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A HOLISTIC INTRA AND EXTRA VEHICULAR MANEUVER STRATEGY FOR FREE-FLYING SPACE ROBOTS

by

Jonathan S. Kohler

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Thesis Advisor: Jennifer Hudson
Second Reader: Jessica L. Herman

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Advancements in space exploration are increasingly dependent on autonomous systems for the maintenance and operation of space stations. This thesis explores the potential roles of free flying robots, leveraging distinct locomotion methodologies apt for various operational tasks. Utilizing the International Space Station as an analogue for future space stations, the thesis identifies tasks that these robots could perform to extend our capacity for manned space exploration. Drawing upon previous work and the projected state of the art in robotic locomotion, it proposes a coherent, task-based strategy for free flying robot operations using combined locomotion methods. The thesis also introduces the implementation of a tube-based model predictive controller for propulsive locomotion. After a series of ground tests, the controller is integrated into NASA's free flying robot, Astrobee. The controller is subsequently utilized in tests aboard the International Space Station to compare the performance of the tube-based model predictive control with a standard model predictive control for cargo retrieval tasks. The thesis concludes by assimilating insights from on-orbit experiments and an examination of locomotion methodologies, proposing a unified, systematic strategy for employing multiple robotic locomotion methods to enhance space station upkeep and operations.

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Jonathan S. Kohler
Major, United States Marine Corps
BS, University of Maryland, College Park, 2011

Submitted in partial fulfillment of the
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June 2023

Approved by: Jennifer Hudson
Advisor

Jessica L. Herman
Second Reader

James H. Newman
Chair, Space Systems Academic Group

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Advancements in space exploration are increasingly dependent on autonomous systems for the maintenance and operation of space stations. This thesis explores the potential roles of free flying robots, leveraging distinct locomotion methodologies apt for various operational tasks. Utilizing the International Space Station as an analogue for future space stations, the thesis identifies tasks that these robots could perform to extend our capacity for manned space exploration. Drawing upon previous work and the projected state of the art in robotic locomotion, it proposes a coherent, task-based strategy for free flying robot operations using combined locomotion methods. The thesis also introduces the implementation of a tube-based model predictive controller for propulsive locomotion. After a series of ground tests, the controller is integrated into NASA's free flying robot, Astrobee. The controller is subsequently utilized in tests aboard the International Space Station to compare the performance of the tube-based model predictive control with a standard model predictive control for cargo retrieval tasks. The thesis concludes by assimilating insights from on-orbit experiments and an examination of locomotion methodologies, proposing a unified, systematic strategy for employing multiple robotic locomotion methods to enhance space station upkeep and operations.

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TABLE OF CONTENTS

LIST OF FIGURES

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LIST OF TABLES

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LIST OF ACRONYMS AND ABBREVIATIONS

AERCam	Autonomous Extravehicular Robotic Camera
AFF	Assistive Free Flyer
AFS	Astrobee Flight Software
ARC	Ames Research Center
DOF	Degree of Freedom
ECLSS	Environmental Control and Life Support System
EF	Exposed Facility
EVA	Extravehicular Activity
EVR	Extravehicular Robotics
FFR	Free Flying Robots
GDS	Ground Data System
HLP	High Level Processor
HLS	Human Landing System
ISAAC	Integrated System for Autonomous and Adaptive Caretaking
ISS	International Space Station
IVA	Intravehicular Activity
JAXA	Japanese Aerospace Exploration Agency
JEM	Japanese Experimental Module
JEMRMS	Japanese Experimental Module Remote Manipulator System
LEE	Latching End Effector
LLP	Low-Level Processor
MA	Main Arm
MBS	Mobile Base Station

MLP	Mid-Level Processor
MPC	Model Predictive Control
MSS	Mobile Servicing System
NASA	National Aeronautics and Space Administration
NMSU	New Mexico State University
NPS	Naval Postgraduate School
ORU	Orbital Repair Units
PFP	Push-Fly-Park
POSEIDYN	Proximity Operation of Spacecraft Experimental Dynamic Simulator
ROS	Robot Operating System
RPO	Rendezvous and Proximity Operations
SLS	Space Launch System
SMPC	Standard Model Predictive Control
SPDM	Special Purpose Dexterous Manipulator
SPHERES	Synchronized Position Hold Engage Reorient Experimental Satellites
SRL	Spacecraft Robotics Laboratory
SSRMS	Space Station Remote Manipulator System
TLTC	Time Limit to Complete
TRL	Technology Readiness Level
TRMPC	Tube Based Robust Model Predictive Control
TTC	Time to Criticality

