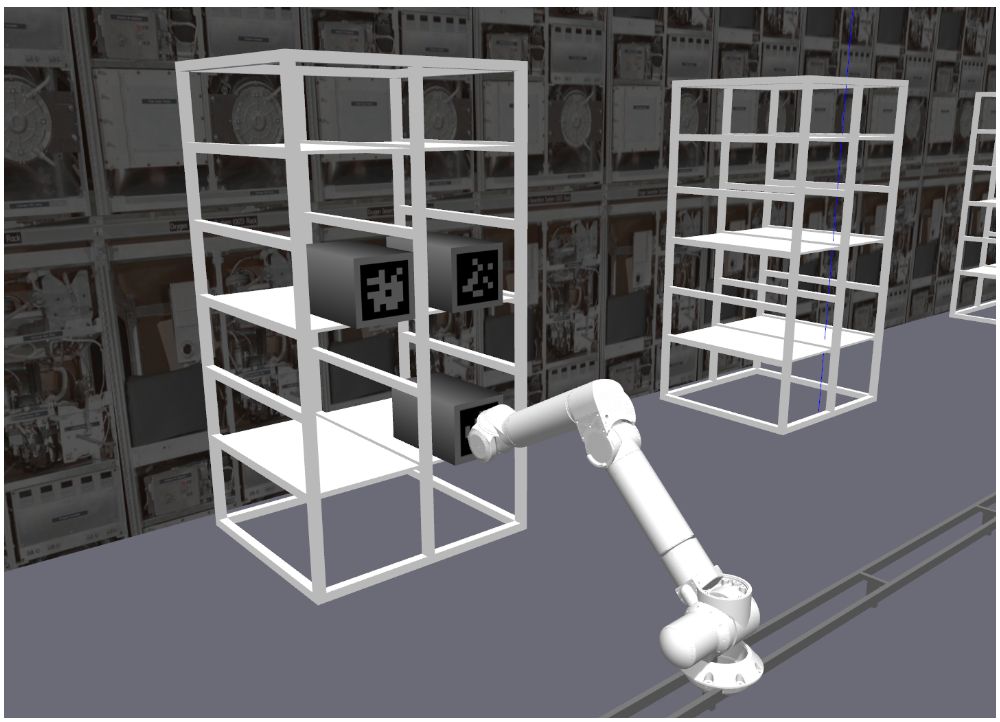

Fig. 30 Snapshot of environment in Gazebo. Ranger TSX is pictured on a T-beam rail removing a CTB from a shelving unit.

In order to investigate the usage of AprilTags for CTB management, a simulated robot and environment were created using ROS Gazebo and are depicted in Figure 30. The environment consists of three International Standard Payload Racks, which are placed in a line spaced 4.5 meters apart. Three half-size CTBs are located on the leftmost rack (with each possessing a unique AprilTag), and a rail is provided to allow the robotic system to move between racks. Justification for the choice of a rail mobility system is provided in section 5.3. The mock Gateway environment, shelving units, and CTBs were developed using NX 12 Software.

The primary purpose of the simulation was to find, in real-time, a motion path that can be executed in order to properly position the robotic arm in front of the specified CTB and pick-up and remove the CTB from its current location. An important aspect of this simulation was taking potential collisions between the arm and its surrounding environment into account. The details behind this aspect of the simulation are further described in section 5.2.2.

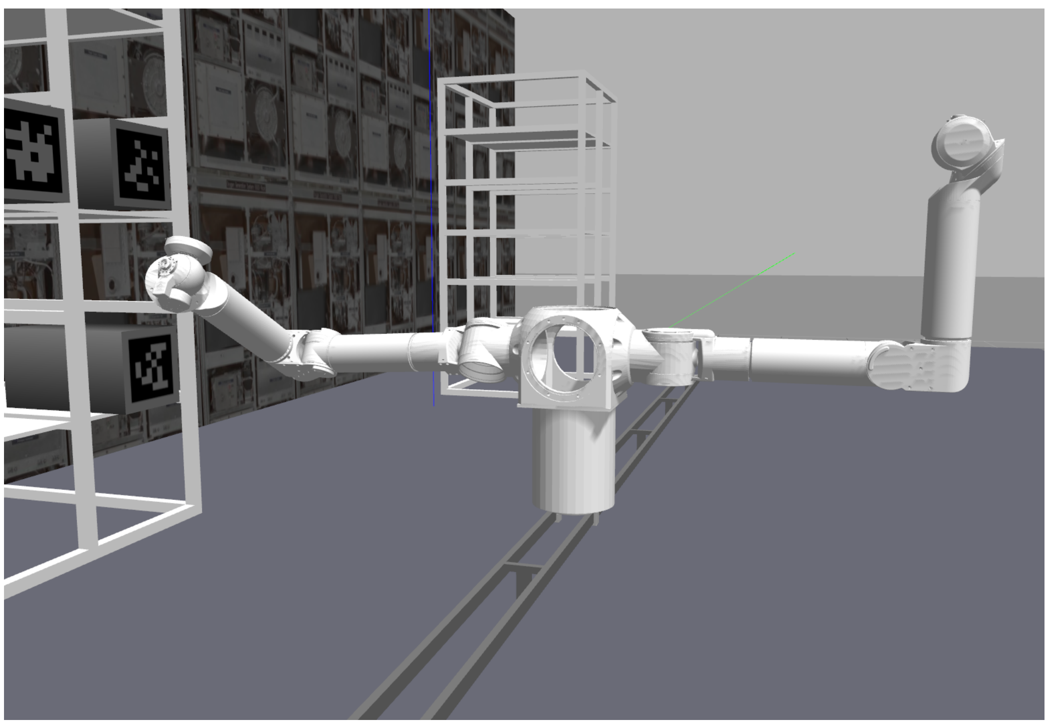

Fig. 31 Snapshot of environment in Gazebo. A two-arm Ranger TSX system is pictured on a T-beam rail.

The unique AprilTag on each of the CTBs determines the nearly exact orientation of the CTB surface relative to the camera system on the robotic arm. By knowing this positioning, an inverse kinematics solver then computes the required joint angles that will allow the end effector to be properly aligned with the CTB surface. The Bi-directional Transition-based Rapidly-exploring Random Trees (Bi-TRRT) motion-planning algorithm generates possible paths for the robot to take. Any trajectories that are not valid under the "no collision with environment" constraint are eliminated as possible paths for the robot to take.

Although only one arm is shown in Figure 30, this was chosen for simplicity in the simulation and the robotic system can easily be extended to include multi-arm robotic systems. The exact configuration of the robotic system is dependent on the needs of the habitat, but it is likely a minimum of two arms will be required. An example of this is shown in Figure 31, which includes the Ranger TSX system with two arms.

5.2.1. Logistics Management GUI

A Graphical User Interface (GUI) was developed to assist with logistics management planning through simulations. The GUI allows for the teleoperator to interact in a variety of different manners with the robot. The simulation begins by selecting a specific location/rack for the robot to approach. After this location is specified, the robot autonomously traverses to the location via a rail system. When the robot arrives at its destination, the operator can adjust the robot's field of view to target the desired CTB. The next command is to have the robot center its end effector over the face of the CTB possessing the AprilTag and pick up the CTB by activating the electropermanent magnetic end effector. Following this acquisition, the final command is to specify a drop-off location in the simulation environment, allowing for the robot to travel along the rail and deliver the CTB to the desired location by disengaging the EPM. This process can then be repeated for transporting as many CTBs as necessary.

Another factor the robot takes into account while moving between locations is to configure itself in a "transit pose," depicted in Figure 32, that allows for the robot to position itself such that it minimizes the total amount of space it is occupying. This ensures that the robot is preventing, to the best of its ability, the possibility of it interfering with other structures or astronauts onboard the outpost.

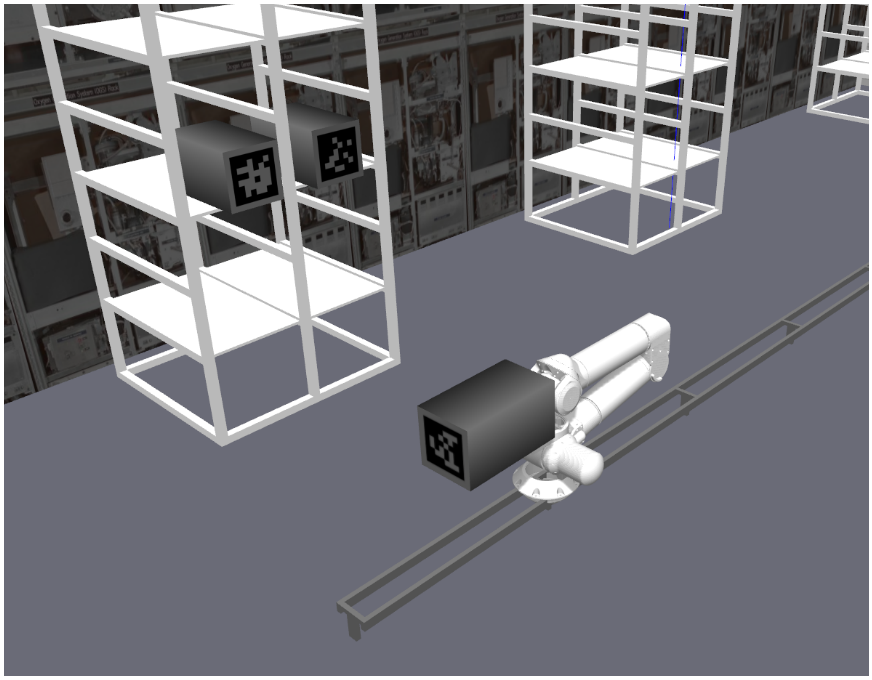

Fig. 32 Snapshot of environment in Gazebo. Ranger TSX is pictured in its optimized stowed "transit pose" to prevent interference with other structures or astronauts.

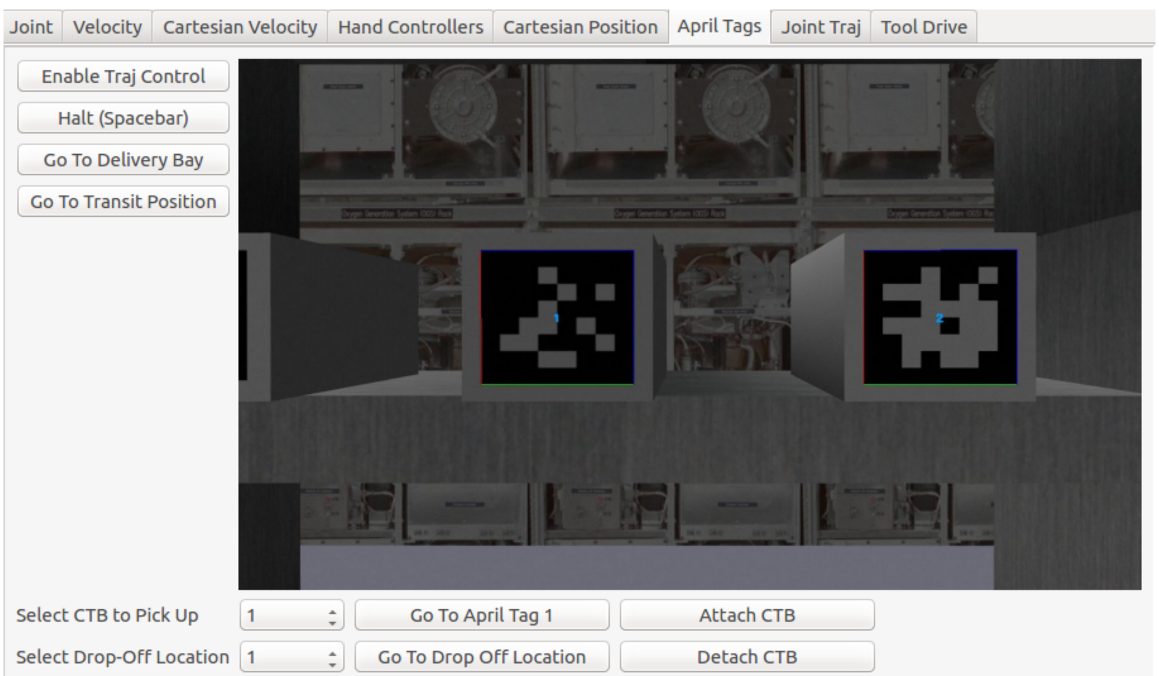

Fig. 33 GUI utilized in simulation testing. Figure depicts graphical user interface with options for user to enable trajectory control, halt the robot's movement, go to delivery bay, go to transit position, go to April Tag 1, attach CTB, detach CTB, and go to drop off location .

This simulation has been used to investigate the feasibility of using robots for CTB management without having to construct an actual test environment with a robotic mobility system. However, building a physical test environment mimicking the simulation environment leaves an interesting area of future work, as this will allow for the validity of the simulations to be further verified. Multiple scenarios have been tested with this GUI, shown fully in Figure 33, particularly having the robot autonomously move a sequence of CTBs.

Based off of the simulation, when moving at 0.3 m/s (with a 0.3 rad/s constraint on joint movements), it was found that it takes the robot approximately 4-5 minutes per CTB transfer. This is incredibly dependent on the velocity limitations of the robot and the distance between pick-up and drop-off locations, but this shows that it is feasible to use both an AprilTag system to identify CTBs and a robotic system to transport them.

5.2.2. Motion Planning & Collision Avoidance

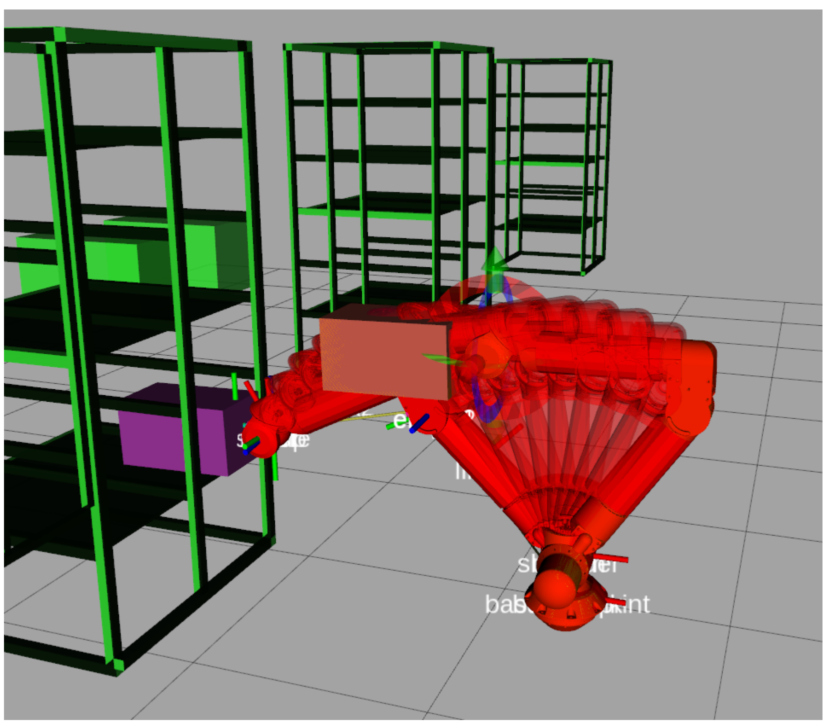

Fig. 34 Collision avoidance path planning trail for picking up and removing a CTB from an International Standard Payload Rack.

In combination with the simulated environment in Gazebo, OMPL motion planning along with the Bi-TRRT planning algorithm and MoveIt! collision avoidance were used to ensure that the the robot did not collide with anything while transporting the CTBs. The collision avoidance algorithm also accounts for the fact that the arm's collision outline changes once it has picked up a CTB. This is important to consider because damage to either the robot or the contents of the CTB must be fully avoided. This path planning portion of the simulation is visualized in Figure 34, which shows the generated safe trajectory for the current scenario. The curved nature of the pictured trajectory ensures that the robotic arm does not accidentally collide with either the shelves or sides of the rack when removing the CTB from the shelf.

5.3. Analysis of Robotic Mobility System

Based on the necessity to have the robotic system move around in the simulation environment, the team performed a trade study on approaches for a robotic mobility system that could be incorporated into future space habitat architecture. This included free flying systems, cable systems similar to that used by the Charlotte™ robot and a rail system for a robot to move along. The free flying system offered the most mobility out of all the systems, but the implementation of autonomous algorithms for this system is extremely complex. In addition, there are multiple safety concerns that would have to be addressed, regardless of whether the robot is operated autonomously or by human control. The largest risk is accidentally having the robot collide with surrounding equipment or humans due to its lack of physical constraints. This system also requires additional fixtures that must be installed throughout the habitat that the robot could grapple onto during actual operations. A cable system was also considered, as it supplies 6 degrees of freedom and has relatively lightweight support structures. However, as seen by the Charlotte™ robotic system, the cables occupy the entire volume of available space and can be intrusive for astronauts. Ultimately, a rail system was considered to be the most practical system for a robotic arm to move around a microgravity environment due to its simplicity for implementation as well as its efficiency in counteracting forces and moments applied by the robot.

The rail system adds an additional degree of freedom to the Ranger TSX arm, resulting in a total of 9 degrees of freedom for the arm. The rail was designed to take a load of 90 N at any point from the robot while performing tasks. Each rail segment is nominally 8.5 meters long to match the length of the ISS Destiny module [54], but this can be adjusted for the final module lengths of the Lunar Gateway. The mount connecting the arm to the rail would have a drive wheel and a motor to allow for movement and braking along the rail. A nominal movement speed of 1 cm/s was selected for safety concerns, but this speed could be increased with the inclusion of proximity sensors to prevent collisions. In order to transfer in between modules, the robot would likely need to reach across a hatch and grab the rail in the next module. Subsequently, it would detach from the rail it is currently on and reattach itself to the second rail. However, this transfer could also include docking stations placed at the intersection of modules to serve as an intermediate transfer location if the distance between rail sections is beyond the robotic arm's reach. The modular design of the rail and transfer method between modules would prevent complications in situations where a hatch needs to be closed to seal off a module. While the end-effector would be designed to allow for transfer between modules, the robot could be detached and reattached manually by an astronaut in emergency situations.

Two rail system designs were considered. Pictured in Figure 35, these consist of a T-beam cross-section, as well as a dual cylindrical rail inspired by modern roller coasters. Since the cylindrical rail featured a larger cross-sectional area, it was determined that it would take up more space and potentially be more likely to inhibit astronauts sharing the same space. In addition to safety, the T-beam was found to be much more structurally capable and as such it was considered to be the better rail design. The final cross-section of the T-beam occupies a 150 mm x 110 mm space.

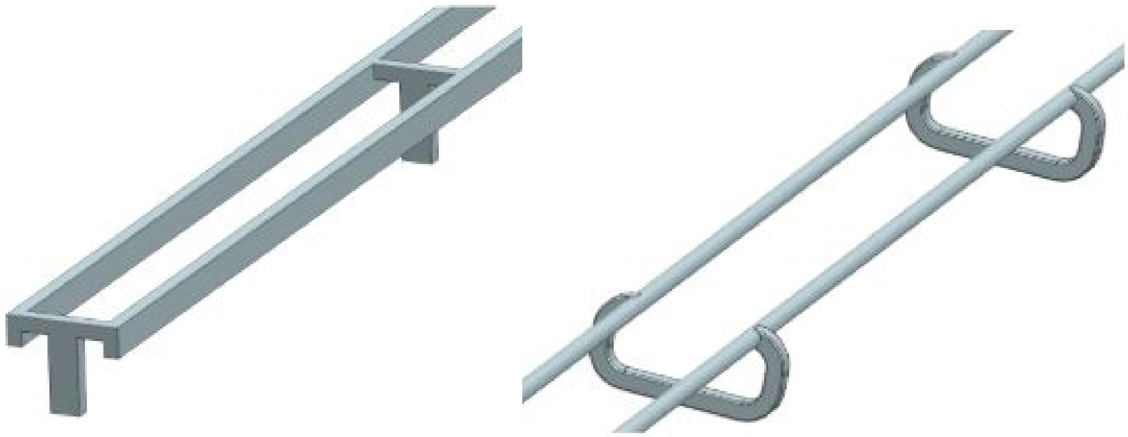

Fig. 35 T-beam rail (left), cylindrical "roller coaster" inspired rail (right).

In order to test the effect the Ranger TSX arm would have on the rail, structural analyses were performed on the T-beam model using the NX Nastran Solver. The results of these analyses are visualized in Figure 36. The first case studied was on the moment induced by a robot arm pulling on the rail. After a 30 Nm moment was applied to the model, it was found to have a maximum stress of 75 kPa. This would be well under aluminum's yield strength, the material considered for the rail. The second case studied was a vibrational study searching for the first 10 natural modes of the structure. Results indicated the first natural mode of the beam to occur at 73.6 Hz. Based off of this initial analysis, it is recommended that the components on the final robotic system be designed to operate under this frequency as a safety measure to avoid unwanted vibrational excitations. In addition, accelerometers could be installed throughout the rail system (and also on the robot itself) to measure induced vibrations. In order to avoid unsafe operation of the system, fail-safes can be incorporated into the overall system if vibrations exceed levels that could damage either the arm or rail, or even disrupt sensitive experiments. Proximity sensors can also be installed to prevent collisions with crew members.