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I. INTRODUCTION

The combined use and strategization of multi-modal locomotion methods for free flying robots (FFR) can significantly enhance the efficiency and safety of intra and extra-vehicular mobility in on-orbit operations. Recognizing the need for an in-depth examination to discover potential locomotion methods, the feasibility of FFRs for space station maintenance tasks, and the integration of these methods within a comprehensive strategy, this study embarks on an extensive analysis.

The second chapter of this thesis delves into an expansive evaluation of the diverse roles that FFRs may undertake, examining the complexity of each task, the speed at which it must be completed, and the factors dictating the autonomy of the robot. Tasks were identified and compiled based on existing literature, simulations, NASA technical reports, and through technology demonstrations conducted by other Astrobee developers. Chapters III and IV are devoted to discerning and scrutinizing the environmental factors that could potentially influence how an FFR incorporates different locomotion methods within and outside space stations. This study analyzes the practical and theoretical locomotion methods which could potentially be utilized by an FFR and organizes the disparate methods into three categories. A qualitative analysis of each category is then conducted to ascertain the strengths and weakness posed by each locomotion method.

In Chapters V and VI, a series of terrestrial and on-orbit tests are conducted to validate the feasibility of an FFR performing a space station maintenance task, propulsive locomotion-based cargo-towing of a load with an unknown mass. As part of the testing we designed, executed, and validated an experimental setup for a dual-Astrobee system simulating a towing maneuver in both a planar ground test and three-dimensional on-orbit testing. The findings from these tests offer insight into the current state of the art in FFR control, highlighting the intricate realities and challenges posed by the use of FFRs in maintenance roles in space stations. Although the test results do not provide enough consistent data to make a meaningful distinction in performance between the two controllers we analyzed, we have included an extensive failure analysis that should assist future researchers with their own Astrobee experiments.

Finally, we develop locomotion strategies by comparing the various tasks that space robots could perform against the advantages and disadvantages of each locomotion category. This qualitative analysis presents valuable insights for roboticists in designing and operating future FFRs for space station operations. The final chapter, Chapter VIII, concludes the thesis with a recapitulation of the results, and proposes potential characteristics for future robot designs.

A. EARLY FREE FLYING ROBOTS

Free flying robots offer an exciting capability which could prove vital for the operation and maintenance of space stations in the future. FFRs are a class of robot which operate in microgravity and use a thruster to move about their environment. Diverse types of FFRs have been operating in space for years. The term free flyer typically refers to the method of locomotion employed by the robot, but additional descriptors can be used to help identify the typical tasks that the robot executes. For example, assistive free flyer (AFF) refers to a class of free flyer that assists humans by conducting repetitive or dangerous tasks, so a crew member does not have to. AFFs can also work with humans by providing additional lighting or retrieving tools and equipment.

One of the earliest FFRs was the Autonomous Extravehicular Robotic Camera (AERCam) Sprint. AERCam Sprint was a 35-pound, 14-inch diameter, experimental, free flying robot which flew aboard STS-87 in December 1997. AERCam sprint was remotely operated and had two cameras which were to be used to provide additional visibility for Astronauts as they conducted extravehicular activities (EVA) [1]. Figure 1 shows an image of AERCam Sprint supporting an EVA. AERCam sprint was the predecessor to the Mini AERCam, which provided improved capabilities in a smaller form factor.

Figure 1. AERCam Sprint on STS-87. Source: [2].

Mini AERCam was a spherical FFR which weighed approximately 10 pounds and was 7.5 inches in diameter [1]. Frederickson et al. state that like its predecessor, the mini AERCam was designed to provide extra visibility for EVA and extravehicular robotics (EVR) activities. Improvements to the mini AERCam included the addition of a GPS receiver, improved cameras, and video capability. Mini AERCam moved using 12 cold gas thrusters with Xenon or Nitrogen as the propellant. Since nitrogen was less dense than xenon it was only used during ground testing. Figure 2 shows a side-by-side comparison of AERCam Sprint and mini AERCam. Although the system's capabilities were demonstrated through ground testing in 2005, mini AERCam never actually flew in space.

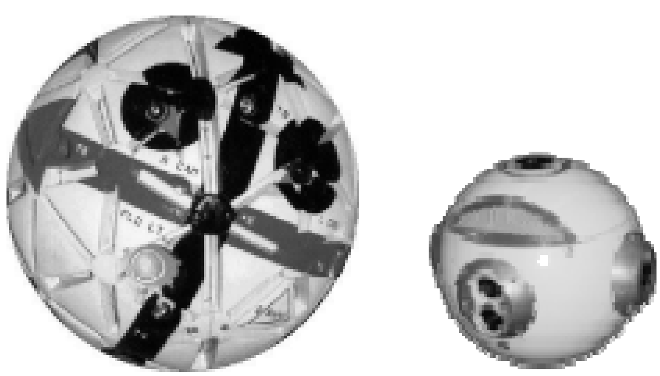


Figure 2. AERCam Sprint and Mini AERCam. Source: [1].

In 2006, the Synchronized Position Hold Engage Reorient Experimental Satellites (SPHERES) were launched to the International Space Station (ISS). SPHERES consisted of three FFRs intended to demonstrate and evaluate FFR autonomous formation flying. Each individual robot was 8-inches in diameter and weighed less than 10 pounds. SPHERES used pressurized Carbon Dioxide as a propellant to provide thrust to the robot. One of the main differences between SPHERES and the AERCam designs was that SPHERES was designed for intravehicular activity (IVA) within the ISS and could not support EVA and EVR. A major improvement of SPHERES over its other predecessors was that it was designed with an expansion port which could be used to attach experiments in support of a larger National Aeronautics and Space Administration (NASA) led guest science effort [3]. During its 10 years in orbit, SPHERES supported 600 test hours spread over 114 sessions.

In 2017, the Japanese Aerospace Exploration Agency (JAXA) launched their FFR to the International Space Station (ISS). The Internal Ball Camera, or Int-Ball, is another spherical FFR the size of a softball, capable of recording images and videos while operating inside the space station. Int-ball can operate autonomously or remotely under the control of operators located on Earth [4]. Int-ball utilizes ultrasonic distance sensors and its onboard cameras to conduct localization. Int-ball is propelled using 12 fans which are fed by inlets on the bottom of the robot [5]. Figure 3 provides a detailed image of Int-Ball's external features. Because Int-ball uses fans instead of a cold gas thruster system, it is not limited by the amount of propellant on board the robot itself. Due to this design change, fuel is no longer a limiting factor. Instead, the lifetime of the on-board batteries constrains how long Int-Ball can move around the space station before it needs to be recharged. Like the SPHERES robots, Int-Ball is limited to operations within the space station and cannot support EVA or conduct EVR.