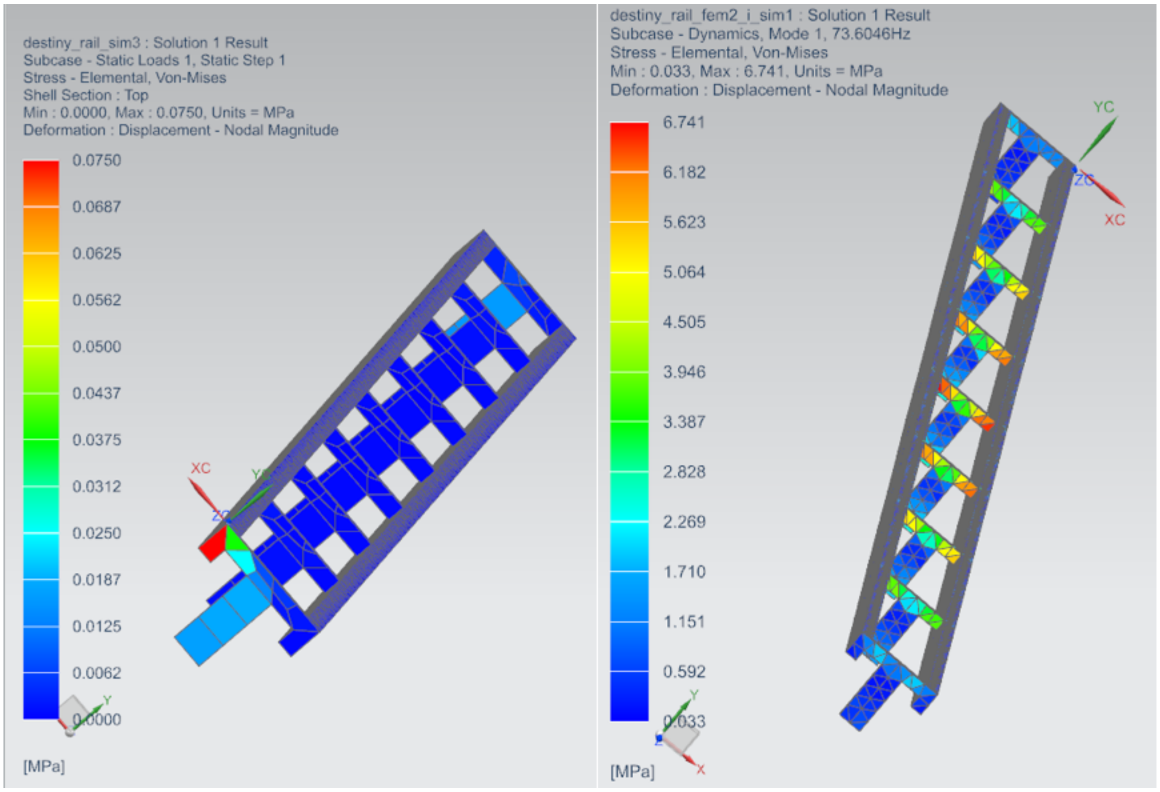

Fig. 36 Static result from applied moment (left), dynamic result from vibrations (right).

5.4. Experimental Testing of AprilTag System

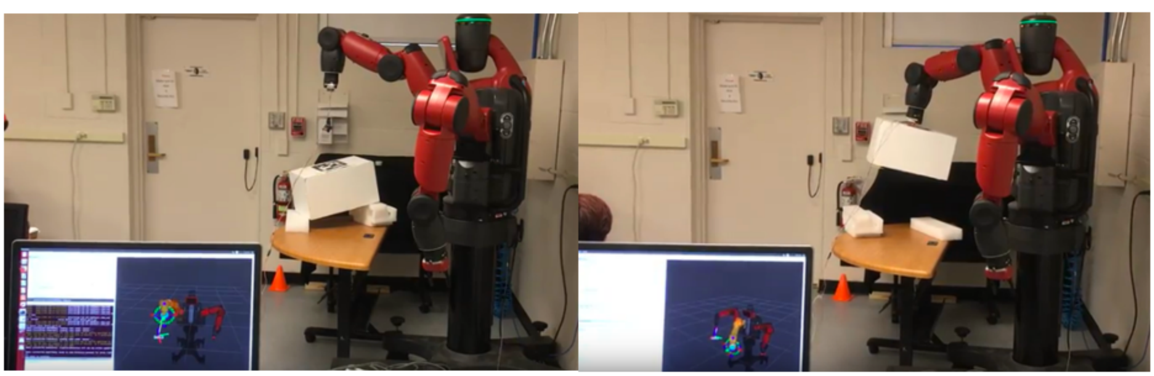

Fig. 37 Baxter robot autonomously picking up a half-size CTB via AprilTag identification.

Testing was performed with the Baxter robot to demonstrate usage of an AprilTag system in a physical environment, as shown in Figure 37. During this test, the half-size CTB mock-up was placed on top of a table in front of Baxter. By using the cameras mounted on the arms of the robot, Baxter was able to successfully detect the AprilTag on the bag and autonomously maneuver its joints to connect with and pick-up the CTB in a matter of seconds. Ultimately, this test complements the results gathered by the simulation, as it shows how quickly and effectively a robot can locate and interact with a CTB.

5.5. Conclusion

Team ASTRO successfully created simulations exploring the feasibility of robotic systems utilizing AprilTags as an identification and situational awareness system. AprilTags increase the efficiency of tracking hundreds of CTBs, and Gazebo simulations show that a robotic arm system can effectively transport an individual CTB on the order of minutes. Additionally, AprilTags have the functionality to be detected both through teleoperation and autonomy, allowing for management of CTBs with minimal human-in-the-loop intervention. Simulation results are corroborated with a physical test where the Baxter robot identified and picked up a CTB using an AprilTag in a matter of seconds. Although the focus of the team's research was on using AprilTags for detection and manipulation of CTBs, this system can be extended to serve multiple purposes. For example, AprilTags can be mounted on hardware such as life support systems spread throughout the habitat. This would work in conjunction with future fault detection algorithms to easily locate anomalies.

The addition of the rail mobility system also provides valuable information on other aspects necessary to make the robotic system fully functional. If a rail were to be incorporated into a future space habitat, it would have to be installed prior to launch and be accounted for in the overall system design architecture. While future habitats may not use a rail, other selected mobility systems will undoubtedly require additional structural support as well. This is something that should be accounted for in the initial habitat design, but the architecture can also be designed such that it has allotted interfaces that would allow for future robotic mobility systems to be introduced later on. In addition, if a robotic arm were to be used, human-robot interaction along the rail must be addressed. Similar to the team's simulations, a "transit pose" can be used to minimize the volume the robot occupies. In addition, designated stowage points throughout the habitat modules can be specified that allow for the robot to fully retract in order to avoid interference or collision with astronauts.

6. Final Discussion

Through the completion of this project, Team ASTRO was able to draw various conclusions about robotic operation, maintenance, and repair of a space station or space habitat. The team used various types of robotic arms for testing and simulations, including Baxter, Ranger NBV, and Ranger TSX, each with different system capabilities. Various end effectors were also designed and tested over the course of the project, including a two-pronged pinching end effector, two different pneumatic grippers, and the NicaDrone electropermanent magnetic end effector. Different tasks required different levels of robotic mobility, which varied with each design. The team also worked predominantly with teleoperation of the robot.

The team was able to conclude that a robotic system capable of completing maintenance in a space habitat, while the space was uncrewed, would require mobility and adaptability. A rail system, such as the one the team designed, would be an important feature in the habitat as it would allow one robot to access a large portion of the habitat. The team also found that the grip strength of the robotic arm needed to be sufficiently strong to complete tasks normally left to the astronauts, with pneumatic grippers proving to be the most successful in the team's testing. While autonomous robotic systems would eliminate the need for human oversight, the team was able to show through their testing that teleoperation of a robotic arm while completing common repair task motions can be successful. The operator could successfully perform actions with the robot using only a camera feed on the end of the arm for visual feedback. It also became clear to the team that end effector design would be extremely important for the proposed robotic maintenance system. Different end effectors are better suited to complete different types of motions, so inclusion of multiple types of self-interchangeable end effectors on a robotic system for a space habitat would best equip the system with the greatest range of capabilities.

Team ASTRO found that the inclusion of AprilTags in any new space habitat would be extremely beneficial for completing tasks with robots. From the team's work with Baxter autonomously identifying the position and orientation of a cargo transfer bag affixed with a tag, as well as the simulations generated in Gazebo, it is clear that AprilTags have the potential to catalog and manipulate cargo and supplies without astronaut involvement. Team ASTRO was able to create a graphical user interface to assist with logistics management planning in a simulation and manipulate a real cargo transfer bag via an electromagnetic end effector and metal plate. To provide astronauts with additional time to complete mission objectives, especially if onboard Gateway for only a short time period, NASA's current cargo management system on the ISS can be improved via the incorporation of AprilTags throughout the habitat. The APRIL Robotics Laboratory at the University of Michigan has already tested a virtual reality device that uses AprilTags to help astronauts with localization in the crew cabin in microgravity [53]. Team ASTRO's cargo management system can be further developed to increase crew capabilities.

6.1. Recommendations for Robotic Outfitting of the Lunar Gateway

Based off of results gathered throughout the course of this research project, Team ASTRO believes that the most important aspect of the research that should be included in the future Gateway outpost is the use an AprilTag system, or some other identification system. This offers many benefits, as it would allow for hundreds of bags to be easily tracked. The identification system could also be improved upon such that a single scan of the bag tag could list every single item within the bag. This could save potentially hours of time when having a robot (or human) searching for a specific item. The use of AprilTags can also be extended to additional hardware. For example, they can be placed throughout the Gateway to provide identification and localization information of vital hardware, such as life support systems, to allow for a robotic system to easily locate the hardware in an event of an anomaly. In addition, if robots are to be used for CTB logistics management, a redesign of the current bags should be thoroughly considered. An electropermanent magnet requires further analysis to prove safety of operation, but something along those lines would greatly improve the efficiency of robot-bag interaction as opposed to attempting to grasp the bag with a dexterous hand-like end effector.

Reflecting on the shortcomings and issues of the three NASA and Canadian Space Agency space-robots, explored in the earlier literature review, the team's findings would be of use in enabling robots to better perform in space habitats. Robonaut and Canadarm were robotic manipulators, similar to the robotic systems that Team ASTRO used to conduct research. AprilTag use throughout a space habitat would be beneficial for the control and manipulation of both of the retired systems. Additionally, Robonaut's arms or Canadarm would be able to interact more easily with CTBs if the team's recommended changes were made. Both robots would be more able to perform significant work in a space station that would justify their costs and necessary upkeep. Although the crowding issues of NASA's retired Charlotte cable-robot would not be mitigated by the team's findings, Charlotte would be able to navigate a habitat more easily with the inclusion of AprilTags. This would increase the usefulness of a similar robot being used in a space habitat.

Robotic systems are absolutely vital for the uncrewed operation of the Lunar Gateway. This project succeeds as a proof-of-concept study for investigating the feasibility of a robotic arm system, and shows this can be a viable solution for operating and maintaining the Lunar Gateway. Robotic devices require a mobility system to traverse through the habitat, and Team ASTRO has shown that a rail system could be used for robotic arm movement. Although this may not be the optimal system for Gateway and requires further trade studies, Team ASTRO has shown that the Gateway architecture must include additional support structures to accompany the selected robotic systems.

6.2. Testing Failures & False Directions

As indicated throughout this thesis, there were a large number of failures the team encountered while performing testing for this project. This section reiterates major failures that hindered the overall progress of the project. To begin, the team's original foamcore taskboard was not rigid enough for the robot to interact with, as it would be damaged with a small amount of applied force. This was mitigated with the construction of an acrylic taskboard. However, the robot was still able to deform the acrylic taskboard. To prevent this, it was then mounted using wooden blocks and a frame available for use in the Space Systems Laboratory.

The initial design of the two-pronged pinching end effector for the taskboard was poor as the end effector tips began flexing away from end effector mount. The flexing became extremely apparent during rotatory movements, indicating the need to be re-printed. Although re-printing did not fix this issue entirely, it greatly improved upon performance. Also, the addition of grip tape to the printed fingers drastically increased the gripping capabilities of the end effector.

When using the pneumatic gripper system, the end effector's fingers were not correctly mounted, as the pins that were supposed to hold them in place broke off. Zip-ties were instead used, but one side of the end effector continuously deformed. Consequently, the grip force of the system was weakened, which resulted in failures during taskboard testing. This concern was addressed by installing a re-printed gripper to the Ranger NBV arm, using m4x0.7 screws rather than zip-ties to attach each finger. Initially, the gripper appeared more stable than before, but it was then capable of deforming the taskboard, which required a better mounting strategy addressed by the addition of wooden planks. However, shearing along the bottom of the mounting between the circular plate and the shaft of the robot occurred. A redesign of the mounting system was required, and fillets were incorporated in order to reduce the stress experienced by the mount.

Over the course of the project, losses of testing sessions were periodically experienced when Ranger NBV was out of operation for repairs. The arm occasionally encountered electrical or software issues that rendered it unavailable for extended amounts of time. The team was not capable of performing repairs on the robotic arm and is extremely appreciative of the significant amount of time SSL graduate students spent to get the arm back in operation.

Since one of the initial goals of this project was to explore full-scale habitat maintenance and repair, in the spring semester of 2019, the team began work on repairing the SSL HAVEN habitat. As debris and rotting wood were removed from the interior of the habitat, it was determined that the necessary repairs to bring Ranger into the habitat would not be possible in the time the team had available for this project. In addition, the floor of the habitat was not strong enough to support the weight of the robot and would require significant repairs to ensure safe operation. Therefore, this aspect of the project was quickly abandoned to prioritize other testing of the robotic system.

6.3. Future Directions

As space stations or habitats are constructed in regions of space beyond low Earth orbit, it will be increasingly important that habitats can be remotely maintained. Even if the habitat is placed in a dormant, minimum operation mode while uncrewed, some amount of maintenance of the outpost will be required to prevent it from entering into a state of disrepair. The research conducted by Team ASTRO serves as a proof-of-concept study that robotic systems have the potential to complete tasks to keep a space station or habitat operational when astronauts are not onboard. However, in order to go beyond a proof-of-concept and develop a fully functional robotic system for the Lunar Gateway, many areas of future work must be addressed.

There were many other aspects that were originally objectives of this project, but had to be modified or omitted due to either time constraints or research restrictions brought on by the COVID-19 pandemic. For example, repair of both the SSL HAVEN and ECLIPSE habitats were an early goal of the project. However, due to safety concerns in an attempt to repair the habitats, this goal was abandoned. After repair of the these habitats was determined to be out of the scope of this project, the team made plans to create a mock-up of an internal ISS module. This module was intended to be used in testing of the robotic arm as it would allow the team to determine how well the system could perform tasks in a simulated space habitat. The team was not able to complete this part of the project due to lost time from the COVID-19 pandemic. Using either the SSL habitats or constructing an ISS module with a compatible mobility system would be extremely useful, as it would be a higher fidelity environment for testing and one could observe how well the robot can maneuver around a constrained space. In addition, testing within the Neutral Buoyancy Tank could be performed in order to observe the efficiency of the robotic system completing a task in a simulated microgravity environment.

Future work should also investigate higher fidelity and more complex maintenance and repair tasks. Team ASTRO predominantly looked at common operational tasks and simplified "remove and replace" maintenance tasks, so expanding upon the breadth of tasks attempted would be a natural next step. For example, repair of faulty life support system mock-ups could be assessed, or full-scale disassembly and reassembly of a life-support system such as an oxygen generator could be evaluated. This will allow for future researchers to determine the complexity limits for what a robotic system is able to achieve.

Other areas of future development that would increase the technology readiness levels of this work include the incorporation of autonomy and fault detection methods. The majority of physical testing in this project was conducted via teleoperation, but Team ASTRO showed in simulations and through a single Baxter test that autonomy can be used for actions like identifying and transporting CTBs. Autonomy can be expanded upon in future iterations by creating autonomous servicing algorithms that can effectively address known or forecasted failures of frequently used hardware within a space habitat. Diagnostic maintenance is another aspect vital to continued habitat operation, so methods of fault detection must be further investigated as well. Specific equipment inspection methods were described in section 2.7, but examples include Command and Control MDMs as well as infrared cameras for anomaly detection. In addition, force feedback of the robot and latency between the robot and operator can also be further explored.

The last immediate area of future work is the exploration of an end effector exchange system. Although Team ASTRO was able to complete most tasks with a gripper end effector and additional modifications, the team did not address all possible tasks and it is unlikely that a single end effector will effectively accomplish all necessary tasks. Therefore, future studies can better identify a set of end effectors, with each designed and optimized for a specific task. The robotic system would then be able to autonomously choose and equip the best end effector suited for the task at hand.

Overall, this project acts as a strong basis for multiple areas of future work, all of which can be addressed if this research project is continued through future iterations.

6.4. Applications Outside of Space Exploration

Over the agency's lifespan, NASA's aeronautics and astronautics research and development efforts have resulted in thousands of products known as spin-off technologies. When advanced materials or designs are created to perform in the extreme environment of space, these products are often later adapted for applications on Earth. These spin-off technologies include products such as memory foam, GPS, wireless headsets, blood pumps, food safety standards, and cloud computing [55]. Spin-off technologies greatly demonstrate the overall impact space research can have on people's daily lives. Research, such as that conducted by Team ASTRO, can not only help people gain a better understanding for what lies beyond the Earth, but it can also improve people's lives on the planet.

Team ASTRO's research, though focused mainly on the application of these robotics in space (i.e., in a microgravity environment), has many applications to other areas of research in Earth's gravitational environment. The field of robotics is extremely broad, and lessons learned by robots in space can easily be extended to other industries. As an example, millions of individuals and families have be impacted by the COVID-19 pandemic. With advanced robotic systems, there are situations where it would be safer from a public health perspective for a robot to perform tasks rather than have a human do it. In hospitals, a teleoperated or autonomous robotic system could have the ability to open doors, hold out pills for patients, or possibly adjust the position of a patient on a ventilator. Although these tasks are relatively straight-forward, if performed by a human they can encourage unintentional spreading of the virus. If these tasks can easily be achieved by a robot, it would be significantly safer since the robot only needs to be disinfected prior to being sent in to work with another patient. There is an existing robot known as Moxi that already assists with common hospital tasks, as shown in Figure 38, and the team's research could supplement Moxi to help further understand and improve robotic capabilities in medical environments [56].

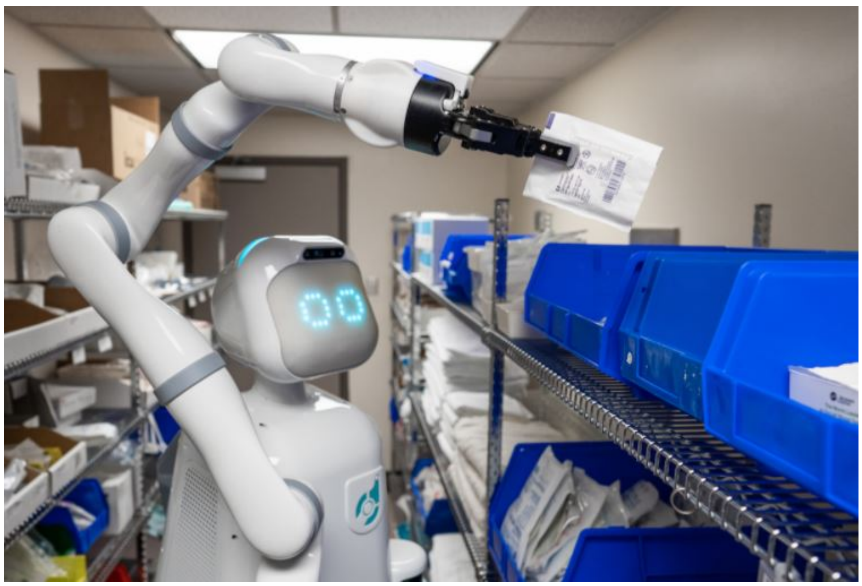

Fig. 38 Image of Moxi, an autonomous robot working in a hospital. It is not currently used for patient interactions, but it can change linens and deliver samples. If it is supplemented with the team's research and given a teleoperated function, it could also be used for patient interaction and a wider variety of tasks [56].

Another example for which robotics could be applied would be in the field of power line maintenance, which is usually performed with a teleoperated robot. Most recently, the main issue within this field is improving the mobility and teleoperational control of these robots. In one study by Jiang et al. [57], the main issue scientists focused on was a lack of structural stability in their robot while it works on certain tasks. Rather than change how the task is done, the researchers improved the robot's spatial awareness [57]. While having a more stable robot is important, this solution ignores how efficiently tasks are completed.

This could be supplemented by the research Team ASTRO has done by mentioning the teleoperational limits of certain tasks and how efficiently certain tasks can be completed. No matter how spatially aware a robot is, if it is teleoperated, the human component of operation is necessary to assess for significant improvements in the system.

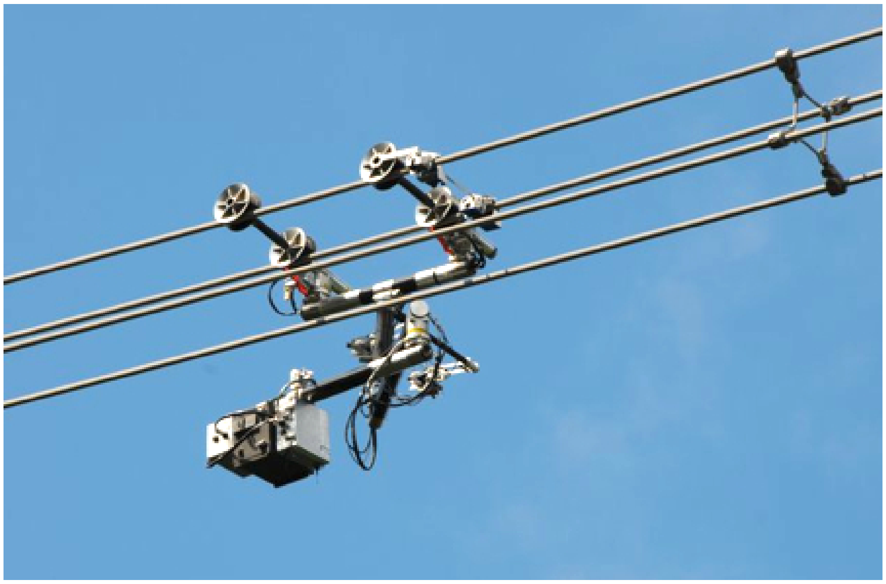

Fig. 39 Example of the a robot traversing a high voltage transmission line during a maintenance check [58].