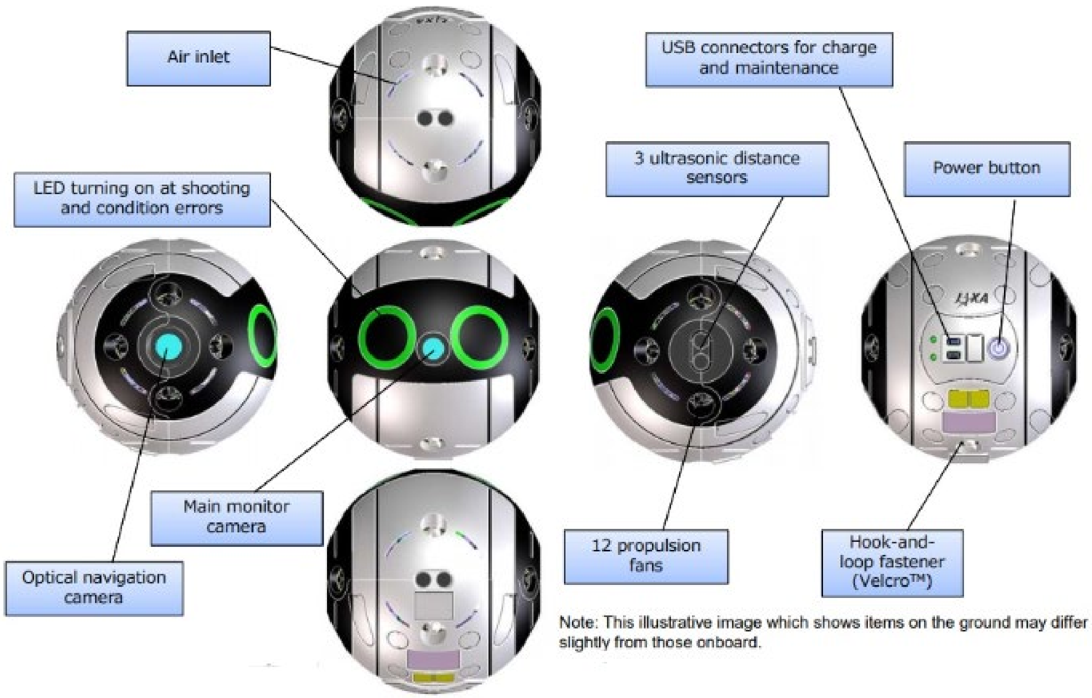


Figure 3. External features of the Int-Ball. Source: [5].

B. FREE FLYING ROBOTS CURRENTLY ON ORBIT

In 2018 NASA launched three more FFRs to the ISS to replace the SPHERES robots that had been operating for over 10 years. Named Astrobee, the FFRs offered a variety of new capabilities. Astrobees are propelled using 12 electric fans fed by an impeller. The Astrobee also features a two degree of freedom (DOF) arm with a tendon driven gripper. This manipulator can use handrails throughout the ISS allowing the Astrobee to perch to either recharge or conserve energy. Additional features can be seen in Figure 4. Astrobee is larger than SPHERES and Int-Ball. Each Astrobee is approximately 12.5 inches wide and weighs about 10 kg [6]. A more detailed discussion of Astrobee's hardware, software, and motion control is included in Chapter V.

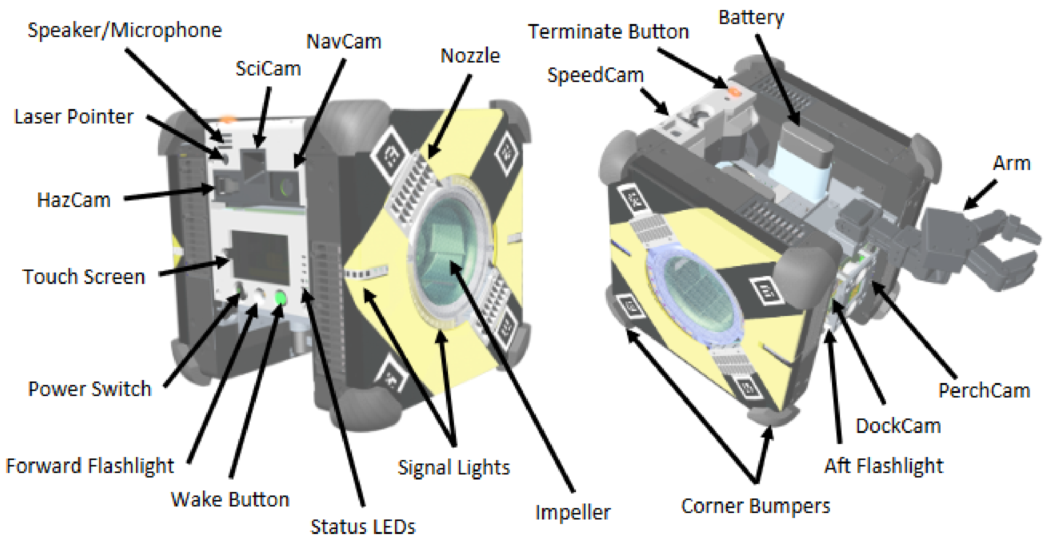


Figure 4. An Astrobee robot. Source: [6].

II. SPACE STATIONS IN SUPPORT OF SPACE EXPLORATION

A thorough analysis of NASA's plans to utilize space stations is useful for contextualizing the use case for FFRs. By analyzing the space stations and their relevant subsystems, this thesis identifies a variety of tasks for which FFRs may be suitable for. Each task is then analyzed to identify the most relevant characteristics which will drive operation strategies. These factors include where the task needs to be completed, the complexity of the task, and the time constraints for completing a task.

A. NASA'S GATEWAY

NASA's future plans for space exploration necessitate an increase in automated and autonomous operation of space stations far from Earth [7]. NASA's human exploration effort "From Earth to the Moon and Mars" will be conducted in 5 phases. Phase 0 will include research and testing on the ISS to solve exploration challenges. NASA has stated that phase 1 will include initial missions into cislunar space, the construction of Gateway, and initiation of the assembly of deep space transport. Phase 2 consists of the completion of deep space transport and the conduct of a simulated Mars mission. Phases 3 and 4 involve sustained crew missions to the surface of Mars.

In support of NASA's phase 1 human exploration plans, they will establish a space station, called Gateway in orbit around the moon. Gateway will serve as a way station for Astronauts on their way to the lunar surface. The intent for Gateway is that incoming crews will launch from earth to Gateway, and then from Gateway to the lunar surface. Once at Gateway crews will prepare equipment and supplies for landing on the lunar surface using Gateway's Human Landing System (HLS). Once operations on the surface are complete, crews will return to Gateway using the HLS. They will then re-board their original launch vehicle and return to earth directly from Gateway [8].

Figure 5 shows an example of Gateway in use for the return of a lunar sample. In this example, the Space Launch System (SLS) is used to pre-stage logistics for a mission to the lunar surface. A lander for sample collection is launched directly to the lunar surface, then returned to Gateway. Since this lander does not need to complete a return mission on its own, it will allow for larger samples to be brought to Gateway. Once the samples are collected by a crew aboard Gateway, the crew and samples are returned to earth [9].

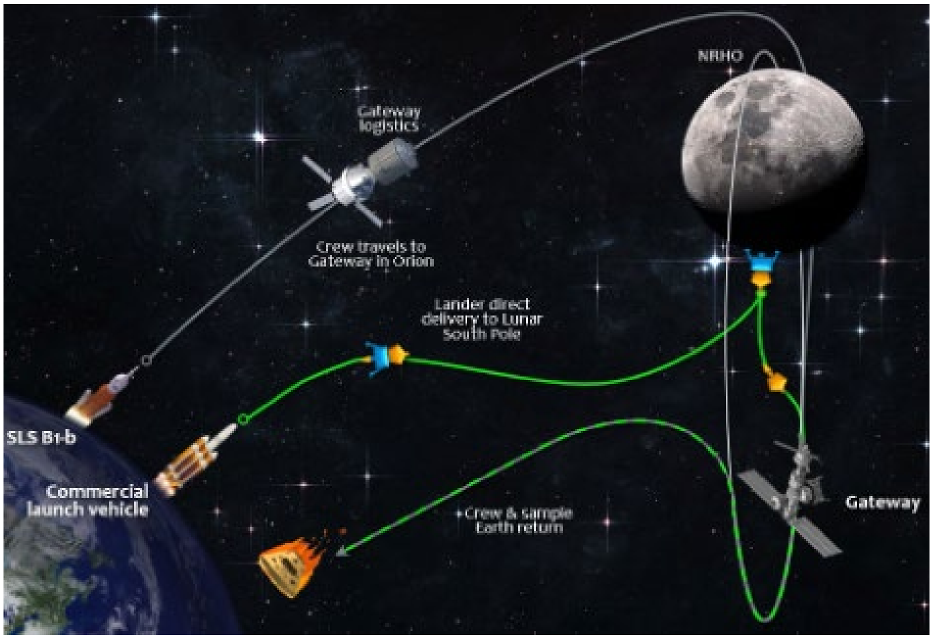


Figure 5. Lunar sample return architecture. Source: [9].

Unlike ISS, Gateway will be uncrewed for most of the time that it is operational. Autonomous and remotely operated systems will be solely responsible for the operation, maintenance, and logistics preparations necessary to facilitate periods of crewed use.

NASA's Integrated System for Autonomous and Adaptive Caretaking (ISAAC) is being developed to support the autonomous operation and maintenance of spacecraft for Gateway. ISAAC consists of the space station's onboard sensors with IVRs to execute caretaking activities [10]. As part of this effort, it is likely that IVRs will need to move within and around the space station to keep the station habitable for crew return. As it supports multiple lunar missions, Gateway will undergo multiple transitions as the station transitions between crewed and uncrewed operations. [11] provides a description of the phases that a deep space gateway would experience in support of a mission to Mars and how those phases drive the deep space gateway's autonomy. Because Gateway will undergo the same types of transitions, this framework serves as a good analog to the phases of operations that the lunar Gateway will experience. As robots support the maintenance and operations of a spacecraft, those requirements will change based on the mission phase.