Furthermore, robots could also be utilized to repair underwater pipelines and cables. Maintenance of underwater utilities can be extremely time-consuming for humans to perform. By using robotic systems to repair pipelines, it could reduce time as well as the risks associated with working underwater for extended periods of time. The prospects of using new robot technologies for underwater archaeology are currently being investigated [59]. There is an increasing interest in underwater projects and additionally, underwater robots are becoming more cost efficient as well as more user-friendly. Underwater robotics could be used for cleaning as well. A recent study details the applications and challenges faced with underwater scrubbing of surfaces from robots [60]. Some limitations posed in this study include that cleaning robots are currently restricted to ferromagnetic surfaces, and they also experience limited flexibility around certain structures. Ultimately, underwater cleaning is a challenging issue and it is certain that more work regarding the flexibility of robots in neutral buoyancy environments is required. Since space, like neutral buoyancy, is a microgravity environment, mobility of robots in space can be studied and applied to these underwater robots. In addition, any end effector exchange system utilized by a space robot can inspire a system targeted towards underwater cleaning and archaeology efforts.

Fig. 40 Aquatic robot designed for looking through dangerous underwater zones that shouldn't be entered by humans, such as complex tunnels, ship wrecks, and severely damaged underwater pipelines. It can be used to clean important artifacts found underwater, and could possibly be improved with the team's research on the use of different end effectors for varying tasks [59].

6.5. Equity Impact Report

In order to address inequity throughout Team ASTRO's research, considerations have been made to make the above findings accessible. The team's thesis is compliant with Federal Section 508 regulations, an amendment to the Rehabilitation Act of 1973. Section 508 ensures those with disabilities have access to federal documents, data, and applications in the same way as those who are not disabled. In order to utilize assistive technologies, all figures have a text alternative for the vision impaired. Tables, plots, photographs, and computer designed images are accompanied by substantial descriptions and short titles that may be processed through screen reading software.

Along with the inclusion of alternative text, all plots and tables are expressed in a color palette that those with any form of color-blindness can easily differentiate (orange-grey-blue), including image backgrounds. This color palette allows for enhanced color perception and the necessary color contrast for color vision impaired readers. This inclusion of alternative text and color-blind accessible images will ensure the team's research is available to any interested party for future investigations pertinent to space robotics.

In preparing the team's literature review, efforts were made to utilize sources from diverse authors and organizations outside the United States. Sources from the Canadian Space Agency (CSA) and Japan Aerospace Exploration Agency (JAXA) were investigated, along with those from Chinese and Russian space organizations. Despite our efforts, the majority of pertinent journal articles and conference papers are from NASA and the Institute of Electrical and Electronics Engineers (IEEE) because there are limited organizations involved in space exploration. The team noted that the majority of the utilized sources had male authors. The lack of female authors provided a candid reflection of gender disparity in the aerospace industry.

6.6. Final Conclusion

With the Lunar Gateway being uncrewed for 11 months out of the year, the development and incorporation of robotic systems is absolutely vital for the continued operation of this outpost. Not only would a teleoperated or autonomous robotic system be capable of maintaining the habitat and addressing emergency repairs while uncrewed, it would also be able to work alongside astronauts. By performing operational and maintenance tasks in a crewed environment, astronauts will be able to maximize their time spent on scientific experiments. Ultimately, Team ASTRO has successfully demonstrated a proof-of-concept project on the feasibility of using robotic systems to achieve this goal and contribute to the continued presence and advancement of human space exploration.

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Appendices

Electrical Connector Removal	Success/Fail	Time	Note
1	F	0:34	Mis-aligned end effector
2	F	0:23	Mis-aligned end effector
3	F	0:32	Mis-aligned end effector
4	S	0:27	
5	S	0:19	
6	S	0:20	
7	S	0:18	

Electrical Connector Insertion	Success/Fail	Time	Note
1	F	0:05	Partial insertion
2	S	0:13	
3	S	0:12	
4	S	0:08	

Unbuckling	Success/Fail	Time	Note
1	S	0:50	Delayed open
2	S	0:14	
3	S	0:12	

Buckling	Success/Fail	Time	Note
1	F	1:27	Second person assisting
2	S	0:40	Camera feedback

Knob Turning	Success/Fail	No. Clicks	Alignment Time	Turning Time	Control method	Note
1	S	2	2:48	0:30	Joint	Board moved at end because electrical connector in way
2	F	0	0:34	-	Hand Controller	Ran into electrical connector
3	S	1	0:20	0:15	Hand Controller	Could not tell if clicked after first one
4	S	2	Not Recorded	0:26	Hand Controller	Very clear how much it clicked

Table 7 Table containing data for each trial during round 2 of taskboard testing, recording times, comments and whether the task was failed or not.

Electrical Connector Removal with Camera Guidance	Success/Fail	Time	Note
1	F	0:29	Too little grip contact
2	S	0:27	
3	S	0:25	

Electrical Connector Insertion with camera	Success/Fail	Time	Note
1	S	0:04	
2	S	0:08	

Knob Turning w/ Camera	Success/Fail	No. Clicks	Alignment Time	Turning Time	Control method	Note
1	S	2	0:27	0:20	Hand	

Table 8 Table containing data for each trial during round 3 of taskboard testing, recording times, comments and whether the task was failed or not.

For Tables 7 and 8: Hand controller (Hand) refers to the use of a joystick-like controller. Joint control means individually moving joints one at a time to accomplish a task.

Robotic Habitat Technologies for Minimizing Crew Maintenance Requirements

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Contents

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I. Introduction

A. Description of Problem

Currently, astronauts onboard the International Space Station spend a significant portion of their time performing maintenance and repair tasks on the station itself, to keep the microgravity laboratory in working order [1]. Unlike the International Space Station (ISS), the Deep Space Lunar Gateway, which NASA hopes to have astronauts visiting by 2024, will be uncrewed for the majority of the year[2]. This means that many of the frequently performed repair or maintenance tasks that the astronauts are responsible for carrying out on the ISS will need to be completed by automated or robotic systems on Gateway. Robotic systems have different constraints compared to humans so they have varying levels of difficulty performing tasks that were designed for human operation [3]. Team ASTRO sought to assemble a database of tasks, which represented operations done on the ISS, that a robotic arm and specified end effector could complete. Tasks that were difficult to complete with the robot could indicate that aspects of the operation should be redesigned to be performed more easily by a robot on the Deep Space Gateway.

B. Research Questions

Team ASTRO sought to investigate the usefulness of incorporating robotics in a microgravity habitat. The primary question that the team looked to address was what specific repair tasks, currently performed on the ISS could be automated on Gateway. In order to conduct useful research, Team Habitat needed to have a good understanding of problem areas and common maintenance tasks on the ISS so useful tasks could be selected for automation with robotics. This information would be very important in designing the taskboard for the robotic arm to interact with. The team also sought to investigate what time saving tasks, that astronauts are currently responsible for completing, could be modified to be performed by robots, ideally in a more efficient manner. Ultimately, this research project was broken down into two categories: nominal repetitive operations (which deals with the capabilities of robots to perform common operational and maintenance tasks) and Cargo Transfer Bag (CTB) management (because this is a time consuming and mundane task but very important for station logistics).

II. Background

There were many aspects regarding the wide variety of operational and repair tasks performed in space that were considered when brainstorming what tasks could most efficiently be performed by a robotic system in microgravity. The most basic tasks, such as flipping switches or pressing buttons, while easy for an astronaut to execute, could prove to be more challenging for a robot to complete based on the positioning or orientation of the panels. For example, a switch with a switch guard that needs to be flipped may require the robot to have two hands, one to hold up the cover, the other to push the button, so it was important to create a taskboard for the robot that had tasks that varied in degrees of difficulty for the robot to complete. By timing the robot when working on different tasks, the efficiency of the robotic system could be compared to that of a human completing the same action.

Additionally, the team investigated the manipulation of Cargo Transfer Bags (CTBs). CTBs are used on the ISS to store cargo. A robot that could effectively organize and transport CTBs could remove a significant logistical drain on astronauts' time. In order to maneuver CTBs the robotic system would have to be able to orient itself relative to a target on the surface of the CTB, attach, and move the CTB. This presents an interesting problem and requires limited changes to the current CTB design in addition to the design of a unique end effector. Determining the feasibility and efficiency of a design would contribute to a proof of concept assessment for a system that could manipulate CTBs in place of astronauts.

III. Nominal Operations

A. Taskboard

The team created a taskboard with which the robotic systems could attempt to perform nominal tasks. These tasks mirrored operations done aboard the ISS and that would have to be done on the Lunar Gateway. Tasks tested included flipping switches (with and without switch-guards), turning knobs and valves, and pushing buttons. Other tasks such as buckling a buckle were tested, but the team found it was too difficult for a single robotic arm to accomplish, and thus did not pursue it.

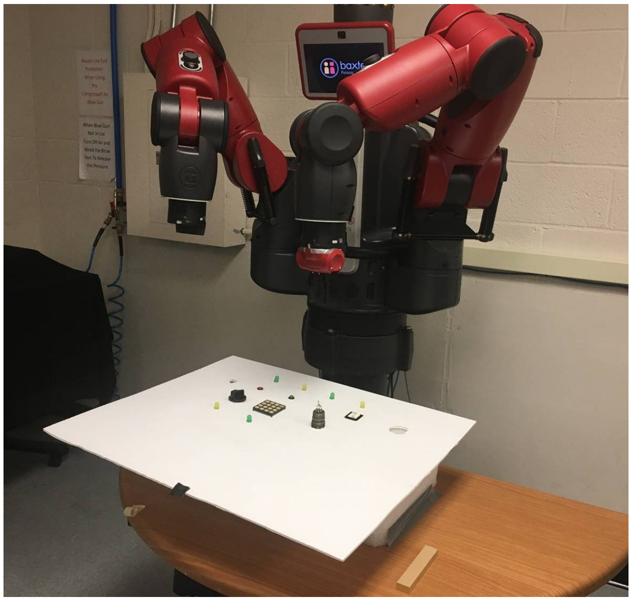

Fig. 1 Setup: The BAXTER robotic manipulator begins above the taskboard before moving to complete a task.

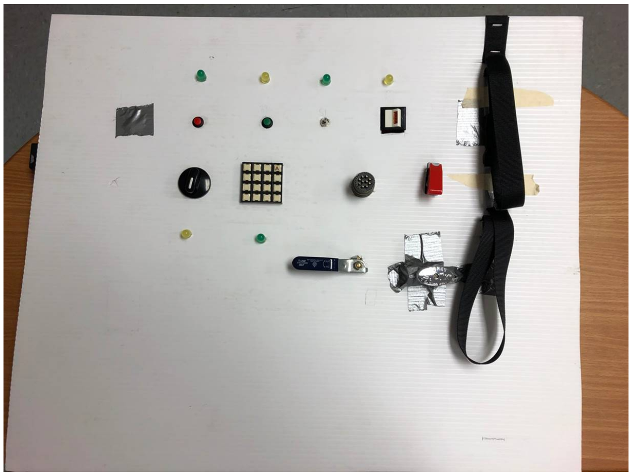

Fig. 2 Taskboard Layout: Pictured are buttons, switches, knobs, valves, an electrical connector, and a buckle.

The taskboard was constructed out of foamcore and was furnished with knobs, valves, buttons, switches, electrical connectors, and a buckle. It measured 18 inches by 27 inches, which was found to be an appropriate size for the various robotic systems to interact with. Testing was conducted primarily with the UMD Robotic Realization Lab's BAXTER robot as well as the Space Systems Lab's Ranger NBV arm (both shown in Figure 3). The team found that NBV offered a stronger grip and more freedom of movement, allowing it to complete some tasks that BAXTER could not, such as turning rotary valves and knobs.

This taskboard served as a preliminary assessment of the difficulty of ten different component-level tasks aboard space station. Though the current board does not reflect the true complexity of such tasks in a crowded microgravity environment, such challenges can be accounted for in the board's next iteration. The team expects to expand into system-level tasks in the near future, constructing replicas of larger systems like ORUs or wall panels. To represent real conditions more accurately, this newer replica is also planned for testing in the Neutral Buoyancy Simulator at the University of Maryland.

B. Robotic Systems

The team has selected three primary robots to test for this research project. The first robot is the Baxter research robot, which possesses two separate 7 degree-of-freedom (DOF) arms. Although the Baxter robot has proven to be imprecise in controlling its movements, the team was able to use this robot for preliminary tests of both nominal operations and CTB management. The second robot the team used for this research is the Ranger Neutral Buoyancy Vehicle's (NBV) 6-DOF manipulator. This robot provided significantly more precise operation as compared to Baxter, and the team used it for additional testing of the nominal operations category. However, due to a number of technical difficulties, the team was limited in its access to this robot. The last robot the team considered using is the Ranger Dexterous Manipulator (DXM), which is a 10-DOF arm capable of underwater testing. The team planned on using this robot to simulate a microgravity condition; however, this testing was delayed because the additional fidelity was not considered significant enough yet to warrant the additional complexity of waterproofing everything, particularly since DXM was being used for research with commercial companies during the spring. Once our simulations have been worked out on dry land with gravity, the possibility of testing in weightlessness will be revisited.

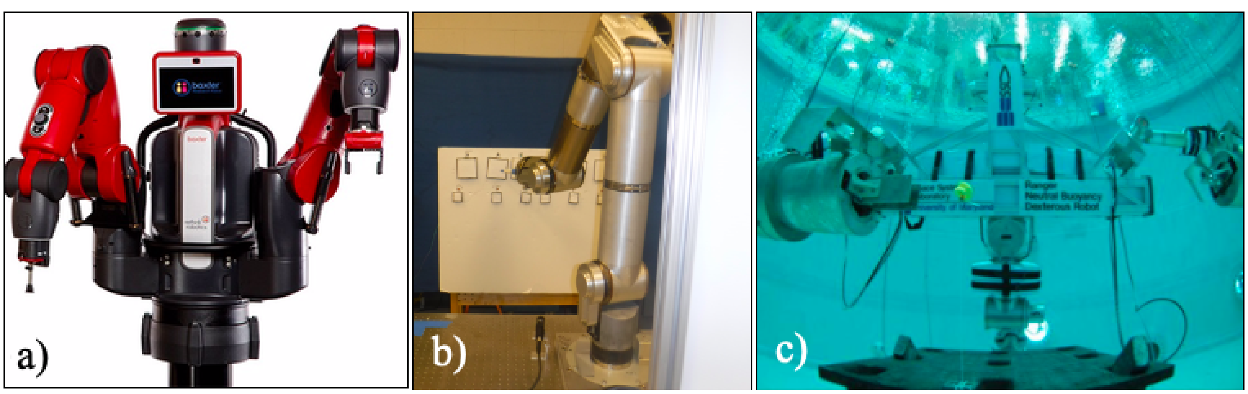

Fig. 3 a) Baxter research robot [4] b) UMd Space Systems Laboratory Ranger NBV robot interacting with taskboard c) Ranger Dexterous Servicing System undergoing testing in UMd Neutral Buoyancy Research Facility.

C. Gripper End Effector

As a primary method for interacting with the taskboard, the team developed a gripper end effector to use in combination with the robot arms. The design started with a TowerPro electric servo. The team then

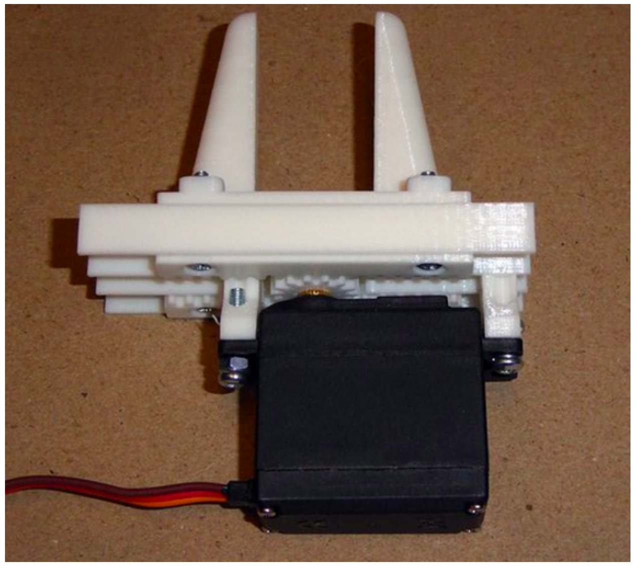

Fig. 4 3D-printed parallel gripper attached to TowerPro electric servo.

used CAD of an existing gripper design, modified it slightly, and 3D-printed it to make it compatible with the servo. The servo was screwed onto the gripper's base, which housed a gear and two connected pincers. Rotating the servo spun the gear, causing the pincers to open and close as commanded by arduino code sent to the servo. This formed the basis of the initial design.

It was then necessary to come up with a way to attach the servo to both the NBV arm and the Baxter arm, as neither arm was capable of steadily holding it on its own without external mounting. Each arm has a bolt pattern that can be used to attach a fixture onto the end of the arm, but the hole positioning was not identical for the two arms. The NBV arm has six holes, arranged in a circular pattern concentric with the main robot arm. The Baxter arm has four holes in a trapezoidal pattern, with several other extrusions extending above the hole plane, meaning the plate had to both match the hole pattern and account for these extrusions. The team created CAD for both mounting devices, and 3D-printed them for use in testing with the taskboard.

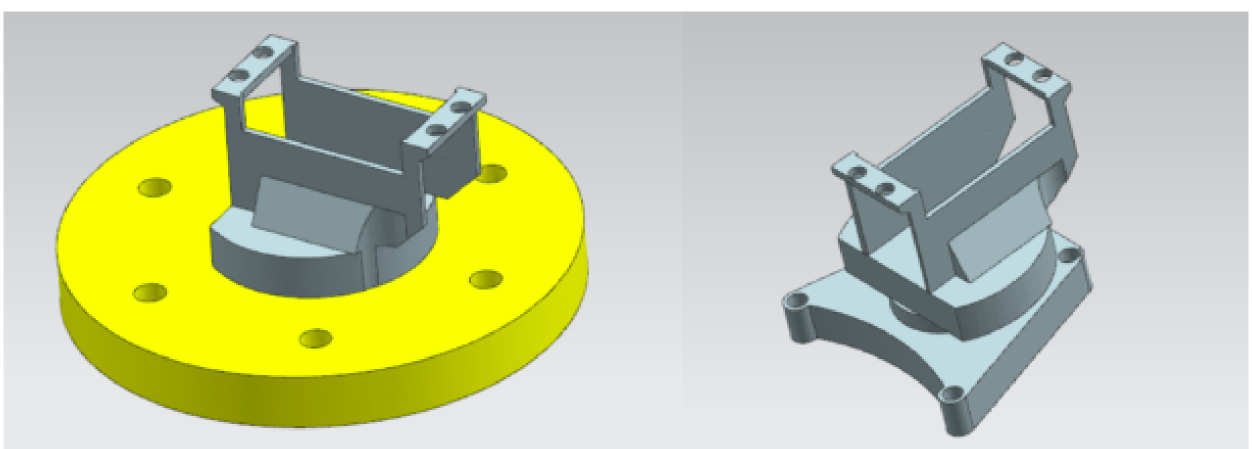

Fig. 5 CAD for mounting servo end effector onto Ranger NBV (left) and Baxter (right).

After initial testing, the team determined that the gripper could not apply enough gripping force with its two pincers. This resulted in reduced test effectiveness due to inability to maintain grip on taskboard components. To resolve this issue, the team applied two different materials to the interior of the gripper's pincers: a rubber layer and a sandpaper-like layer. Due to time limitations the team was unable to test with the sandpaper-like modification, but the rubber modification did prove effective at enhancing the robot's ability to maintain a grip on the taskboard components.

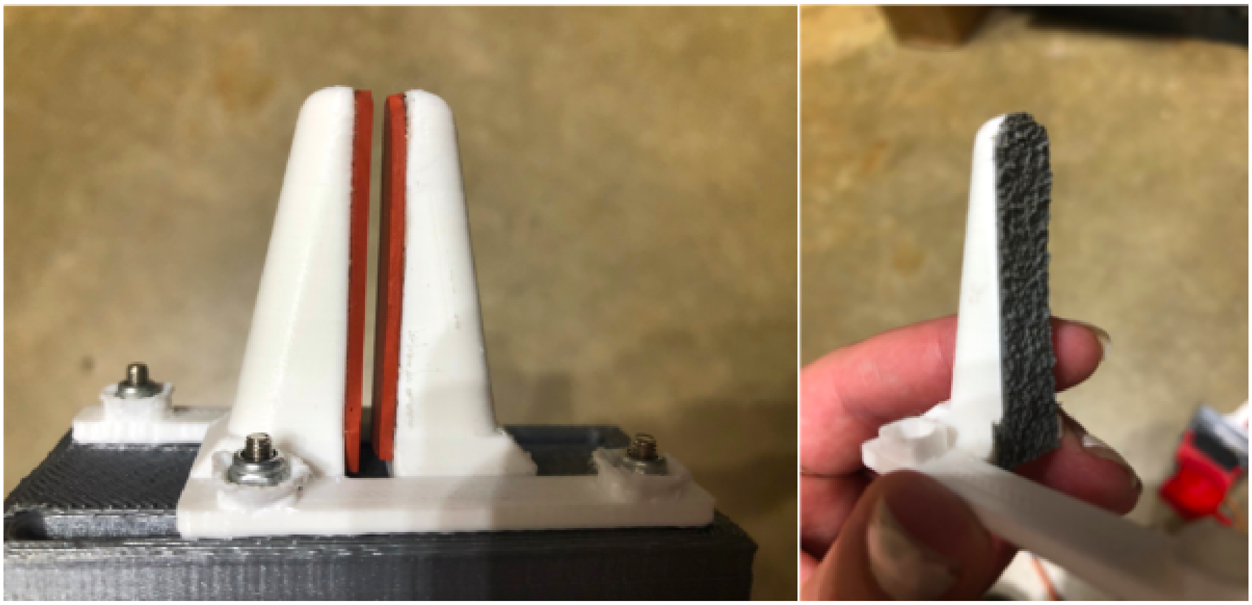

Fig. 6 3D-printed parallel gripper with rubber modifications (left) and sandpaper-like modifications (right).

Ultimately, the finalized gripper design involved a 3D-printed plate and mounting. This mounting housed the TowerPro electric servo, which was attached to the 3D-printed gripper. Lastly, the gripper was modified with two rubber surfaces, expanding the end effector's grip effectiveness. When used in conjunction with the NBV and Baxter arms, this gripper was able to effectively interface with the knobs, valves, buttons, and switches on the taskboard. The modularity of the gripper's design indicates that it could also be effectively used with other robot arms, in addition to NBV and Baxter. All that would need to be done is to create CAD for a new mounting fixture that can be bolted or attached to the new arm.