B. GATEWAY'S AUTONOMY DRIVERS

The uncrewed phase of spacecraft operations is referred to as the dormant phase. The main characteristic of the dormant phase is that no human beings are on board the spacecraft. Since the spacecraft is uncrewed, certain subsystems may be non-operational and others may have their requirements reduced. For example, sewage processing is not necessary during the dormant phase because no sewage is being produced by crew members. Since the sewage processing system will remain unused maintenance requirements will be reduced as well. This will result in reduced power requirements for the space station during this phase. Environmental Control and Life Support System (ECLSS) subsystem monitoring will be less critical during the dormant phase as well. This subsystem is responsible for maintaining breathable air and keeping the station livable for crew members. When no crew are aboard, ECLSS functions like atmospheric monitoring and water quality monitoring are less critical. Figure 6 shows the dormant configuration of the ECLSS and highlights which functions become unnecessary when crew are not aboard the station.

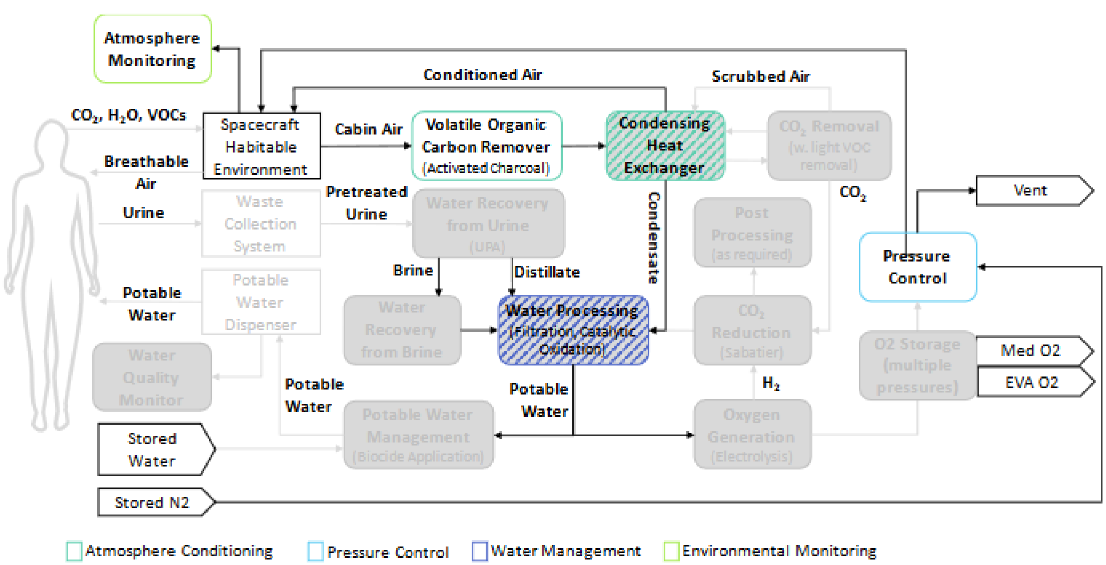


Figure 6. Dormant configuration of the ECLSS. Source: [11].

During the dormant phase, time to complete many typical tasks becomes less critical. The workload on robotic systems aboard the station is reduced during this period. Operators may find this a beneficial time execute logistics related mission to re-stock supplies for follow on crewed missions.

Transition out of dormancy is the next major phase in spacecraft operations. This phase is characterized by preparing the spacecraft for human occupancy. A livable environment is established by restarting all of the processes which were temporarily shut down during dormancy. This includes monitoring the atmosphere to ensure that the air is breathable, flushing sewage systems and ensuring operability, and that the interior space is pressurized appropriately. A failure to complete any of these, or the multitude of other tasks during this period could result in delays to missions caused by the additional time required to troubleshoot failed subsystems. During this phase robotic systems will be increasingly relied upon to carry out inspections and repairs of systems as they come back online.