IV. CTB Management

A. CTB Modifications

Cargo Transfer Bags (CTBs) currently in use on the ISS are made of a thick canvas material with reinforcing straps that form handles. These are likely to be difficult to manipulate with standard robot arms because of the flexibility of the fabric and handles. It was therefore decided that the traditional CTB design would need to be slightly altered in order for a dexterous robotic manipulator to be able to grab it and move it effectively. In order to make CTBs compatible with standard robot arms, a few simple components were added to the CTBs in such a way as to not interfere with the way that astronauts interact with the CTBs. The expectation is that CTB logistics may be more easily and efficiently handled by dexterous robotics rather than humans, but NASA would have to alter the CTB design by adding three things: a small steel plate, an April tag, and an RFID tag. With these modifications, an electro-permanent magnet, called a Nicadrone, could be used attached to an end effector along with a camera, to grasp the CTB and manipulate it. The steel plate was added to provide a contact point for the electro-permanent magnet. This is described in further detail below.

The team considered other options such as adding rigid components to the CTB structure to help dexterous robotics manipulate it, but that option probably would not allow a CTB to be as flexible and easy to fold when emptied. This ability to fold up compactly for storage is an important and necessary feature for any viable CTB design. By simply adding a small steel plate to interface with the magnet, maximum folding flexibility is preserved. As for the April tag and RFID tag, they give the robot key pieces of information it needs to complete logistics tasks. The April tag tells the robot what the position and orientation of the CTB is relative to the Nicadrone electro-magnet mounted to the end of the robot arm. And the RFID tag gives the robot information on what the contents of the CTB are, thereby allowing it be sorted and stowed appropriately. So far, only testing with April tags has been done, but future testing using RFID tags to show the contents of the CTB is being considered.

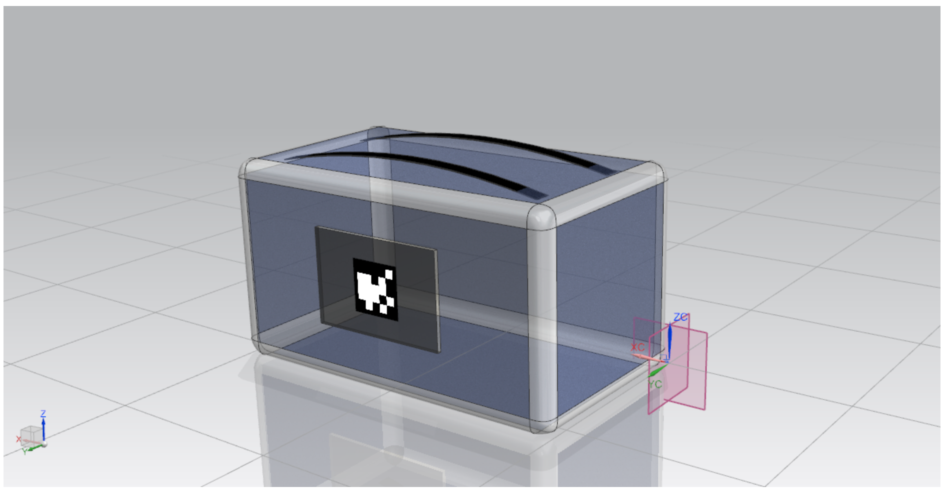

Fig. 7 The modified CTB design with an April Tag on the outside and a steel plate on the inside.

B. NicaDrone End Effector

It was necessary to design a new end effector to properly interface with the modified CTB. Pictured below are two current end effector designs: a basic 3D printed PLA mount for a single NicaDrone magnet, as well as a more advanced modification for our pneumatic end effector (discussed further in Future Directions). The left hand design has been used for basic proof of concept CTB testing, to avoid the unnecessary complications posed by the pneumatic system; however, the right hand image constitutes our main design. This end effector features two main components: the dual NicaDrone setup, and the central camera (in this case, a GoPro 5). By utilizing two NicaDrone magnets, the end effector is capable of improved manipulation of the bags, as it creates both a stronger "grip strength" (double the magnetic force), as well as providing improved moment capabilities by having two separated points of contact rather than just a single point of contact. Centered between the NicaDrone magnets is the camera lens. The camera assists in the positioning of the arm and end effector by using data obtained from viewing the April Tag (discussed below) which would be printed onto the metal plate. The camera is able to read the tag and maneuver the end effector to attach to the CTB at the correct orientation of the plate. By centering the camera between the NicaDrone magnets, it isn't necessary to account for any offset of the camera in attaching to the CTB; if the camera is centered on the April Tag, it means that the end effector is properly centered on the plate. This design will be tested and modified based on test results to evaluate various parameters, such as, for example, the spacing between the NicaDrone magnets.

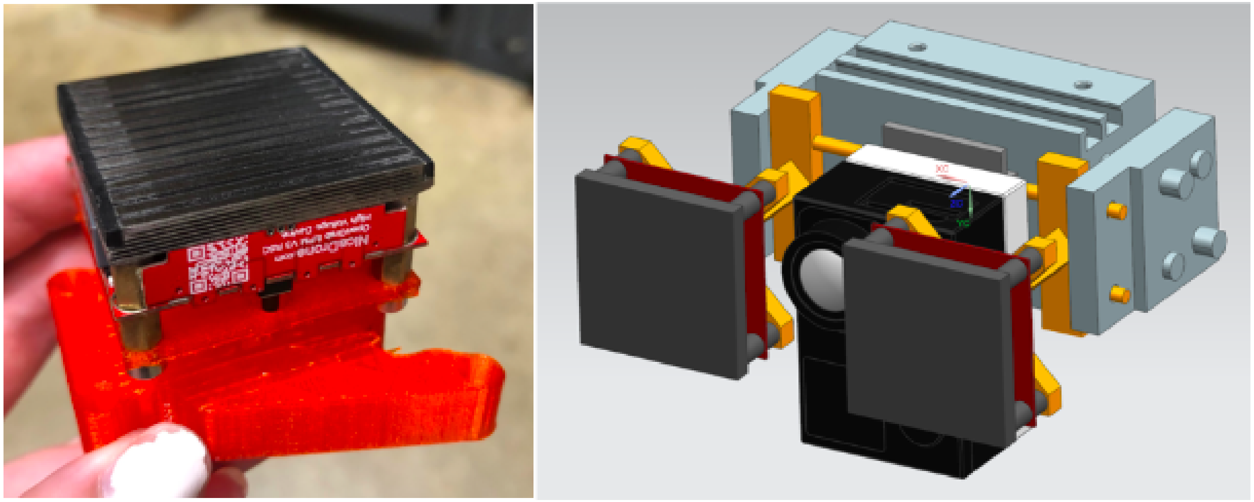

Fig. 8 Mount for single NicaDrone magnet (left) and alternate mount designed for dual NicaDrone magnets and GoPro camera (right).

C. April Tags

The final modification the team introduced to the CTB design was the inclusion of fiducial markers called April Tags. These function similarly to QR codes, but instead of storing information, an algorithm that has information about the camera parameters can report the translation and rotation of the tag relative to the camera. The set of possible tags is rather large, therefore it is unlikely that two tags will be mistaken for one another. Although the tags do not store information, they can be used to distinguish CTBs as each unique tag has its own ID number that the algorithm recognizes. The tag itself introduces a minimal amount of weight, as it can be a simple laminated label that is attached to the side of a CTB. The team developed software that allowed a robotic arm simulated in Gazebo to detect and approach a CTB. Though laboratory testing is yet to be conducted, it is likely that it will be successful once the system is properly set up. Overall, the introduction of April Tags is a relatively easy way to simplify the task of an operator controlling a robotic arm with a Nicadrone end effector on the inside of a space station because it allows for rapid recognition and motion towards the desired CTB so that it can be transported elsewhere.

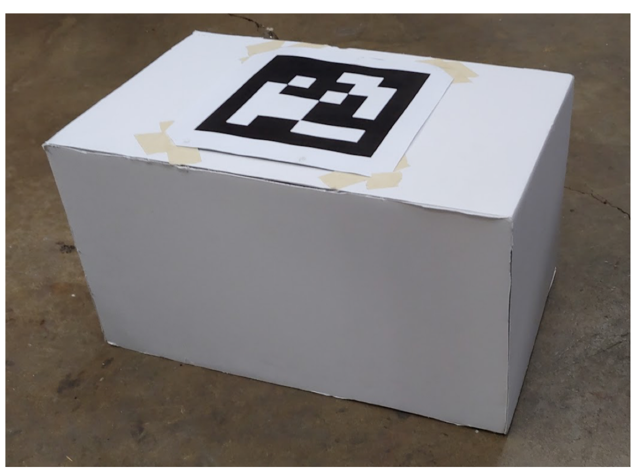

Fig. 9 Half-size CTB Mock-Up with attached (oversize) April Tag.

V. Results to Date

Task	Trial #	Elapsed Time, Robot (s)	Robot Successful?	Destructive?	Trial Notes	Avg. Elapsed Time, Robot (s)	Success %	Overall Notes
Rocker Switch Flip	1	163			Positioning and alignment too difficult; restarted	118	50%	Rocker switch must be pushed in at a ~45 degree angle to the board, rather than straight back like the push buttons; BAXTER's parallel end effector had extreme difficulty with this.
	2	87		Y	Popped rubber tip off of end effector			
	3	300			Over 5 min			
	4	250	Y		Rubber tips came off mid-test, making the task significantly easier			
	5	42	Y					
	6	62	Y					

Fig. 10 Section of preliminary results database.

The figure above details a section of the spreadsheet the team used for recording testing results. During testing, the team recorded the number of trials for each task, elapsed time for task completion, whether or not the robot was successful at completing the task, whether or not the robot was destructive (i.e. did it harm either itself or the taskboard), average elapsed time per task, overall success percentage for task competition, and overall notes to keep in mind for future trials. In order to develop this database, the team created both testing protocols (step-by-step instructions on how to test one component of the taskboard and record data) and quantitative criteria (numerical criteria to evaluate how "good" an end effector is at a given task) to be followed for each test. They are as follows:

Testing Protocols:

1) Position Ranger NBV exactly 3 feet away from the base of the taskboard
2) Start with arm and end effector at given "zero" position
3) Attempt 6 trials for each task
4) Repeat for each task on taskboard
5) For next test subject, do tasks in different order

Quantitative Criteria:

1) Record time for robot to accomplish task.
   - Start time when operator touches controls
   - Stop time when task is marked completed (e.g. LED flashes, Arduino records input, etc.) or after 5 minutes of trying
2) Record time for human to complete same task under same conditions
3) Count number of successful attempts

  - Successful Attempt defined as when task is marked completed (e.g. LED flashes, Arduino records input, etc.)
4) Count number of failed attempts.
  - Failed Attempt defined as “task not completed” (e.g. button not pushed) or 5 minutes elapsed time
5) Calculate ratio between times (how much longer it took a robot to perform the task than a human).
6) Calculate percentage of successful attempts

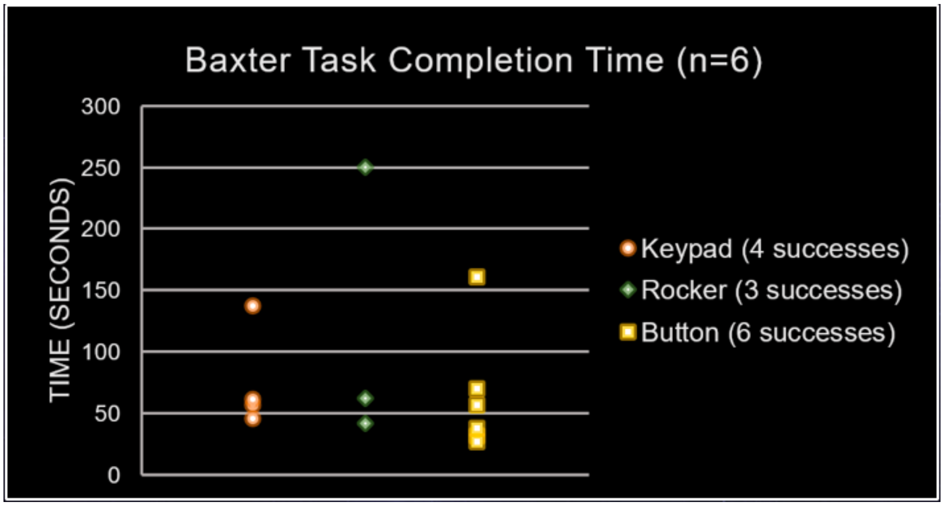

Fig. 11 BAXTER preliminary results, with three taskboard components.

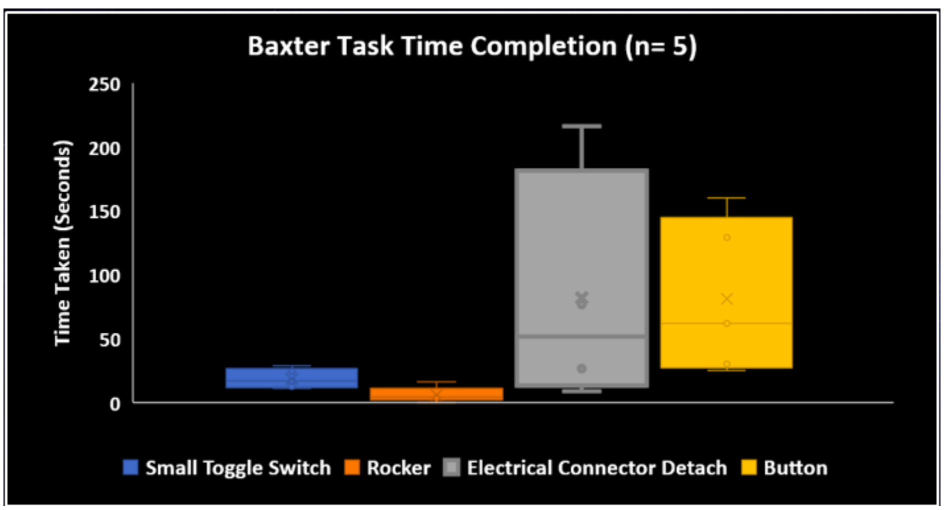

Fig. 12 BAXTER preliminary results, with four taskboard components.

As the above two figures detailing Baxter Tasks Completion Times show, component-level tasks can be accomplished in a reasonable amount of time with a relatively simple robotic arm. Although there are a few outliers in the data due to operator adjustment, the data points are relatively consistent with each other, indicating reliability in the system set-up. However, although the times for task completions are reasonable, they still take significantly longer than a human would to complete the task. For example, it took the Baxter robot anywhere from 30 to 150 seconds to push button; this would take a human less than a few seconds to complete. Nevertheless, it is likely that the robotic times can be improved upon with more training for the operator and a more precise robotic arm, and there are certainly situations (like requiring many switches to be flipped in a particular sequence) where an autonomous robot may well outperform a human.

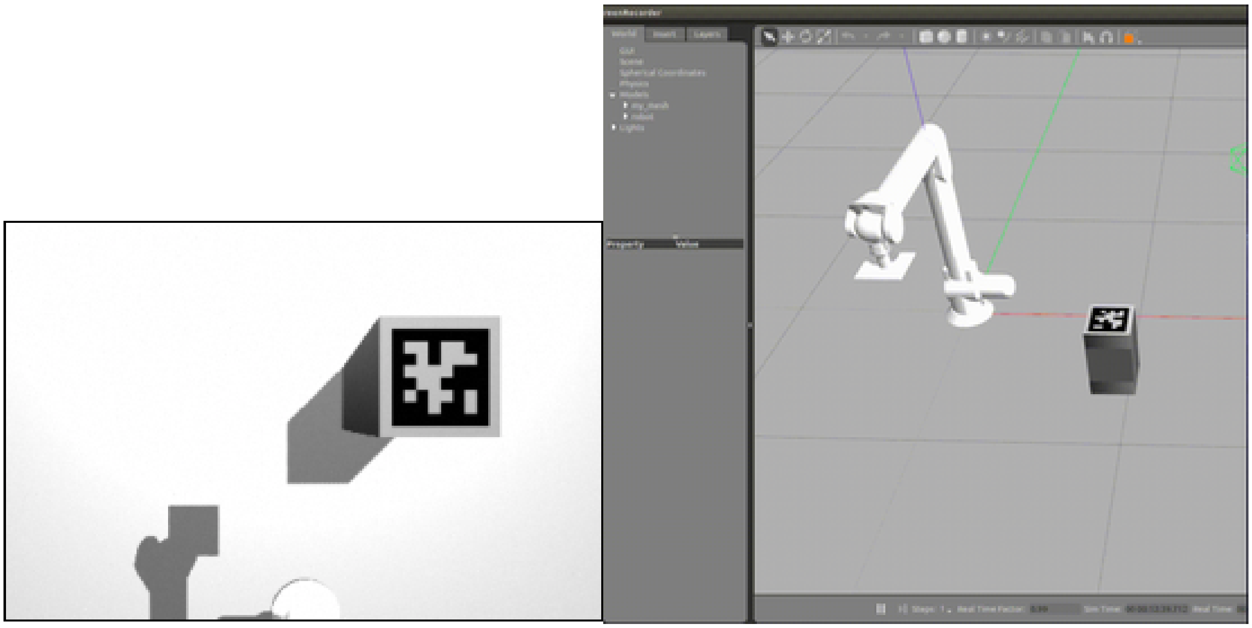

Fig. 13 Robotic simulation in Gazebo from robot's perspective (left) and still image from dynamic simulation of Ranger DXM interacting with CTB using April Tag identification.

Throughout this research project, significant progress was also made with the team's robot simulations using Robot Operating System (ROS) and Gazebo. As shown in the figure above, the team was able to successfully develop a working dynamic simulation of the Ranger DXM robot locating a CTB via April Tag, moving toward the CTB, picking it up, and transporting it to a specified location. This simulation, along with others being developed, are and will be used in conjunction with physical hardware tests both to verify that a certain test is in fact feasible, as well as to validate the accuracy and usefulness of the corresponding simulation. The simulations will also be used for further April Tag development and other purposes, which are discussed further in the "Future Directions" section of this paper.

VI. Lessons Learned

The team learned many valuable lessons throughout this research process. While testing, the team noticed the Baxter robot was imprecise, a serious impediment to testing. The Ranger robot arm was superior in terms of precision, but unfortunately, it was not operational for a large part of the testing period, and Baxter therefore had to be used. In addition, the team found that the taskboard should have been constructed out of a material stronger than foamcore, as the pressure from the robotic arm moved and warped the board too easily.

Regarding the end effectors, the team realized that the servo wears out the PLA end effector much more quickly than expected, rendering it practically useless. This caused the team to lose some testing time. In addition, it became clear that more grip force was necessary for the robot to accomplish certain tasks than could be produced by the robot. When grip tape was added to the end effector, it did help somewhat but the grip force was still too low for certain tasks. Preliminary assessment of the NicaDrone electromagnet indicated that it has a very high magnetic force when interacting directly with metal and it can pick up many things. However, if fabric is placed between the NicaDrone and the metal plate it interfaces with, the strength of the NicaDrone decreases considerably. This is important for future designs of CTBs if NicaDrone magnets are to be used in any way.

Assessing robot operation, the team had initially used a joint control method to control the position of the robot arm. However, it became clear that using Cartesian coordinates proved a more efficient and effective manner of controlling the robot's motion. With Cartesian coordinates, the operator was able to input the final desired x, y, and z coordinates of the end effector and allow the software to position the robotic joints, rather than relying on imprecise human input to declare the angular position of each individual joint for joint space control.

VII. Future Directions

A. Pneumatic End Effectors

Through the design process, several tasks were identified as likely requiring increased grip force to be completed. This hypothesis was confirmed during testing, as the electric servo end effector was unable to complete certain tasks, such as turning the small valve and removing the fully inserted electrical connector, due to a lack of grip strength. To provide the necessary grip force, a pneumatic end effector was considered and purchased for the completion of these force-intensive tasks. The pneumatic features a 40 millimeter stroke length, and provides a max force of roughly 5 pounds. As this research continues, the pneumatic end effector will be put into use to complete these and other more force-demanding tasks. Additionally, the use of the pneumatic allows for investigation into the potential for removable, task-specific modifications. As different tasks have different demands, having various end effectors would assist in the completion of these varied tasks. By using the pneumatic end effector as a base, different specialized modifications can be attached to complete a given task. The image of the CTB Nicadrone end effector (Section IV, B) features one such example of a task-specific end effector; in this case, this specific modification could be attached to the base end effector, and then removed and replaced with a different modification for the next task. In any case, the pneumatic end effector will certainly feature more in future research.

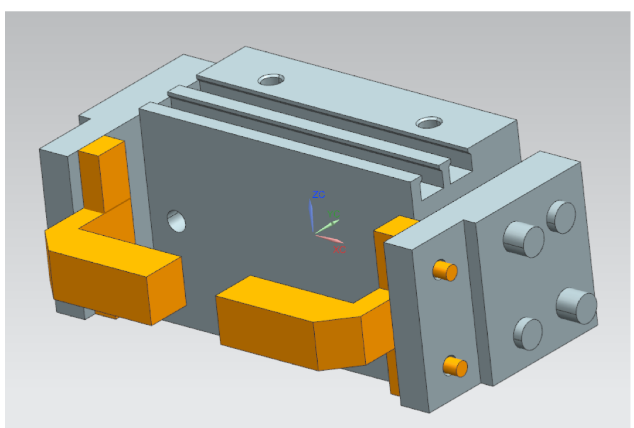

Fig. 14 Pneumatic end effector with parallel gripper modification.

In addition to the further development of the pneumatic end effectors, the team also plans to potentially explore the feasibility of designing a robotic system that can autonomously interchange a variety of end effectors. Due to the complexity of certain tasks, as well as the shear variety of tasks that are performed on space habitats, multiple end effectors will be required in order to complete all these tasks. Therefore, developing a system that allows the robotic arm to switch between end effectors with ease would be extremely beneficial.

B. CTB development

The team has a few different approaches to further CTB development in the future, which all revolve around making CTB maneuvering as seamless as possible while reducing factors like cost as much as possible.

The first area the team will explore is the interaction between the magnetic end effector, the metal plate, and cloth in between. Based on our testing, the team has only attached the metal plate to the outside of the mock CTB. This was to achieve preliminary results, as well as to test the functionality of the NicaDrone in conjunction with the Baxter arm. However, in order to hopefully make a modified CTB stable, testing will be done on different fabrics, with different thicknesses, so as to determine if the metal plate could go inside the CTB, or maybe in between the fabric walls of a CTB. From preliminary testing, we know that the NicaDrone's magnetic force decreases very quickly with distance. This would mean any design would most likely have an outer metal plate or a metal plate just under the surface of the cloth to ensure a strong connection. However, to find out what the limit of the thickness is, further testing is required.

Another area for further testing is the construction of the plate in terms of both the type of metal as well as the structure of the plate. The main idea behind this is to see if, for example, a metal mesh could achieve similar, or at least satisfactory, results when compared to a solid plate. Being able to use a mesh in place of a solid plate would not only allow more flexibility in the CTB, but also would reduce the overall added weight to the modified CTB.

This ties into the third area, which deals with testing the weight content of the CTB versus the weight of the needed plate to maneuver, as well as the accuracy of the robot in manipulating the CTBs. This is because the more accurate the robot can be, the smaller the attachment plate can be, thus adding less weight to the CTB.

Therefore, the eventual goal is to find the smallest and lightest plate possible that can be attached to with relatively good accuracy, precision, and speed, and that will still allow for manipulation of a filled CTB without detachment. This will hopefully embody a cheap but effective method of achieving autonomous robotic manipulation of CTBs aboard the gateway station.

C. Software Development

The team will continue to explore a variety of different software applications for the task of enabling efficient robotic operations and repairs in a space station environment.

The first goal is to fully implement an algorithm that detects CTBs on a real system. This would involve camera calibration, ensuring that all edge cases are accounted for, and implementing a confirmation system so that the operator can visualize where the robotic arm intends to move based on the detected CTB position. Once this is completed, it will be possible to perform tests and evaluate the functionality of the algorithm.

Other directions the team will explore with regards to software are to investigate ways that an operator can be assisted and potentially ways to automate simple sequential repair operations like unscrewing a lid to gain access to a component. Assisting an operator could involve using a camera to recognize common components such as buttons and switches on a panel and presenting them as potential targets. Automation of composite tasks would require significant work to enable a vision system to be able to continuously operate on the system. Additionally, for tasks involving assemblies, an ontological representation would be required so that an algorithm would be able to plan a series of actions.

Overall, there are a lot of software applications that will be implemented and analyzed to determine their viability for use on Gateway.

D. Life Support System Mock-Ups

In addition to focusing on nominal operations and CTB management, the team would also like to explore the feasibility of having robotic systems perform repair tasks on space habitats such as the Lunar Gateway. These tasks include objectives ranging from replacing faulty connectors to full repair of malfunctioning life support system hardware. The team plans to simulate complex repair procedures using an Oxygen Generator Assembly (OGA) within the Space Systems Laboratory, as well as potentially developing a full-scale mock-up of an ISS life support system rack.

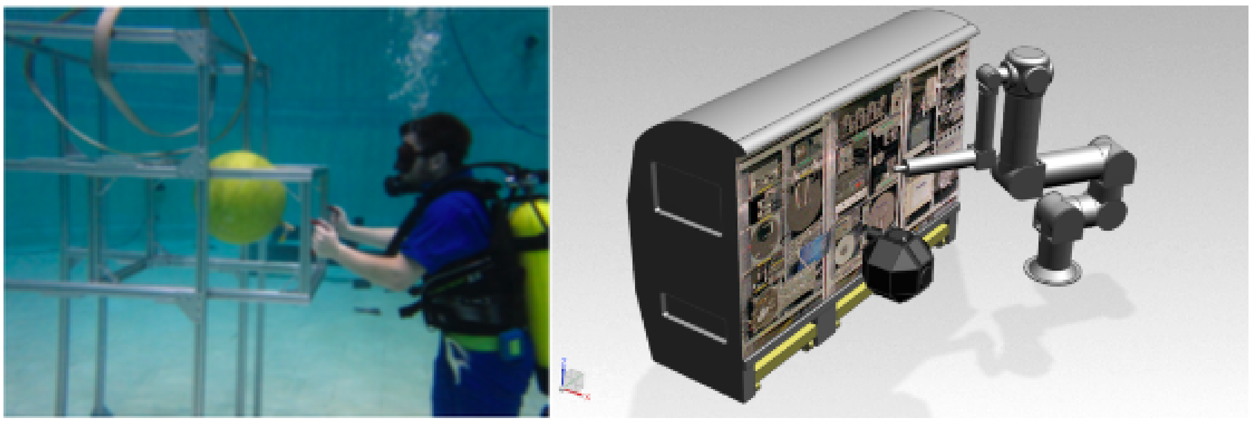

Fig. 15 Testing functionality of rack slides in oxygen generator assemby (OGA) mock-up (left) and CAD model of SSL's Ranger robotic arm and SCAMP free-flier interacting with concept Gateway life support system rack (right)

VIII. Conclusion

Team ASTRO accomplished many goals we had set out to achieve for this academic year, with the focus of this project being a proof-of-concept research project in the area of space robotics. In summary, the team has accomplished the following:

1) Demonstrated completion of a variety of nominal operational tasks with gripper end effector and taskboard.
2) Redesigned Cargo Transfer Bags (CTBs) utilizing minimal modifications such as the addition of a metal attachment for interfacing with a NicaDrone end effector, as well as the implementation of AprilTags for the identification and sorting of CTBs.
3) Demonstrated feasibility of using a semi-permanent electromagnet as a robotic interface for manipulating with and transporting CTBs.
4) Developed robotic simulations using Robot Operating System (ROS) and Gazebo that allow the team to verify the feasibility of robotic hardware tests (such as interacting with CTBs) and explore the option of implementing AprilTags on CTBs.

In conclusion, Team ASTRO has demonstrated that the integration of dexterous robotic systems is both feasible and vital for the future of space habitats. With the development of the Lunar Orbital Platform Gateway and the fact that it will be uncrewed eleven months of the year, both teleoperated and autonomous robots will allow for the continuation and long-term operation of the habitat. These robotic systems can be utilized for maintenance and repair of Gateway and other space habitats while uncrewed, and also handle nominal operations while the station is crewed to allow astronauts to maximize the time they can dedicate to mission-specific goals and scientific research. Ultimately, the future of space habitats is dependent on the integration of dexterous robotic systems, and Team ASTRO has shown that the implementation of these systems is in fact possible and beneficial for the operation of the station.

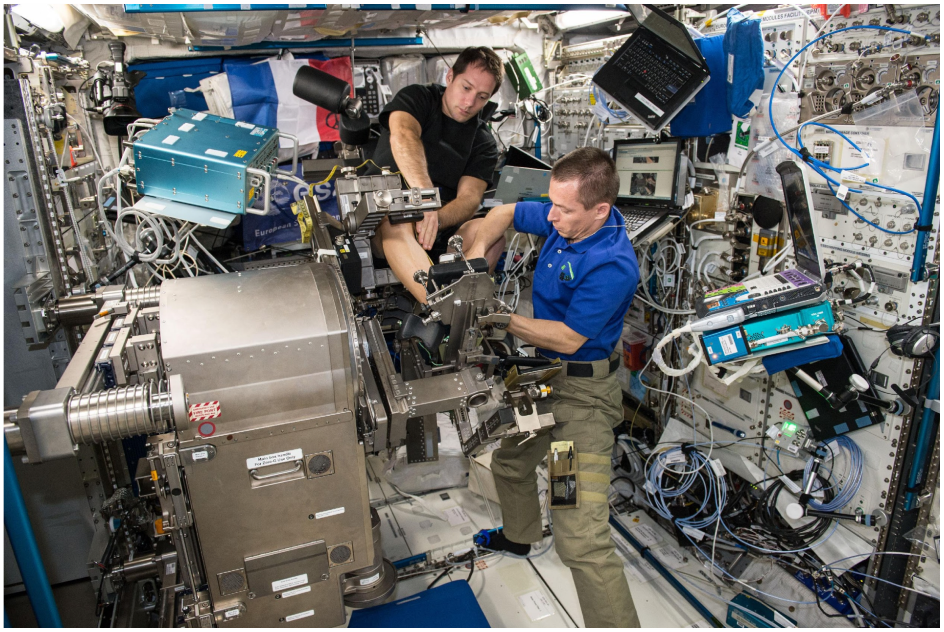

Fig. 16 Big Picture: enable robots to help astronauts in this environment (credit: NASA).

IX. Acknowledgements

Team ASTRO of the University of Maryland, College Park would like to thank the Space Systems Laboratory for hosting and supporting this research project, as well as the Gemstone Honors Project for allowing the team to pursue this area of research. Additionally, the team would like to thank our mentors, Dr. Dave Akin and Dr. Mary Bowden of the University of Maryland for guiding us and providing expertise throughout this research project. Lastly, we would like to thank the NASA eXploration Systems and Habitation (X-Hab) Academic Innovation Challenge for funding this research for the 2018-2019 academic year, as well as Dr. Julia Badger of NASA Johnson Space Center for providing valuable feedback and assistance throughout this process.

X. Appendix

A. References

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Robotic Habitat Technologies for Minimizing Crew Maintenance Requirements

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The International Space Station (ISS) is crewed continuously by astronauts conducting scientific research in microgravity. However, their work is not limited to scientific research alone; in fact, logistics, maintenance, and repair tasks on the ISS require more than 80% of available crew time, severely limiting opportunities for scientific experiments and technological development testing. NASA is planning a new project known as Gateway (also referred to as the Lunar Orbital Platform-Gateway or LOP-G) which will orbit the Moon and be uncrewed for 11 months out of the year. Since astronauts will not be available to do repairs and maintenance continuously as is required for Gateway to operate, one or more robotic systems are necessary to regularly accomplish these tasks in the absence of astronauts. This paper discusses the feasibility of integrating dexterous robotic systems in space habitat architectures which will allow for routine and contingency operational and maintenance tasks on Gateway, ultimately allowing for astronauts, when present, to focus on exploration and scientific discoveries. This research project leverages the unique capabilities of the University of Maryland (UMD) Space Systems Laboratory (SSL), which includes a variety of dexterous robots, space habitat mock-ups, and the Neutral Buoyancy Research Facility (NBRF). The team is conducting this research through four approaches: robotic end effector assessment, Cargo Transfer Bag (CTB) manipulation and logistics, Gateway component analog taskboard development, and computer modeling. Based on analyses and experimental results gained from this research, this paper also proposes and discusses specific system concepts and recommendations for optimizing the Gateway design to facilitate uncrewed operations, robotic servicing, and human-robotic collaboration to improve crew productivity when present.

I. Nomenclature

CTB	=	Cargo Transfer Bag
Gateway	=	NASA's Lunar Orbital Platform-Gateway
ISS	=	International Space Station
ORU	=	Orbital Repair Unit
SSL	=	Space Systems Laboratory at the University of Maryland, College Park
UMD	=	University of Maryland, College Park

II. Introduction

The International Space Station (ISS), which is the current space habitat used for conducting micro gravity research, is crewed by astronauts year round [1]. Although intended for scientific research, much of the astronauts' time on the ISS is spent doing repair and maintenance tasks. These tasks include things such as organizing and unpacking cargo transfer bags (CTBs), fixing life support systems, cleaning surfaces inside the station and verifying the status of air filtration systems [2]. NASA is now in the process of building the Lunar Orbiting Platform - Gateway, which will be in orbit around the moon [3]. Unlike the ISS, Gateway will only be crewed one month out of the year [4]. This means that in order for the habitat to remain functional, operational tasks will need to be able to be completed by robotic systems

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when astronauts are not onboard. Since Gateway will be in orbit around the moon, communications will be impacted and reduce signals during portions of each orbit [5]. This means that it would be greatly beneficial for the robots to be autonomous so they can operate even when Gateway is behind the moon.

The team seeks to address these design challenges by developing a robotic system that could be incorporated into the architecture of the Gateway habitat and that is capable of performing a range of maintenance tasks. The tasks to be tested will be tiered, with low difficulty tasks such as flipping switches and pushing buttons, moderately difficult tasks such as wiping a surface to disinfect it, and high difficulty tasks such as unzipping and arranging the placement of CTBs. The team will create a database of the operational tasks the robotic system needs to perform to verify the relative difficulty and accuracy associated with each task.

In addition to relative difficulty of task completion, the evaluation of robotic ability will include both teleoperated and autonomous performance. Since autonomous completion of tasks is predicted to be more difficult, the various tasks will first be completed by a teleoperated system. Once a task has been identified to be possible to complete while teleoperated, automation of the action can then be explored, as additional sensing and safety measures would likely need to be included. The task database will also include information about the type of robotic arm that was used, including the degrees of freedom and size of the arm as well as the end effector that was used. Analysis of this information will provide an understanding of the capabilities that a robotic system on Gateway would need and if there is a sufficient, universally useful end effector that can attach to any robotic arm in the system. Any tasks that cannot be completed by a robot would indicate that there may need to be a redesign to the system when implemented on Gateway. For example, the current CTBs that are used on the ISS have zipper fasteners, which are difficult for a robot to manipulate [6]. More robot friendly CTBs would save astronauts time as supplies could be transferred in and out of the habitat without their presence.

The team currently consists of four sub-teams which specialize in end effectors, taskboard design, CTBs, and software. The end effector team is working to design an end effector that is compatible with a robotic arm in the Space Systems Laboratory (SSL) and would be capable of completing the widest range of repair tasks. This information is identified by working with the taskboard team. The taskboard team is designing and constructing a taskboard to be used with the robotic arm to perform a wide array of tasks, such as flipping switches, turning knobs, and replacing electrical connectors. The performance of the robot while interacting with the taskboard will provide much of the information for the team's database of tasks. The CTB team is working to minimally redesign the cargo transfer bag to be more robot friendly. The team seeks to make improvements to the current bag design to make them easier to track, manipulate and unload robotically. The modifications to the CTBs could allow for remote resupply and restocking of Gateway and prevent the misplacing of the CTBs within the habitat. The software team is tasked with creating simulations of the SSL Ranger robot performing different actions. Simulations could be used to plan out more complicated repair and operational procedures like the transport of cargo.

III. Summary of Background Research

Robotics have been occasionally utilized in habitats, but a large majority of these robots have failed for various reasons. A big problem that has persisted through multiple designs is that the robots used to be too large and dangerous to work around. For example, Charlotte was a robot used on the Space Shuttle that moved along a large tensioned cable system. Charlotte proved to be problematic onboard because astronauts could not work or move in the same space due to the cables restricting their movement [7]. Another reason robotics have been unsuccessful is that the robots are not able to operate in space the way they were intended to. An example of this is Robonaut 2, a humanoid robot used on the ISS, which was used for a short time but issues with the electronics prevented continued operations and it was eventually sent back to Earth. Robonaut 2 was used to take air pressure and flow measurements at vents, a monotonous job that required astronauts to waste time carrying a sensor around and holding it for a minute or so at each vent [8]. This shows how robots do not always have to be able to do every complicated task onboard, they can do simple tasks that save a lot of time. The goal of the project is to determine which tasks can be performed by robots in a habitat to make a database describing the task, the difficulty of the task, and the robot's success with the task. The more simple tasks will be analyzed with a taskboard and more complicated tasks will follow such as CTB transport and repair of life support systems. This way, the database can show how dexterous robotics can handle each type of task at varying levels of difficulty.

As for the mobility and dexterity of the robot, there is a wide range of robots varying in complexity and cost. There are some basic designs like a robotic arm on a track and there are some more complex designs like free-flying robots, tendril-based robots, and tetrahedral robots. While the more complex robots can complete very specific, specialized tasks like carrying large loads and moving over complicated terrain, they are not readily available and are more difficult to study. Robotic arms were considered and selected as the first system to be tested since they are present in numerous research labs, allowing easy access, as well as being ideal for experiments involving dexterous operations. A mobility platform that best complements the manipulation system will need to be decided upon in the future. Alternative approaches will be considered to address tasks that tested systems were incapable of performing once experimental data is available.

IV. Review of Habitat Maintenance and Operational Tasks

In order to assess the capabilities of a robotic system for the maintenance and operation of a space habitat, the tasks that go into this must be identified. This means subdividing complex tasks, like the repair of an Orbital Repair Unit (ORU), into primitives and identifying gaps in task coverage of the system. Additionally, the importance of tasks in terms of how often they need to be performed and how critical the task is to the function of the habitat needs to be understood so that the search for solutions can be directed at solving tasks that are common and essential.

Based on an evaluation of the ISS day-to-day logs, the time that astronauts spend onboard has been well categorized. There is a wide variety of other activities related to the upkeep of the space station that the astronauts perform on a regular basis [9]. By examining the tasks that are conducted on the ISS, three groups were determined to be worth investigating further due to the relative proportion of time that they take up, as well as their potential to be addressed by a robotic system. These groups are: routine operations, logistics management, and repair and maintenance. Fig. 1 below is a chart detailing the proportions time allocation on the ISS.

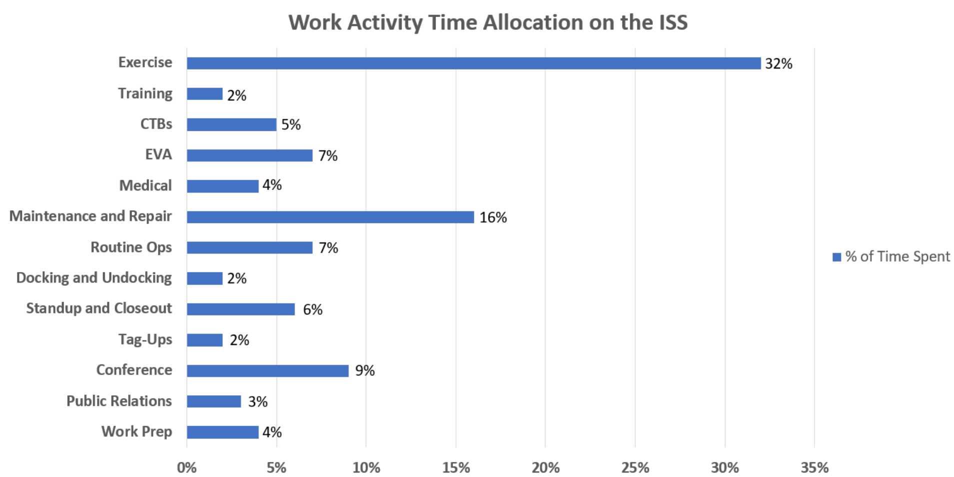


Fig. 1 Chart detailing how much time astronauts aboard the ISS spend on different work tasks [9].

A. Routine Operations

The first task group that is considered is Routine Operations, which includes systems and consumables management, housekeeping, organization, and software upkeep. These tasks take up around 7% of the scheduled crew time. The systems management task involves plugging and unplugging various connectors, flipping switches, pressing buttons, and taking readings from monitors. Consumables management is the transport of materials between different sectors of the station - taking them in and out of various storage containers. Housekeeping and organization include general clean up of the station as well as the sanitation of surfaces. Software upkeep is the testing of communications links, data management, and software updates. Routine Operations lend themselves well to robotic automation due to the relatively low complexity of tasks like button pressing and flipping switches [9]. However some, like the sanitation of surfaces and plugging and unplugging of connectors, are still too complex to be performed effectively by most robotic systems.

B. Logistics Management

The second task category that can be examined is logistics, which includes vehicle loading/unloading and routine logistic operations. It takes up around 5% of scheduled crew time. The process of vehicle loading and unloading involves the transfer of CTBs to and from a vehicle. A single CTB takes approximately 10 minutes to load onto or unload from a vehicle. Routine logistics operations are related to the process of moving cargo, which can be time consuming due to the size of the space station, as well as issues presented by tracking particular packages [9]. These types of tasks are possible to address with certain robotic systems alongside potential adjustments to the internal structure of the space station.

C. Repair and Maintenance

The final group involves system repair and maintenance, which takes up a significant 16% of the crew's scheduled operations. There is some variance within this category both in type of tasks and time allotted due to the unpredictable nature of system failures. The amount of repairs necessary is key in determining crew availability on the ISS for other tasks, as these take priority due to their importance to life on the station. The ECLSS - Environmental Control and Life Support Systems - includes the oxygen generation and water recovery systems, temperature and humidity control, air filtration and several other systems. This is a very diverse set of complex equipment, repairs of which is usually a long process involving the disassembly and manipulation of electrical and fluid connectors. These tasks clearly have a high dexterity requirement, and thus make them very difficult to address with a robot. Maintenance is not limited to the repair of these systems; it also includes diagnostics. Diagnostics need to be conducted on a regular basis to verify whether systems are functioning properly or require repairs [10]. This sub-category is partially covered by 4% 'Medical' tasks, which involve water and air quality monitoring. Lastly, one of the most common issues that occurs on the ISS is air leaks. These leaks must be monitored to ensure long-term habitability and prevent equipment failure. If possible, having a robot able to detect and fix the leaks would relieve the astronauts from having to do so constantly [11].

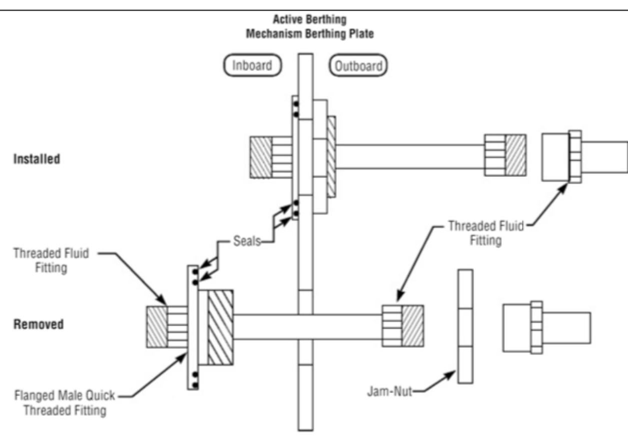
Task	Image	Description
Category: Primitive		
Turning a Lever-like Valve	 a)	Turning a valve with a lever-like handle by a specified amount to regulate fluid flow
Category: Tool-Assisted		
Removing a Screw	 b)	Turning a screw with a custom end effector to remove it
Category: Composite		
Disconnecting a Fluid Connector	 c)	Disconnecting a "Threaded Fluid Fitting Feedthrough" type fluid connector

Fig. 2 Portion of the database featuring an element from each task category. a) A typical valve [12]; b) A basic fastener screw [13]; c) An example of a special fluid connector present on the ISS [14].