Full operations follow next. Full operations are characterized by the presence of crew aboard the spacecraft conducting mission preparation and execution. During full operations, crewmembers will execute a larger proportion of inspection, maintenance, and repair tasks than in the other phases. Crewmembers will also be able to conduct troubleshooting and maintenance of robotic subsystems as well. As crewmembers prepare for missions to the lunar surface, robots will be relied on to conduct repetitive tasks and reduce crew workload requirements, assist with staging of supplies in the lunar landing module, and aid any manned EVAs that require direct human interaction. It is likely that the majority of robotic teleoperation will come from ground stations on Earth to reduce crew requirements, but crewmembers will now be able to control the station's robotic subsystems directly. This reduces the need for autonomous operations during this phase.

After the full operations are complete, the station will undergo the final planned phase of its life cycle, transition back to dormancy. This phase is characterized by both crewed and uncrewed operations. During this phase crew members will power down unnecessary subsystems as they depart the station. For the station's robotic systems, this phase will require monitoring of essential environmental systems until the crew departs and then a transition back into fully autonomous and remote operations.

In addition to the planned phases of the space station life cycle, the contingency phase refers to the execution of emergency operations. For the analysis of FFRs in support of space station operations, contingency operations are examined apart from the other phases because they will require unique timing requirements and the execution of unique tasks. Anomalies that could trigger contingency operations will have a shorter time to criticality. In these situations, the role of an FFR will be to search, detect, identify, and correct the anomaly that has triggered contingency operations. Contingencies typically rely heavily on ground control because they require the solution of an unknown or uncertain problem set. In situations where ground station control is not available or high latency makes remote operations difficult, the goal of the FFR should be to extend the time to criticality.

The Gateway phasing framework can inform the mobility requirements of FFRs because it begins to identify which types of tasks need to happen during specific periods as well as which types of tasks will be more time sensitive. For example, atmospheric anomalies during the dormant phase are less critical than those occurring during full operations. As a result, FFRs would have to respond more quickly during full operations than they would need to in the dormant phase.

FFRs will be responsible for various tasks throughout all phases of space station operations. The specific tasks, the time required to complete a task, and availability of remote operators should shape the optimal mobility strategy used for execution. Tasks can be placed into the following functional categories: maintenance, repair, inspections, assistive operations, logistics support, and contingency support. Each task can be described by the available time for completion, complexity, location (either intra or extravehicular), availability of remote operators, distances that the FFR will be required to move, stability requirements, and dexterity requirements.

C. THE CURRENT STATE OF SPACE STATION ROBOTICS

The ISS is the best analog available for analyzing and characterizing tasks an FFR may be responsible for conducting on Gateway or other deep space exploration missions. A variety of robots are actively supporting operations aboard the ISS. Most maintenance activities aboard the ISS occur within the station and robots account for the majority of extravehicular maintenance.

It was estimated in 2004 that EVR could significantly reduce crew time requirements by reducing the amount of EVA related activities by nearly 930 hours per year. It was also estimated that EVR to support preventive maintenance would double that savings. Combined, robots could save crew nearly 77 days per year [12]. This is time that could be spent doing more critical, complicated, emergent, and non-repetitive tasks.

The operations and tasks that are being executed by robotic systems aboard the ISS can provide excellent insight into tasks that external FFRs could support, the limitations of that support, and the additional design requirements that may be necessary to conduct EVR. The majority of extravehicular robotics activities and maintenance are conducted mainly by external robotic arms. The main robotic system aboard the ISS is the Mobile Servicing System (MSS). The MSS consists of the Space Station Remote Manipulator System (SSRMS), also known as Canadarm2, the Special Purpose Dexterous Manipulator (SPDM), also known as Dextre, and the Mobile Base Station (MBS). The MBS dramatically increases the Canadarm2's workspace by allowing the base of the arm to move the entire length of the ISS. The MBS weighs in at more than 1500 kg and operates in a similar way to a rail car, rolling along truss segments on the exterior of the ISS [13]. Canadarm2 and Dextre can connect to the base of the MBS allowing them to traverse the length of the ISS as well.