V. Database Description

The operations and repair categories are comprised of a variety of tasks, both primitive and composite. These tasks were determined by considering the details of the ISS life support systems and general operational procedures [14]. These tasks were compiled into a database that would provide a structure for recording the capabilities of a robotic system.

It was found that there was significant overlap among these tasks, so they were categorized by degree of complexity. The simplest degree chosen was primitives, which are tasks that require no specialized tools, like the press of a button or pulling on a handle. The next level of difficulty is tool-assisted operations. These tasks cannot be completed without the use of a specialized end effector, like a screw driver for turning a screw. The final degree is composite tasks which require multiple steps or more than one arm to complete, like connecting a fluid connector. Bi-directional tasks like removing a screw and inserting one are separated since they should be examined separately for a more comprehensive understanding.

The database currently consists of task descriptions and proposed testing procedures. As testing proceeds, the matrix will be expanded to include information such as outcome of testing, decisions with regard to end effector performance, and time and force required to complete task. See above for a sub-section of the database that shows one element from each category.

VI. Methodology

The team will test and evaluate the capabilities of a teleoperated or autonomous robotic system aboard the ISS. Various tiers of tasks will be created to quantify a robot's effectiveness at performing essential operations. The robot must be able to successfully interact with two different surfaces: a taskboard representative of control surfaces onboard ISS, and a storage unit similar to NASA's cargo transfer bags (CTBs). The team will develop an end effector which will be both be compatible with the robotics used for testing and be capable of interacting with essential surfaces on ISS or other future space habitats. While designing the hardware needed to perform essential operations, the team will also develop the software needed to effectively operate the robot. The focus will initially be on remote teleoperation, with autonomous operation being developed afterwards.

A. End Effector Design

The end effector portion of this research seeks to select, design, and fabricate various robotic end effectors and end effector modifications to allow robots to complete essential space habitat repair tasks. Specifically, the sub-team is examining a gripper end effector with specialized attachments, which would enable the robotic arm to complete a variety of tasks. Initially, one pneumatic and one electric servo end effector have been acquired. Testing will first be conducted with the electric servo, given its relative ease of operation as compared to a pneumatic system. End effector modifications will be designed and fabricated through 3D printing. For instance, an attachment could be printed from an elastic material for gripping a rotary knob. As tasks begin to escalate in difficulty, the electric servo is anticipated to be insufficient for testing, and the more complex but more powerful pneumatic system will replace it. Analysis will be conducted on the merits of the two options, pneumatic versus servo, and future end effector design and selection will be influenced accordingly.

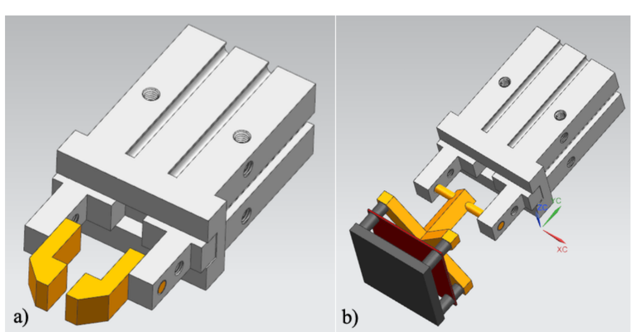


Fig. 3 a) Gripper end effector modification and b) NicaDrone electromagnetic end effector modification fixed to parallel pneumatic end effector.

B. Cargo Transfer Bag (CTB) Modification

The current design for CTBs on the ISS is adequate for handling by humans, however, the task of organizing and sorting CTBs expends precious time that astronauts could be using for research experiments. In order to remedy this, CTBs must undergo a modification of some kind that will allow for a robotic end effector to grasp it, thereby allowing the possibility to automate the process of organizing and sorting. The most prominent problem with trying to automate the process is that it is quite difficult for robots to mechanically grip flexible materials like nylon fabric, which is what the current CTBs are made of, so the redesign is necessary for eventual robotic automation.

Some aspects of the current CTB design will remain the same. First, the dimensions of the CTB should remain the same because there is no reason to change such a precedent. Second, they must retain their overall flexibility in order to allow for a collapsible frame when emptied so that it takes up less space in an already cramped environment. The team came up with a design that would work best with an electromagnetic end effector. There would be a small square of conductive steel mesh on the inside one of the faces of the CTB, which would allow for a magnet to easily attach it in space. On the same face as the steel mesh square, there will be an AprilTag, which is a visual label similar to QR codes, that can provide information on the distance and orientation of the CTB. There may also be an RFID tags for identifying CTB contents. After creating a general design, the team will conduct experiments to determine the limits of CTB acceleration with varying amounts of steel mesh in the lining of the CTB, CTB mass, and various magnet strengths. These experiments will be carried out on an air-bearing table, which is a near frictionless surface that simulates a microgravity environment in two dimensions.

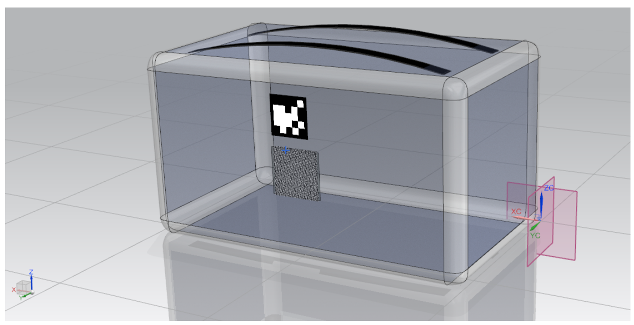


Fig. 4 CAD drawing of CTB assembly showing steel mesh on the inside of the bag and an April tag on the outside of the bag.

C. Testing Protocols

To quantify the effectiveness of modified cargo transfer bags and end effectors, the team will conduct a series of tests that simulate function in habitats like the Lunar Gateway Platform.

End effectors are being selected based on their ability to conduct operational and maintenance tasks in microgravity; their experimental verification should, therefore, represent such tasks. To begin these tests, the team will construct a taskboard of relatively simple mechanical and electrical components for end effectors to perform work on. Some representative primitive tasks are as follows:

1) Detach 10-Pin Electrical Connector
2) Twist Rotary Knob
3) Push Large Button
4) Flip Rocker Switch

These fall primarily under the aforementioned "Routine Operations" category of tasks. They will then be supplemented by more difficult tool-assisted and composite tasks, falling into the "Repair and Maintenance" category, such as:

1) Attach Fluid Connector
2) Remove HEPA Filter
3) Unscrew Small Fasteners

Data from all of these trials will be compiled into a database, then analyzed to determine which end effectors are best suited to specific repair tasks (such as, eventually, performing maintenance on a larger system). Specifically, the team will evaluate an end effector's performance in any given task based on the following criteria:

1) Elapsed Time for Robot to Accomplish Task

- Starting from when operator touches controls
- Ending when task is marked complete (by LED flash and Arduino input from board)

2) Elapsed Time for Human to Accomplish Task
3) Ratio of Successful to Failed Trials
4) Attempts to Reach Operator Proficiency
   - "Proficiency" defined as the point at which an operators successful trial times no longer significantly change; that is, a numerical representation of how "intuitive" an end effector is for the given task
5) Damage Incurred by Robot (if applicable)

The apparatus for conducting these tests will be a foam-core board mounted vertically to a wooden frame, standing roughly four feet tall. Similar criteria will be used to evaluate an end effector's ability to interact with a cargo transfer bag, though the testing apparatus will, of course, be the bag itself. The CTB will represent the third and final category of tasks, "Logistics Management", thereby giving the trials a broad coverage of scenarios within the Gateway habitat.

VII. Results to Date

The division of the team into four sub-teams and the creation of the robotic database has allowed for the team to group robotic tasks into three categories: routine operations, logistics management, and repair and maintenance. In the category of routine operations, a taskboard has been developed that contains primitive task analogs such as flipping switches, turning knobs, pressing buttons, etc. The taskboard is currently in the construction phase and will soon enter the testing phase in conjunction with a servo actuated end effector in a laboratory (1-g) environment.

The logistics category encompasses the re-design and management of CTBs on space habitats. This involves the identification, transportation, and stowage of CTBs in habitats such as the ISS and Gateway. A variety of grasping mechanisms and end effectors are being explored, with a focus on an electromagnetic logistics management systems. Currently, CTB mock-ups have been developed and electromagnetic end effectors are being prototyped. A test incorporating the CTB mock-ups and magnets with a 25 pound attractive force will soon be conducted on an air-bearing table to simulate magnetic manipulation in a microgravity environment. Data will be gathered to determine the maximum acceleration a CTB can undergo in different cases of varying magnetic force and CTB mass. This test will ultimately determine the feasibility of incorporating an electromagnetic logistics management system onboard space habitats.

Fig. 5 Testing functionality of rack slides in prototype Oxygen Generator Assembly mock-up.

The maintenance and repair category focuses on a variety of tasks that crew focus their time on while aboard the ISS. These tasks range from replacing faulty connectors to full repair of malfunctioning life support hardware and other critical systems. The team will simulate maintenance and repair tasks using an oxygen generator assembly (OGA) mock-up rack (Figure 5). The mock-up will be used to simulate complex maneuvers and repair procedures, and will be developed further upon the completion of initial nominal operations and logistics tests.

Significant progress has been made in the software development portion of this research project. Initial models of robotic systems and life support mock-ups have been developed and incorporated into a computer simulation through Gazebo (an open-source simulation environment) and are controlled via the Robot Operating System (ROS) (Figures 6a and 6b). Aside from robotic mock-up simulations, the software sub-team is also focusing their efforts on developing algorithms that will enable the eventual autonomy of the robots. This autonomy will then be used for the operational and maintenance tasks performed by the dexterous robotic systems. Software also plays a role in the CTB logistics management portion of the project. The sub-team is currently working on the incorporation of AprilTags, optical targets that allow for position and orientation data of objects, into the computer simulation and robotic systems themselves (Figure 6c). The usage of these AprilTags will then eventually assist in the automation of the robotic system.

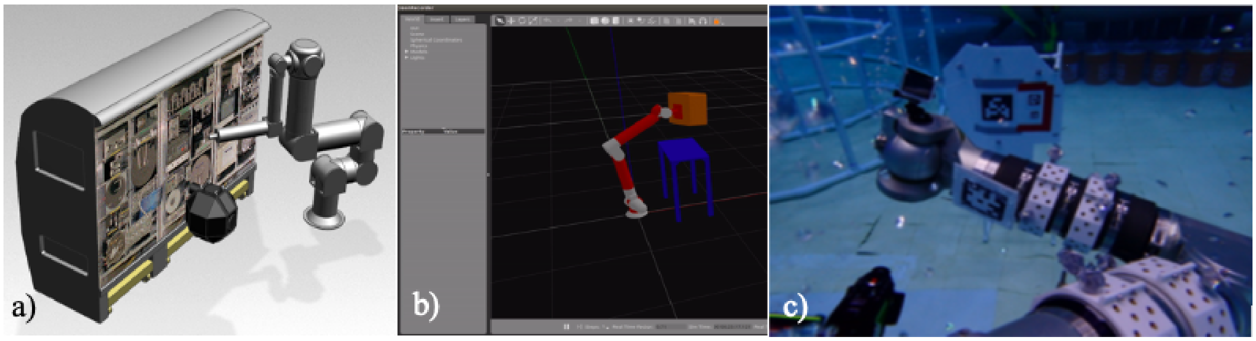


Fig. 6 a) CAD model of Gateway life support rack concept with SSL manipulator "Ranger" and free flier "Scamp." b) Still image from Gazebo-based dynamic simulation of CTB manipulation. c) Testing of AprilTags for position and orientation measurements for arm and simulations.

In addition to hardware and software development, progress has also been made in regards to the robotic database. This database details the capabilities of robots and end effectors housed within the SSL when used in space habitat applications. In addition, this database also categorizes routine and contingency tasks conducted on the ISS into the three categories discussed earlier, as well as by expected difficulty of being conducted via robot. Anticipated applications of this robotic database are discussed further in the following section.

VIII. Future Directions

In the future, the team will continue to add to the database as future tasks are completed. For now, the team will focus on constructing the taskboard and performing tests on robotic capabilities for simple tasks, i.e. flipping a switch, turning a knob, pushing a button. The team is starting with rudimentary tasks and then increasing difficulty of tasks to see how a robotic system will be able to handle the increase in difficulty. The end effector team will interface the servo and pneumatic grippers with a robotic arm so tasks can be tested. Once task testing begins, the team will attempt to enhance the functionality of the end effectors by modifying as needed. If deemed necessary, the sub-team will design and create a new end effector for a specific set of tasks. Regarding the taskboard sub-team, they will work to complete testing of the taskboard. Once the taskboard is complete, they will work to improve functionality of the taskboard through modifications and redesigns. The CTB sub-team will continue working on the design and creation of a CTB which will have a magnet to ensure a robot could easily pick it up and move it to a desired location. AprilTags or RFID tags will also be tested to ensure efficient and successful movement of CTBs. This research aims to develop a fully autonomous robotic system that can correctly identify a CTB, retrieve it, and transport it a designated location. Another long-term goal of this project is to develop a fully autonomous system that is capable of repairing a sub-system of Gateway and other space habitats, such as an oxygen generator assembly.

IX. Conclusion

Integration of autonomous dexterous robotic systems is absolutely vital for the operation of future space habitats. As space exploration ventures further out into the solar system and beyond, it will continually become less feasible to crew a space habitat at all times due to logistics and cost. In the absence of crew members, intelligent robotic systems would be able to ensure the long-term continuation and operation of the space habitat. When crew members are present, the systems would also allow for the crew to focus on scientific research and discovery, requiring only a small portion of their time to be dedicated to assisting with basic habitat operations and maintenance. The development of autonomous robotic systems is extremely applicable to the future use of the Lunar Orbital Platform-Gateway currently being developed by NASA. Designed to only be crewed one month out of the year, dexterous robot systems onboard the habitat are necessary for operation of the habitat throughout the eleven months that the crew is absent, and will maximize the time the crew can dedicate to mission specific research goals while the habitat is crewed. Ultimately, the future of space habitats lies with the integration of autonomous dexterous robotic systems.

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NASA RASC-AL Competition Final Paper 2020

THEME 5: AUTONOMOUS UTILIZATION AND MAINTENANCE FOR SCIENCE PAYLOADS ON THE GATEWAY AND/OR MARS-CLASS TRANSPORTATION

Robotic Habitat Technologies for Minimizing Crew Maintenance Requirements

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1. Introduction

1.1. Background & Motivation

The International Space Station (ISS) has greatly helped to advance humanity's understanding of the effects of microgravity and the space environment, as the station has been continuously occupied by astronauts since November 2000 [1]. Although astronauts onboard the station have been able to spend numerous hours conducting a wide variety of scientific experiments, they are also required to dedicate a significant portion of their time to operating, maintaining, and repairing the station. For example, astronauts spend approximately 12% of their time spread between routine operations, routine logistics operations, and vehicle loading/unloading, and an additional 16% of their time on maintenance and repair work [2]. Dedicating this time to routine monitoring and emergency repairs is a feasible way to run the ISS, as it is permanently staffed with a five to six member crew[1](soon to be expanded to seven when the Commercial Crew Program reaches operational status), but this will not be true for the planned Lunar Gateway station. Not only will Gateway be much farther from the Earth than the ISS, but it will also house a smaller crew that will be present only for a portion of the year [3]. Since the current concept of operations plans for Gateway to be uncrewed eleven months out of the year [4], robotic systems will be necessary for the continued operation of the outpost.

1.2. Problem Definition

This project is addressing RASC-AL Theme 5 - Autonomous Utilization and Maintenance for Science Payloads on the Gateway and/or Mars-class Transportation. The main requirement of this theme is to develop and demonstrate a system that can autonomously support utilization and/or maintenance of science payloads on Gateway in 2023 and/or Mars Deep Space Transport in the 2030's. This project mainly focuses on a near-term maintenance-based robotic concept that supports crewed and uncrewed operations on the Lunar Gateway.

1.3. Theme Compliance & Design Overview

The proposed robotic system to be utilized on the Lunar Gateway is a teleoperated two-arm dexterous robot, based on the Ranger TSX system from the University of Maryland Space Systems Laboratory, which has already been certified by NASA for space flight. The robot will traverse through the Gateway modules via a T-beam rail mobility system, detailed in section 5.1 and shown in Figure 1. The robot will also use an end effector exchange system, which will allow the system to select the most appropriate end effector for the maintenance/repair task at hand. This design complies with all Theme 5 maintenance-based project requirements.

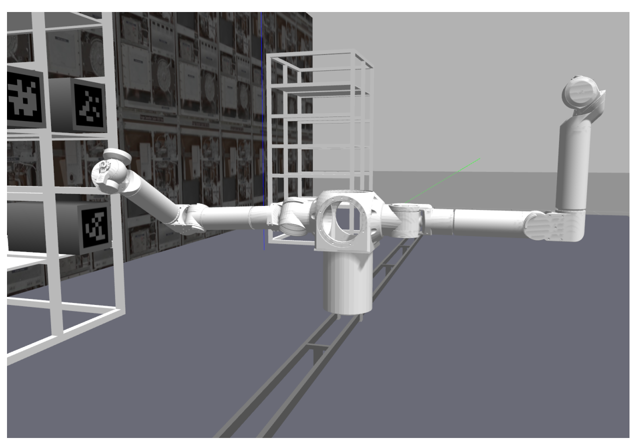

Fig. 1 Ranger TSX on T-beam rail

On a full system level, anomalies on the Lunar Gateway while crewed could be detected using the same technologies currently used onboard the ISS. These involve diagnostic maintenance, the process of detecting where faults occur [5]. This will include internal camera systems that can be used to monitor large-scale mechanical aspects, and to provide diagnostic maintenance procedures to the robot system when faults occur. This concept also assumes the ability of the maintenance system to tie into the data network on Gateway to monitor operations and report any anomalies

[5]. When Gateway is uncrewed, anomalies will need to be detected by and appropriately dealt with by the robotic maintenance system. Known or forecasted failures will be used to develop a suite of autonomous servicing algorithms which will allow the robotic system to operate without external real-time commands, although it is expected that human approval will be required for all but the most time-critical tasks. There will also be some failures which are entirely unexpected, and will have to be mitigated using supervisory control or other human-in-the-loop control approaches.

Following a review of options, the situational awareness required for this project concept is based on a system of AprilTags fiducial targets used to identify cargo and/or system components, which is detailed in section 5.4. The robotic system will have cameras mounted to it which will allow for visual detection and identification of surrounding hardware. Placing AprilTags throughout Gateway is a very simple way to provide identification and localization data on important pieces of equipment on the station.

This management approach will result in large time savings for the astronauts while the Gateway outpost is crewed, and will allow for maintenance and operation of the outpost while uncrewed. When astronauts are onboard Gateway or other future stations or habitats, they will be able to focus their efforts on exploration and scientific experiments, rather than fixing habitat-related problems. In addition, it will also save the crew from having to perform time consuming tasks. The ISS crew spends a large fraction of their time on logistics management, primarily on the packing/unpacking of cargo transfer bags (CTBs) of varying sizes. It takes an astronaut approximately 10 minutes to load/unload a single CTB, with the total number of CTBs being in the hundreds [2]. Therefore, CTB stowage, retrieval, and inventory would be a beneficial way to allocate robot time. This would allow astronauts to better prioritize their tasks, and would enable purely robotic resupply missions to Gateway. Images depicting this conceptual approach are shown in Figure 2.

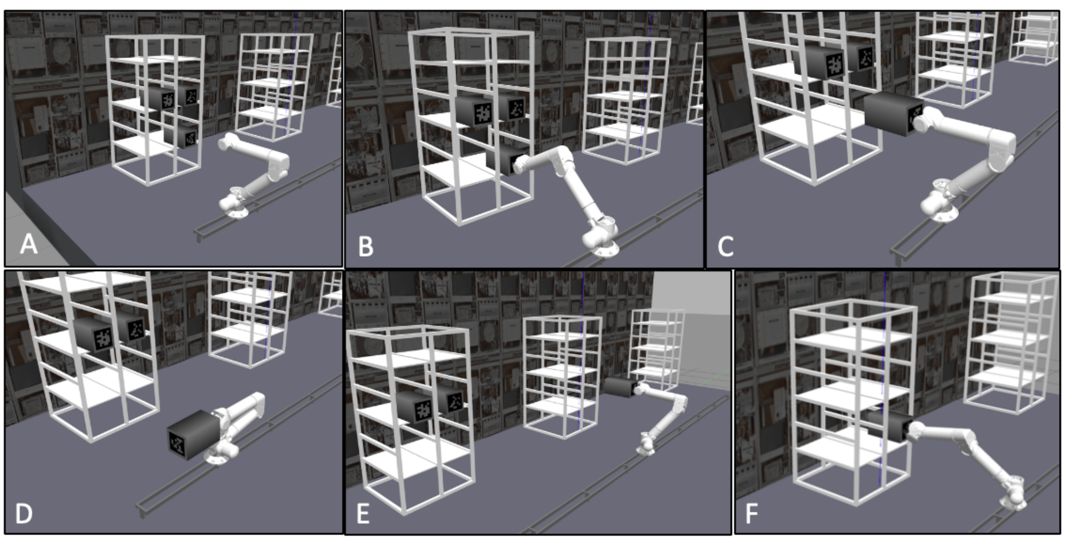

Fig. 2 Sequence of images depicting Ranger dexterous manipulator (DXM) retrieving a CTB from a shelf and transporting it along the rail mobility system

2. Design Maturity

2.1. COVID-19 Pandemic Impact

The approach taken in designing and progressing with this project has evolved since the initial proposal was completed, due to unforeseen circumstances resulting from the Coronavirus pandemic. Although experimental investigations using available robotic systems at the University of Maryland had been underway since the start of this project in August 2019, Team ASTRO lost access to the University of Maryland campus and lab spaces after mid-March. Since there was no feasible way to move the robotic systems and test hardware off-campus, the physical testing that could be completed for the project was fixed at that time.

These circumstances resulted in changes being made to how Team ASTRO continued to progress toward the completion of project goals. Experimental activities were refocused on the development and use of computer simulations, which allowed the continued testing of concepts such as the automated grapple and manipulation of CTBs. An expanded effort was also placed on the design of the servicing system for operation on Gateway. The mobility system design inside the habitat could largely be approached in the originally intended manner. Engineering design and analysis was needed to determine what the best habitat robot mobility system would look like. CAD and structural analysis could be completed and discussed remotely between team members. The largest impact to this portion of the project was the small amount of time lost as team members worked to acquire the resources they needed to be able to continue work remotely.

2.2. Evolution of Design

To best fulfill the requirements of this project and to create a system that was capable of maintaining the interior on a space habitat or payload, it became clear that it would be necessary for the robotic arm(s) installed in the habitat to have a mobility system. Although carefully considered, neither a free flying or wire rail system would be best suited for this task. A free flying robotic system would be more destructive if the system were ever compromised due to mechanical or software failure. Additionally, neither system would be able to provide the torques and forces needed to fully stabilize the robot as it moved and worked if it were designed with sufficient force and torque capabilities to accomplish the same maintenance tasks currently performed by astronauts. For these reasons, a rail system was further explored due to its higher technology readiness and less risk. Two different types of rails were initially considered - a single T-beam and a dual cylindrical rail. Either rail system would allow for smooth travel within the pressurized volume, which would be beneficial for science payloads. Limiting machine noise and vibrations in the station would prevent disrupting any microgravity experiments being carried out. Even though a T-beam was determined to be more massive, it is able to withstand greater loads than a dual cylindrical rail. The dual cylindrical rail would also have a larger profile than the T-beam. This means that this design would be more likely to cause something or someone to get caught on it, and would also be more inviting as a handrail for an astronaut, potentially resulting in damage to the system. Ultimately, this trade study concluded that a T-beam rail system was the best option for robot mobility. Minimizing risk due to design failure and the heritage of rail systems used in building lead to the conclusion that the T-beam would be the best mobility system for the robot.

3. Concept of Operations

The final system concept of operations (CONOPS) can be described as sending a command to the robot telling it to repair something, and then simply watching the robot complete the task. This is best illustrated through a scenario. After the robotic system and rail mobility system are integrated into Gateway(ideally prior to launch), the systems will be continuously monitored by mission control. Once an operator observes an anomaly in the outpost, they would send a command to the robot specifying the location of the anomaly, the task that needs to be completed, and the required end effectors, diagnostic equipment, and repair hardware. The robot would autonomously take over from there, collecting the required components from a robotic maintenance node and propelling itself along the rail to the site of the required maintenance action. Key maintenance points throughout the outpost are marked with AprilTags to provide precise location data to the robot's sensing systems. Mission control would be able to monitor the actions of the robotic system, and verify successful task completion. AprilTags also mark the station's cargo transfer bags (CTBs), which the robot can identify and re-position via a magnetic end effector. As a whole, this would allow the robotic system to organize cargo before astronauts arrive and eliminate the necessity of requiring the astronauts to perform resupply and other logistics operations, as well as to perform routine maintenance, freeing up the astronauts' limited time aboard the Gateway station. Specification and validation of the robotic system, mobility, maintenance tasks, and cargo manipulation are explored in the sections below.

4. Experimental Testing & Validation

4.1. Robotic System(s) Used for Testing

Three dexterous robots were available for testing of possible implementation in the proposed design solution: Baxter, the Ranger Neutral Buoyancy Vehicle (NBV) arm, and the Ranger Dexterous Manipulator (DXM), one arm of the Ranger Telerobotic Shuttle Experiment (RTSX) servicing system developed and qualified as a shuttle flight experiment, but never flown. As shown in Figure 3, Baxter is a two-armed industrial robot with seven degrees of freedom. The maximum reach of Baxter is 1210 mm, and its maximum payload mass is 2.2 kg. Ranger NBV, a six degree of freedom single arm dexterous manipulator, has a maximum payload of approximately 5 kg in Earth gravity. Ranger RTSX (Ranger Telerobotics Shuttle Experiment) consists of two dexterous arms (right and left) with eight degrees of freedom each and a maximum Earth payload of 10 kg. RTSX will be used for future testing once University research restrictions due to the Coronavirus pandemic are lifted.

Fig. 3 From left: Baxter, Ranger NBV, and Ranger RTSX

4.2. Operational and Maintenance Tasks Capability Testing

On the ISS, there are three main types of in-flight maintenance: preventive maintenance, corrective maintenance, and diagnostic maintenance [5]. Preventative maintenance involves the regular inspections of systems and hardware to make sure no errors occur in the future. Corrective maintenance involves repairing or replacing hardware that is no longer functional. Diagnostic maintenance is, as it sounds, a diagnostic check for what is causing a problem, where afterwards corrective maintenance will occur to fix the problem that the diagnostic found. This team's initial focus was on preventative maintenance tasks, in order to test what a robotic system can do. Team ASTRO created a task board with actions that would typically be done during preventative maintenance. This task board included a push button, a

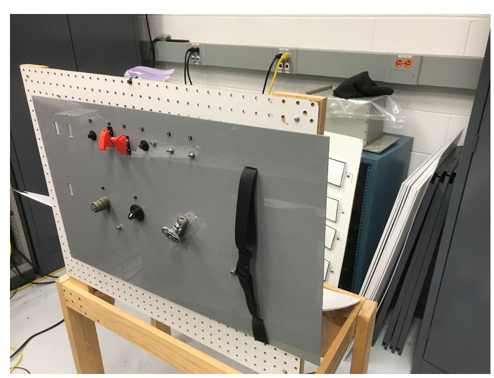

Fig. 4 Task board. Top row, from left to right: push button, switch with switch guard (flip up), switch with switch guard (flip down), push button, switch without switch guard (x2). Bottom row from left to right: electrical connector, knob, buckle.

knob, an electrical connector, a switch (with and without a switch guard), and a buckle. Testing on this task board (shown in Figure 4) was based around successful task completion rather than the time it took to complete the task. With more testing opportunities, Team ASTRO was planning to measure completion times. The following are what Team ASTRO defined as a completed task for each of the task board actions.

- *Push button*: When fully pushed in, the button would click and stay pushed in until clicked again.The pushed in state will count as this completed task.
- *Knob*: The knob has 8 rotational points. When turned, the knob would click when it is turned from one point to another. One click is considered a completion.
- *Electrical connector*: Pull apart/ disconnect and fully reconnect. Fully reconnect meaning it must be back in the state it was before disconnecting.
- *Switch* (without switch guard): Flipping the switch one way or the other.
- *Switch* (with switch guard): Opening the switch guard to a point where it will stay open without support, flip the switch, and close the switch guard.
- *Buckle*: Completely unbuckling. Buckling would most likely require two arms and Team ASTRO initially only had a one armed robot, so this task completion focuses only on unbuckling.

For testing on this task board Team ASTRO used Ranger NBV with a 3D printed, two pronged end effector, powered by a servo motor as seen in Figure 5. It is designed to simply open and close, and is actuated using a rack and pinion design.

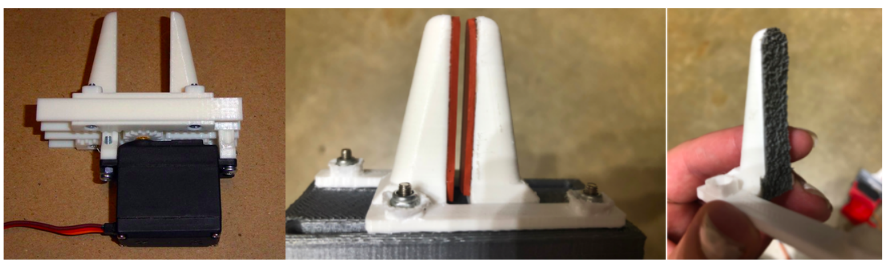

Fig. 5 Left image: 3D printed, two pronged end effector on top (white) and servo motor power on bottom (black. Center image: rubber gripper modification. Right image: sandpaper-like gripper modification.)

Before the closing of campus due to the virus, Team ASTRO completed 3 of the aforementioned tasks: the push button, switch without switch guard, and switch with switch guard. Whether the buckle task can be completed is still untested, however, the electrical connector and knob tasks are feasible. The reason they were not completed is due to the weak material of the end effector. When turning the knob, Ranger NBV was fully capable of completing the task, but not without the torque breaking the 3D printed end effector. The electrical connector task can also be completed, however, the acrylic task board was cracked under the strain of Ranger NBV's pull. In addition, it was observed that the end effector experienced slipping while performing tasks that include rotary motion. Two different modifications were made to the grippers in order to increase the friction and improve the grip of the end effectors. These can be seen above in Figure 5. Based on these tests, Team ASTRO can say that with stronger materials, all tasks, excluding the buckle, can be completed by a teleoperated robotic system. As testing progressed, it was planned to develop and demonstrate the capability to perform all of these tasks autonomously using AprilTags markers as well.

As stated previously, all taskboard tests were conducted with an electromechanical system. Design had begun of using a pneumatic gripper pre-pandemic and will be further investigated in the future as a method to apply more force and get a better grip on the object that the end effector is grasping.

One key component of the robotics systems onboard is to perform necessary maintenance tasks to keep the station operational. In order to further test the capabilities of robotic systems, Team ASTRO began to implement a mock-up for an ISS life-support rack. This structure would not only expose panels to work on, but would also contain slide-mounted modules with mockup life support systems inside. By requiring robots to open drawers and subsequently perform servicing inside, this adds an additional level of complexity that tests the range of motion and dexterity a robot arm possesses. Team ASTRO aims to complete construction of the ISS life-support rack mock-up to gather more data on robotic capabilities aboard a space station.

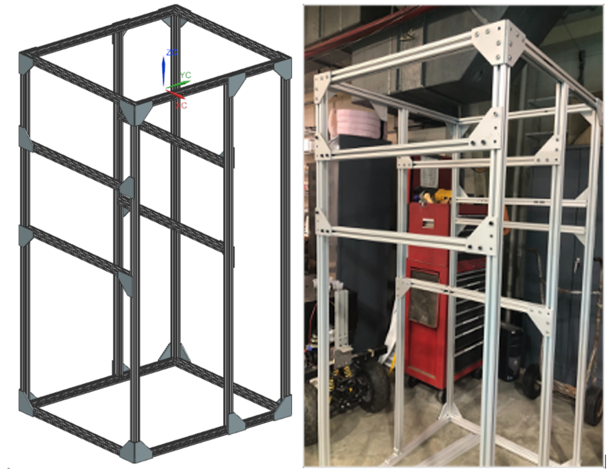

Fig. 6 Life-support rack mock-up. CAD model on left, manufactured model on right.

With the understanding developed through experimental testing thus far, and with a $2 million budget in mind, the RTSX robot from the UMD Space Systems Laboratory was selected as the best choice for a teleoperated robot for station maintenance since it is accessible, flight certified, and the costs to produce a flight unit are well known.

4.3. CTB Manipulation Testing

Team ASTRO has also conducted experimental testing of a potential logistics solution where April Tags [6] are used to detect and position a robot end effector which is equipped with an Electropermanent Magnet (EPM) [7]. An EPM functions by switching its external magnetic field on and off with short bursts of current. In the on state it is a standard magnet; in the off state it is a piece of metal with almost no external field. The Baxter robot was used to validate the functionality of this configuration. Tests were conducted with a custom NicaDrone EPM end effector and modified CTB (shown in Figure 7). These are discussed in greater detail in section 5.4. The robot control algorithm used a camera installed in the robot's end effector to detect an April Tag on a CTB, position its end effector, toggle the EPM over a wired connection to connect the CTB to the robot, move the CTB to above a platform, and then release the CTB onto the platform. This operation has been repeated numerous times with no failures from either the EPM or the positioning process, regardless of starting robot or CTB orientation and position, proving the robustness of such a logistics management solution.

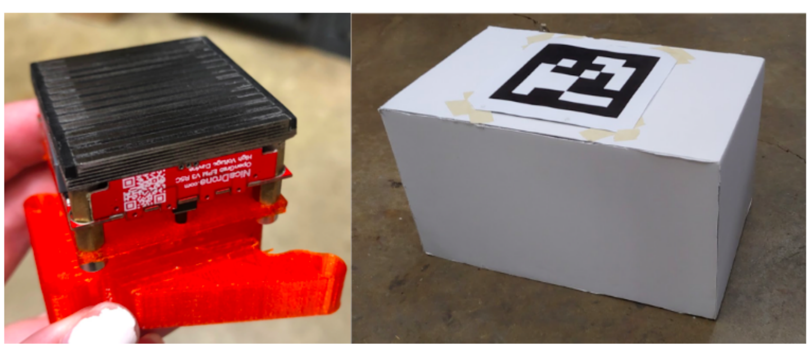

Fig. 7 NicaDrone Electropermanent Magnet on Baxter mount (left), modified Cargo Transfer Bag mock-up with AprilTag (right)

Additionally, a Graphical User Interface has been developed for the purpose of streamlining a logistics management scenario. The step by step process that is possible in the GUI is as follows. An operator begins by commanding the robot to approach a specified delivery location. Once there, they can adjust the robot's view to view the CTB they desire to pick up. Then they can command the robot to move its end effector directly to the center of the CTB face with the April Tag. Next, they command the simulated attachment mechanism to activate. Then, the operator will select the drop off destination and command the robot to deliver the CTB there. This uses the OMPL motion planner with the T-RRT planning algorithm and MoveIt! [8] [9] [10] [11] [12] collision avoidance to plan a path that makes sure that both the robot and the CTB attached to the robot do not collide with anything along the way. Once this is done, they can release the CTB and return the robot to the start location to repeat the process anew.

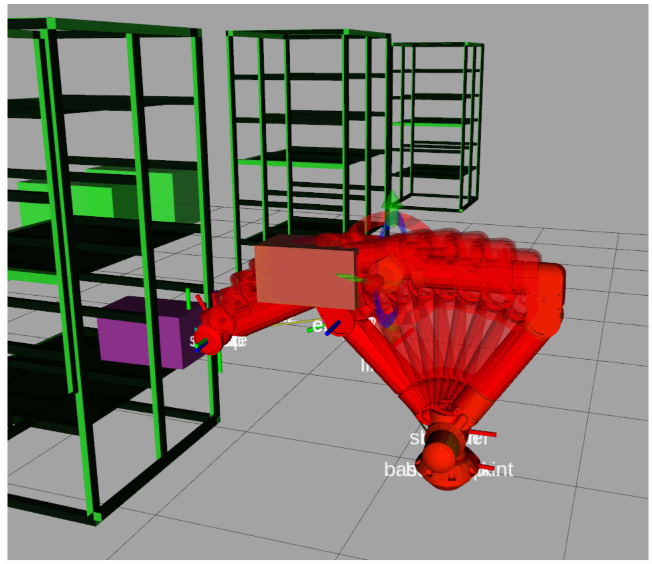

Fig. 8 Collision Avoidance Path Planning Trail

The GUI has been tested with a simulated robot in Gazebo in a mock-space station environment as shown in Figure 8. Although not yet tested with a real robot, it is expected that it would function similarly in a laboratory setting. The time taken for such a task would depend on the hardware velocity limits, primarily that of travel along the rail, and distance between delivery and drop off locations, but a reasonable approximation based on Gazebo testing is on the order of four to five minutes per CTB.

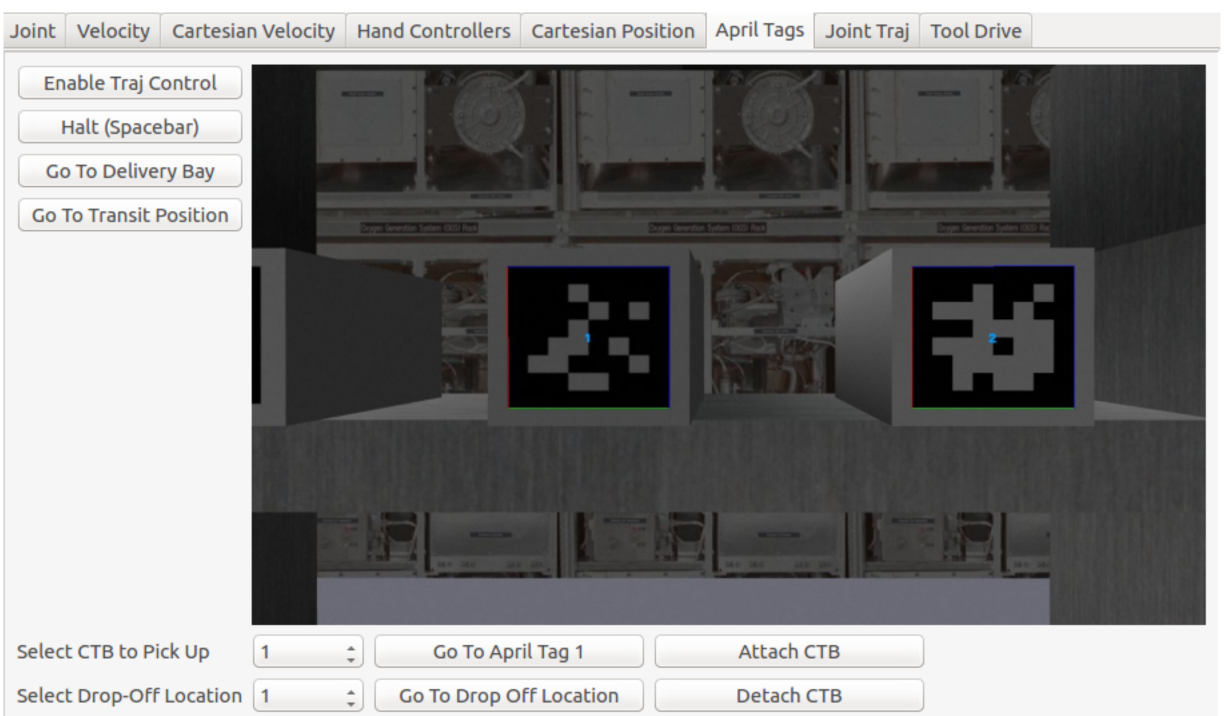

Fig. 9 GUI Used in Simulation Testing

4.4. Simulations

Multiple simulations were developed concurrently with the experimental testing. The simulations were used to assess the feasibility of using AprilTags for CTB detection and manipulation. By having both simulations and experimental work simultaneously, the simulations allowed for determining the viability of our experimental work, and the experimental work allowed for validation of the accuracy of the simulations. However, the fidelity of the ISS rack mock-up system Team ASTRO could create in the physical world was limited due to the coronavirus pandemic. Instead of utilizing a modular habitat developed by a Senior capstone team under the NASA X-Hab program to investigate the effect of habitat shape, size, and layout on the design and efficacy of a robotic servicing system, as originally intended and stated in the proposal, simulated environments were relied upon more heavily.

5. Proposed Flight Design

5.1. Rail System

A rail system was selected as the primary mobility system for the robotic device. This system will allow the robot to move quickly and reliably throughout the space station while completing different tasks. Meanwhile, the rail system will be able to add an additional degree of freedom to the 8 degree of freedom arm, resulting in 9 total degrees of freedom. The rail has been designed to withstand over 90 N of force applied at the tip of the robot arm during any given operation. Each module will have a built-in 8 meter long rail segment that will allow the robot to move freely throughout the full length of each module. For mobility within a module, the mount connecting the robot to the rail will feature a drive wheel and motor for translating the robot through the module and providing emergency braking when necessary. The robot will operate at a nominal speed of 1 centimeter per second, as higher speeds present additional safety concerns. An additional emergency brake device could be housed in the mount as well; however, as the robot will likely be operating at slow speeds, the braking provided by the drive wheel should be sufficient even in an emergency. For transfer between modules, a rail crossing through the connecting hatch would present a danger in an emergency where the hatch has to be quickly closed. Instead, the robot will reach across the hatch and grab the rail in the next module, and proceed to disconnect from the first rail and reconnect itself to the second rail segment. The end effector for this task will be chosen so as to be capable of performing this inter-module transfer. In an unusual or emergency situation, the robot could be detached and reattached to the rail manually by an astronaut. Some of the drawbacks of using a rail system include the additional amount of mass and space required to mount the rail. However, the rail system has been designed to be as small and compact as possible to minimize mass and volume requirements.

Once a rail system was selected, two options were designed for further analysis and final selection. As shown in Figure 10, the first design was a single T-beam, and the second a dual cylinder rail inspired by modern roller coasters. Quantitative stress analysis was conducted, as well as a qualitative comparison, in order to select the final design. Stress analysis was conducted both with hand calculations and computer modeling. For qualitative analysis, mass, noise, vibrations, and safety were considered. The cylindrical rail was nearly half as massive as the T-beam; however, this meant the system was able to withstand far less stress. Both designs would feature the same robot, which operates at inaudible noise levels. The other source of noise, the motor and drive wheel, would be nearly the same for both systems and also operate at inaudible or near-inaudible levels. For safety considerations, concerns were raised about the likelihood of objects or astronauts getting caught on the extruding rail. The cylindrical rail design features a larger cross profile than the T-beam design, meaning it sticks out further, and is in turn more likely to catch something moving past. Concerns were also raised about the likelihood of an astronaut using the robotic rail as a hand rail for personal mobility, which could be harmful to the rail structure, the robotic arm, or the astronaut themselves. Of the two designs, the cylindrical rail was deemed to be a greater concern in this regard, as it presents a far more appealing hand rail than the T-beam. The T-beam was chosen as the final rail design; while the design is more massive than the cylindrical rail, the increased safety it provides both in terms of structural capability and qualitative safety points to the T-beam being the superior design.

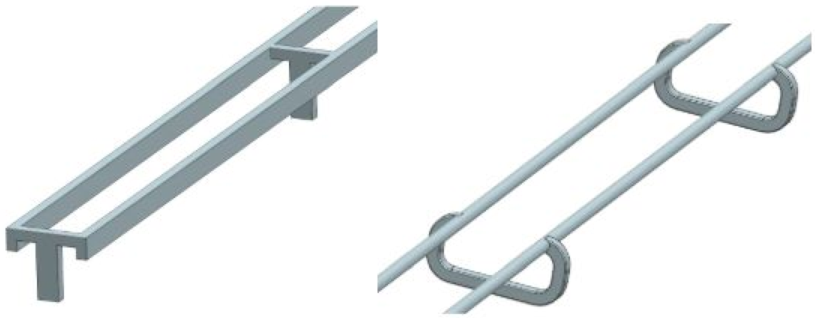

Fig. 10 T-beam rail (left), Cylindrical "roller coaster" rail (right)

In order to validate the selection of the T-beam rail design, structural analysis was performed on the beam using the NX Nastran Solver (Figure 11). First, a static load case was set up to determine if the moment induced by a robot arm pulling on the rail would cause yielding. Results indicated that a 30 N*m moment resulted in a maximum stress of 75 kPa, well under the yield strength of aluminum. Next, a dynamic load case was set up to determine the first 10 natural frequency modes of the beam. It was found that the first mode occurred at a frequency of 73.6 Hz. In order to avoid elevated stresses due to external vibrations, the components on the robot would be designed to operate well below this frequency. In addition to structural implications, the components will not have any significant acoustic issues. With the internal motors and controllers inaudible or near inaudible while operating, it is unlikely to disrupt the activities of humans sharing the space. Since the rail system requires the robot arm to remain close to the walls, it will be less obstructive to humans occupying the space.

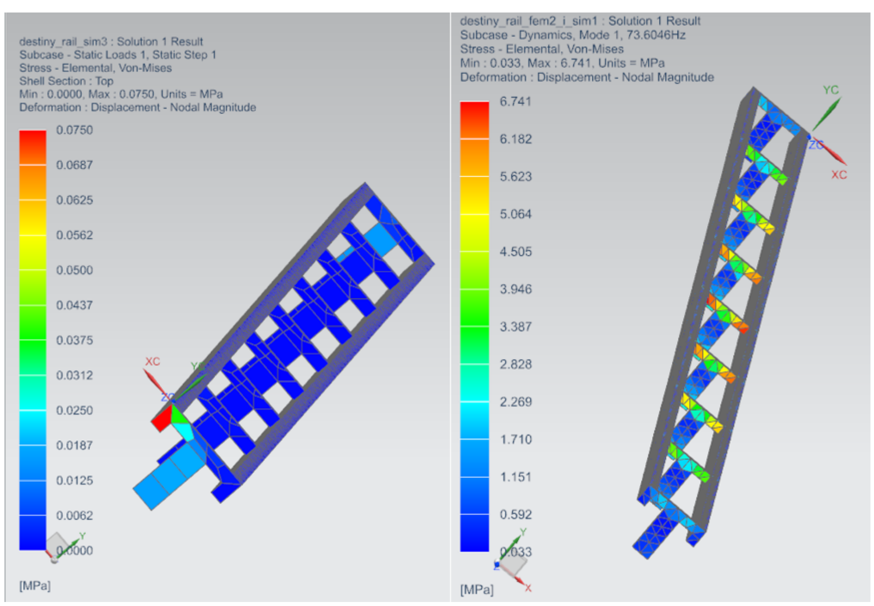

Fig. 11 Static Result from Applied Moment (left), Dynamic Result from Vibrations (right)

5.2. Sensing Systems Required

Autonomous implementation of the intravehicular mobility system will be based upon the usage of AprilTag markers for situational awareness. AprilTags, in addition to being on CTBs, can be applied to different sections of Gateway, allowing the robot to direct itself to an intended location, based on the position and distance data given by the video camera viewing the AprilTag. In terms of CTBs, this would involve both an AprilTag on the CTB itself, as well as a tag at or near the location at which it needs to be stored. For maintenance tasks, this would only require a tag on a local section of Gateway, and for the robot to know the relative positions of each component to the AprilTag. In order to make use of these markers, the robot would have to be equipped with a camera in a position where it can easily be used to view the surrounding area and detect markers relative to the robot.

In order to prevent excessive vibration of the dexterous arm moving on the rail, accelerometers will be placed along the rail, dexterous arm, and the arm's mobility pedestal. These accelerometers would allow for the vibrations of the different components to be monitored. Having accelerometers on the arm itself specifically allows for the vibration to be measured while the arm is in motion, as well as performing tasks. This is especially important, because having the arm operate at its resonant frequency can cause fatigue failure [13]. In order to avoid dangerous operation, when vibrations reach levels that could either damage the arm and rail, or disrupt experiments, the robot could self-correct and a warning could be sent to an operator in order to let them monitor, or even teleoperate for a short time, in order to ensure safe and effective use of the arm.

Anomaly detection will be dealt with by the robotic maintenance system. Expected failures will be used to develop a database of autonomous servicing algorithms which will allow the robotic system to operate without external real-time commands, but human approval will be required for all but the most time-critical tasks. Unexpected failures will inevitably occur, and will have to be detected and mitigated using operator monitoring and supervision.

5.3. Mass/Power Estimates

The RTSX robotic system is already designed, and the development/qualification unit is in routine use in the Space Systems Laboratory, so the masses for those components are accurately known. It should be noted that part of the philosophy which enabled the University of Maryland to design and qualify a robotic payload for shuttle flight for only $14M is that no effort was placed on optimizing the structural design to save mass. Therefore, this system for Gateway will be more massive than might be expected, but this was necessary to meet the extremely aggressive target of $2M total for flight system development. There is an obvious trade study here between additional funds and minimizing robotic system mass. The rail system is designed as a linear structure to be mechanically fastened into any module to be robotically serviced; for the purposes of mass and cost estimates, the assumption was made that only one module would be initially outfitted. The mass estimates are summarized in the following table. Module-mounted cameras will be less than one kg total, and are not included in the mass table.

Component	**Quantity**	**Mass (kg)**
Manipulators	2	80
Robot body	1	50
End effectors	5	3
Rail Mobility System	1	40
Total mass		**265**

The RTSX robot operates at 28 VDC, has a quiescent power requirement of approximately 10 W. Average operating power for the manipulators is 350 W each. Peak power draw can go to 5 kW if all motors are fully driven while stalled, but this is precluded in software and hardware. The maximum operating power for RTSX is currently 1 kW.

5.4. Logistics Management System

One of the most important tasks on a space station is unpacking a resupply mission and distributing the cargo transfer bags throughout the space station. Fortunately, Team ASTRO has come up with a solution to enable a robotic system to perform this task with minimal operator input. The solution consists of four parts: AprilTags, an EPM gripper, the robotic mobility system, and a GUI controller.

First, the CTBs must be labeled with the aforementioned AprilTags fiducial markers. These enable an operator to select the tag they desire to pick up and command the robot to position its end effector exactly in front of the cargo transfer bag to enable correct operation of the gripper.

Since CTBs are generally made of cloth, handling them with a traditional robotic gripper is difficult and time-inefficient, therefore an alternative which Team ASTRO have tested is to use a NicaDrone Electro-Permanent Magnet (EPM) which Team ASTRO has found to be effective for the purpose of manipulating CTBs. By installing a small plate made of ferrous metal with dimensions 40mmx40mm, which is exactly the size of the magnetic surface of the EPM, directly under the center of April Tag, the EPM can establish a secure connection between the robot and the CTB once it is in the correct position. The minimum holding force is 200N, which is sufficient for most low speed operations in zero gravity, and is greater than the largest axial force an RTSX arm can exert, 90N; therefore, dropping a CTB is unlikely. From there, the robot can begin to move the CTB as needed, provided velocities are low enough to ensure that resulting moments throughout the arm do not cause current overdraw. Due to the fact that the EPM imposes a magnetic field, there is potential for brief interference with sensitive components that are within the CTBs during handling, prior to closing the magnetic circuit with the metal plate. This can be mitigated by positioning these items away from the face of the CTB where the interface will occur, providing them with a magnetic field-shielding material, or by having the robot switch its end effector to a traditional two-finger gripper for handling CTBs with these components. The possibility of the CTB slipping from the robot's grasp is minimal compared to a two-fingered gripper. This is very important if the task is to be performed within a short time frame, as well as to ensure the safety of both the components inside the CTB and those already on the station, as unwanted release may lead to a damaging collision.

The mobility system would then enable the robot to transport the CTB away from the delivery module and into an operator designated location within the station. The previously discussed rail system is the approach selected for this task. During the transportation phase of this task, the robot would enter a stowed position and move through the station in a clean manner that avoids unwanted contacts with either crew or equipment. Also notable is that during transportation, the magnetic field of the EPM can be made to not interact at all with on-board equipment by positioning it at a sufficient distance away from the walls of the ISS, which is what has been done by configuring the robot in a stowed position shown in Figure 2D.

The final component that ties all this together is the aforementioned GUI that has been experimentally tested in Gazebo. A distinct advantage of using this GUI is that all it does is compute and provide trajectories that can then be sent to a robot, meaning that the only portion of the code that would require flight certification is the actual robot hardware interface that would communicate with the robot on Gateway to receive information about the joint states and send controller commands to actuate the robot. An operator on the ground would see the inside of the space station through one of the connected cameras and then execute the necessary steps to unpack a delivery module, with minimal slow joint-space control required. All collision avoidance is taken care of by the ground based controller; the planned trajectory is displayed to the operator prior to confirmation, so in the unlikely event of an incorrectly planned trajectory, the robot can be halted safely.

Enabling a robot to take over the resupply mission unpacking operation could allow for deliveries to take place before the arrival of astronauts, meaning they would have all the supplies already in the exact place they are expected to be - no more going around looking for a stray CTB. If a rail system can be implemented, then the solution outlined here would lead to very effective logistics management aboard Gateway.

5.5. Maintenance & Repair on Gateway

Results gathered from the experimental testing portion of this project indicate that dexterous robots can be used for a variety of routine and contingency maintenance and repair tasks on Gateway. Based on common repair tasks completed by astronauts on the ISS, these tasks include (but are not limited to) "remove and replace" tasks, disassembly/reassembly of malfunctioning life support systems, and end-to-end repair of an oxygen generator assembly. Due to COVID-19, Team ASTRO was unable to test these tasks in a laboratory environment, but plans to investigate these maintenance and repair tasks in the future.

6. Technology Readiness

6.1. Technology Assumptions

Team ASTRO's design of an intravehicular mobility system is based on existing module standards for the ISS. The system was designed with the assumption that the Gateway architecture will closely resemble that of the ISS (this being a modular design that consists ofracks similar to ISS International Standard Payload Racks). Rather than modifying the existing architecture, all designs were adapted to the ISS module standards, with the only required modifications being rail and docking station mounts. The rail station being implemented was inspired by a common T-beam cross-section; while this has been demonstrated in a 1-g environment, this design has not yet been flight-proven.

In addition, the EPM has also not been flight-proven. Multiple concerns exist on the possibility of the brief electromagnetic pulses interfering with sensitive equipment both onboard Gateway and in the CTBs, so further extensive testing must be conducted with the EPM to verify safety of use.

6.2. Technology Readiness Levels

All technologies for this proposed design were evaluated using the NASA Technology Readiness Levels (TRL) [14]. The table below shows the current TRL levels of all technologies used for the proposed mission design:

Technology	**TRL**
RTSX	6
Rail Mobility System	4
AprilTag Identification System	5
EPM Gripper	3
End Effector Exchange System	6

All low-TRL components will continue to be advanced until they are at TRL 6+ for launch readiness. The timeline for this advancement is further detailed in section 7.

6.3. Risk Analysis

Eighteen risks have been identified and categorized in the following risk analysis chart. These risks were assessed by their likelihood of occurrence and resulting consequence severity. These risks include robotic component failures, robotic mobility system failures, robot-crew interaction failures, and programmatic risks.

Likelihood	Negligible	Minor	Marginal	Critical	Catastrophic
Almost Certain					
Very Likely					
Likely		[14]		[1][11][12]	
Unlikely		[3]	[2][7][13][18]	[16]	[5][6][10][15]
Rare				[4]	[8][9][17]

Severity of Consequence

1. Budget Cuts
2. Robot Actuator Failure
3. Robot Stuck On Track
4. Robot Coming Off Track
5. Robot Moving Without Warning
6. Loss of Power
7. Loss of Comms B/w Gateway and Ground Station(s)
8. Launch Failure
9. Robot Colliding With Crew
10. Robot Impeding Crew Objectives
11. Robot End Effector Failure
12. Robot Failure to Complete Maintenance Objective(s)
13. Robot Control System Failure
14. Robot Sensor Failure
15. Robot Damaging Gateway
16. Damage to Track
17. Fire Accident
18. Robot Wiring/Electronics Failure

Although most risks were deemed low probability, proper mitigation was determined in order to prevent some of the more pressing critical and catastrophic events from occurring. For example, a robot moving without warning could potentially cause harm to the crew or damage to the Gateway outpost, so a redundant braking system was added to the mobility design to address that risk.

7. Schedule of Operations

For the designed rail system to be fully functional on Gateway, it will ideally be integrated during the construction phase of the interior of Gateway. All necessary components of the design (including the rail system and RTSX) will be installed in a module prior to launch, and then integrated with the rest of the Gateway outpost following arrival at Gateway. TRL improvements will continue through 2023. Initial launch of the module containing the rail system is targeted for early to mid 2024, with launch and integration of RTSX to be completed by late 2024. After that, the robotic maintenance system will be fully functional, with mission control having full monitoring and command up-link capabilities. The system can be used not only for maintenance, but to finish the interior outfitting of Gateway prior to it being fully operational. Figure 12 below shows a prospective schedule of operations for the integration of the robotic maintenance system into Lunar Gateway.

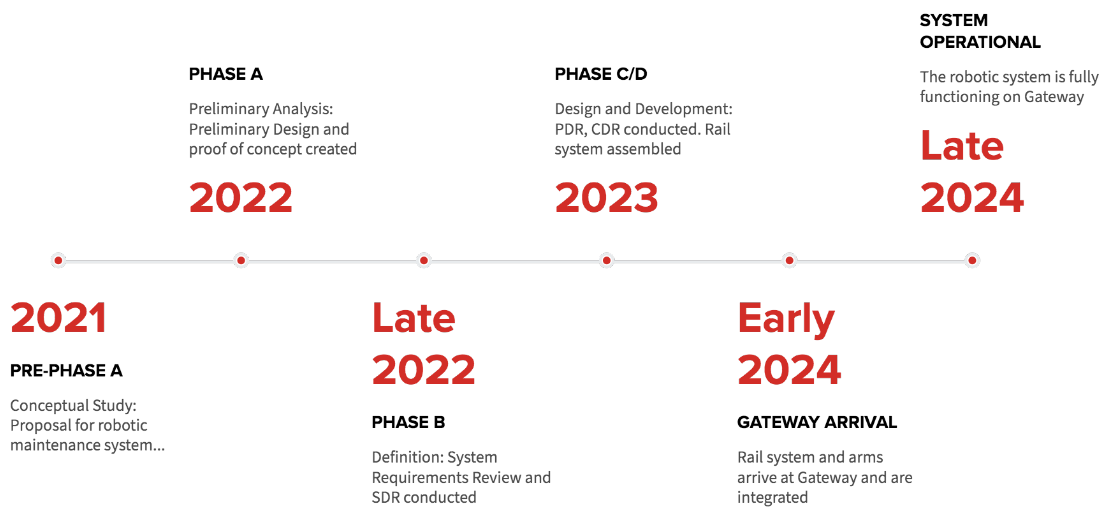

Fig. 12 Schedule of Operations for integration of the robotic maintenance system onto Lunar Gateway

8. Budget

For the budget estimates, Team ASTRO conducted research on analogs that would be helpful in cost determination for the hypothetical robotic system.

Team ASTRO evaluated analogs in industry, space and research applications. The Kuka Arm is a 6 degree of freedom robotic arm that is used in space applications including project INVERITAS. It was used to hold a client satellite and cost approximately $30,000-60,000. There are also industry versions of the Kuka arm that have different specifications and a wide range of options with different functionalities [15].

A second analog Team ASTRO looked at was Robonaut. Robonaut was the first robotic humanoid functioning aboard the ISS to aid in day-to-day tasks. Robonaut has two seven degree of freedom arms, costing approximately $2.5 million [16].

The robotic system chosen is the Ranger TSX system, from the University of Maryland Space Systems Laboratory. The initial development cost for the system was $14 million, including research and development and flight qualification for shuttle flight and operations. However, for our purposes Team ASTRO will exclude any research and development costs, as Team ASTRO plans to build-to-print from the current system. Manufacturing costs for two flight-ready manipulators are around $1.2M total [17]. Each robotic arm has 8 degrees of freedom, and the majority of our operations testing was completed Ranger NBV, the precursor to this flight system.

The robotic system Team ASTRO designed requires cameras to identify AprilTags, as well as for assessing problems and tasks to be completed aboard Gateway. RTSX already includes cameras mounted in the wrists for guiding end effectors, and cameras in the body providing wide-field images of the arms; costs for these cameras are included in the estimate for the robotic system. Cameras would also need to be integrated into Gateway around the expected volume of robot operations to provide situational awareness for the system. Experience with the current system has verified that AprilTags is completely functional with cameras providing 1080P resolution, although 4K cameras would provide greater resolution upon need. It is estimated that five cameras mounted around Gateway would be sufficient, at an estimated cost of $10K each. [17].

The rail system Team ASTRO has designed is 8 m x 12 cm x 15 cm, and is made of T-7075 Aluminum. This aluminum was chosen as it is commonly used for aerospace grade parts. Based on the number of pieces, complexity of machining, and standard machine shop costs, as well as flight qualification, the rail system cost was estimated at $200K.

End effector pricing varies greatly. For an end effector that can withstand being on Gateway, a price of at least $10,000 is suitable given the necessity to be robust and long lasting [18]. UMd research showed that all of Hubble Space Telescope servicing could be done robotically with ten unique end effectors; it is assumed that five should be adequate for the initial set of Gateway applications.

The software costs of the system would be manageable by making maximum use of open source and legacy code. The robotic systems Team ASTRO are using utilize open source software. Team ASTRO has budgeted for two programmer-years of effort for tweaking the existing code and interfacing to Gateway systems.

System	Cost (USD)	Total Cost
Robotic System	$1,200,000	
Rail System	$200,000	
Cameras	$50,000	
End Effectors	$50,000	
Software	$300,000	
Flight Integration	$200,000	
		$2,000,000

Flight testing and qualifications for the whole system would be extremely costly. Testing for sustainability of the electronic parts under the extreme conditions of the ISS or Gateway station requires structural testing, vibration testing, life-cycle testing, contingency testing, testing of functionality with trapped protons, moderate trapped electrons, partial solar particles, minimal cosmic rays, and a human presence [19]. Team ASTRO is allocating $200K to flight integration and testing, but due to the extreme cost constraints of this theme, as well as the lack of any published requirements for Gateway integration, Team ASTRO is assuming that the flight qualification which took place on Ranger TSX for shuttle flight will be adequate for Gateway qualification.

9. Conclusion

The International Space Station has been essential in furthering scientific discovery and space flight. As the station continues to age and space exploration objectives change, the need for a new space station becomes greater. The new Lunar Gateway station will enable humanity to accomplish more challenging exploration missions but will also have different design features than that of the International Space Station. A driving factor in the design of Gateway is that the station will only be crewed for about thirty days out of the year, but must remain fully functional without humans on board so that when astronauts do show up, they will find a safe living environment.

The University of Maryland's Team ASTRO is addressing the problem of designing a space habitat that can be kept functional, year-round, despite intermittent human occupation, with a two faceted approach. Team ASTRO has been investigating the Intravehicular Mobility System that would be required in the interior of the Lunar Gateway for a robotic system to be able to navigate around the station, as well as the sensing system that would be required to keep hardware and humans safe. Additionally, Team ASTRO has been working to identify, enable and improve the intravehicular activities that would be required by a robotic system to maintain the Lunar Gateway without the assistance of astronauts onboard.

Using Siemens NX and mathematical analysis, it was determined that eight meter long rail segments will best allow a robot to move freely throughout the full length of the habitat module. Movement between modules will be possible with the robot using an arm and gripper to reach and latch onto the new desired rail. A T-beam was shown to be able to withstand the predicted loads of the robotic system and would be less likely to cause objects to catch and snare on the beam. This relatively simple and inexpensive system allows for one robotic arm to traverse and service the entire interior of the space habitat.

To aid with robotic sensing onboard the Lunar Gateway Station, AprilTags have been shown to be extremely effective. In addition to successful laboratory testing of autonomous robotic management of a cargo transfer bag identified by the robot's camera sensing system, simulations developed by Team ASTRO verify the ability of a robotic arm to move CTBs within a confined space.

After developing and mounting a 3D printed rack and pinion end effector to Ranger NVB, Team ASTRO was able to accomplish operational tasks including button pushing and switch flipping, with and without a switch guard. Material strength prevented successful manipulation of electrical connectors and knobs. Due to research restrictions resulting from the Coronavirus pandemic, team members were unable to improve the gripper design and continue the experimental testing in hardware. In order to continue the research, simulated environments were relied on more heavily. A GUI was developed by Team ASTRO that allows an operator to send the robot to the start location, adjust the robot to view the desired CTB and command the robot to move to the CTB and use its end effector to place the bag at the desired location.

The efforts and research completed by Team ASTRO indicate that robotic operation and maintenance of the Lunar Gateway station, while both crewed and uncrewed, is feasible. A rail system running through the interior of the station provides the necessary mobility for the robot, AprilTags can provide necessary position data for the robot as well as streamline previously time consuming tasks such as cargo transfer bag management, and appropriate end effector designs enable a robotic system to accomplish many operational tasks that have been previously required of astronauts. While the requirements of the RASC-AL Theme 5 specified an unrealistically low budget cap for this program, by using legacy robotic designs and hardware developed at minimum cost in the university environment, a feasible solution was identified that met the cost caps while enabling robotic maintenance on Gateway.

10. Appendix

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