At 17 meters long and a mass of nearly 1500 kg, Canadarm2 is a large and very capable robot arm [14]. In addition to the mobility provided by the MBS, Canadarm2 is also capable of moving end over end in an inchworm-like motion. With a Latching End Effector (LEE) at both ends, the arm can attach the LEE to external power data grapple fixtures of the ISS and release the LEE that was serving as the old anchor. In this way, the end effector becomes the new base, and the old base becomes the new end effector.

Canadarm2 is responsible for conducting maintenance, moving supplies, moving astronauts, and executing "cosmic catches" when it latches onto and assists space vehicles conducting rendezvous with the ISS. In its first decade on the ISS, Canadarm 2 unloaded hundreds of tons of equipment and supported almost 100 spacewalks.

Dextre provides additional capability Candarm2. Dextre is a 15 DOF robot which typically operates while attached to the LEE of Canadarm2. This gives the entire system increased reach, a larger workspace, and the ability to utilize more specialized end effectors which give additional capability to the standard Candarm2's LEE. Figure X shows a typical configuration for the three subsystems of the MSS.

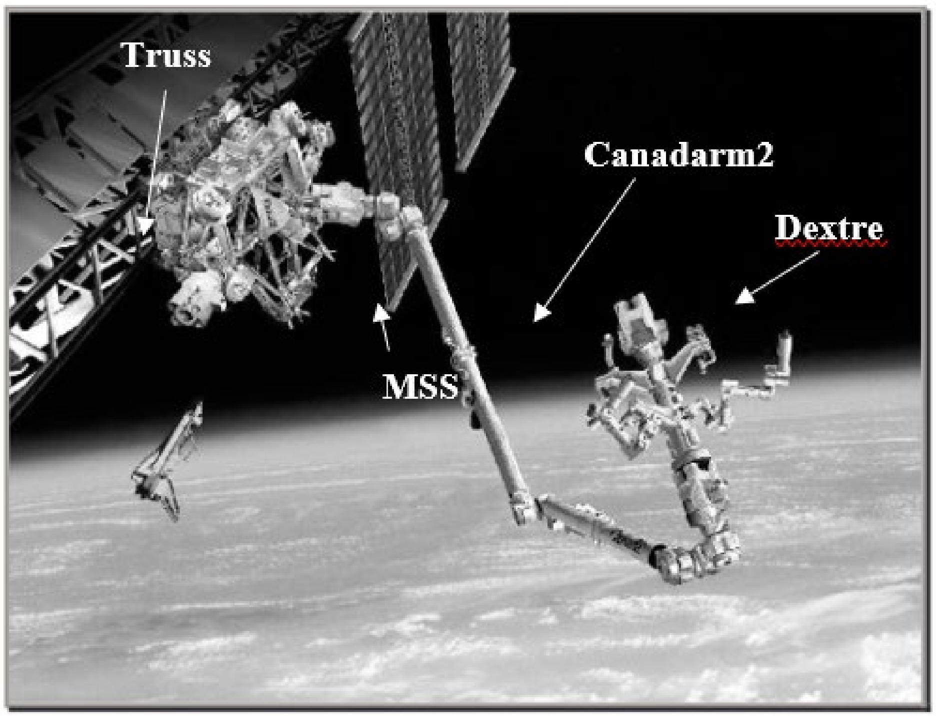


Figure 7. MSS and its subcomponents. Adapted from [12].

Much of the external maintenance on the ISS is accomplished through the removal and replacement of Orbital Repair Units (ORU). ORUs are "black boxes" on the exterior of the space station which require periodic replacement in support of maintenance. ORUs may contain components that include replacement batteries, air filters and scrubbers, sensors, or transonders. ORUs are designed with standard interfaces which make it possible for a robot like Dextre to grab, unlatch, move, and replace the units relatively simply [15].

The modular design of ORUs are so prolific to the ISS that the ELCSS alone has 29 different ORUs [16]. Spare ORUs are stored in external storage bays on the exterior of the ISS. ORU storage quantitites are prioritized according to which ORUs need to be replaced the most often and by ORU criticality.

External maintenance outside of the replacement of ORUs will often require crew support in the form of EVAs because the MSS does not have the end effector required for every possible maintenance and repair scenario. Figure 8 shows an example of a typical battery ORU which would be located on the exterior of the ISS. The dimensions of the ORU pictured is approximately 1m x 0.5m x 0.25m. ORUs can vary drastically in weight. They range in mass from about 90kg to more than 700 kg.

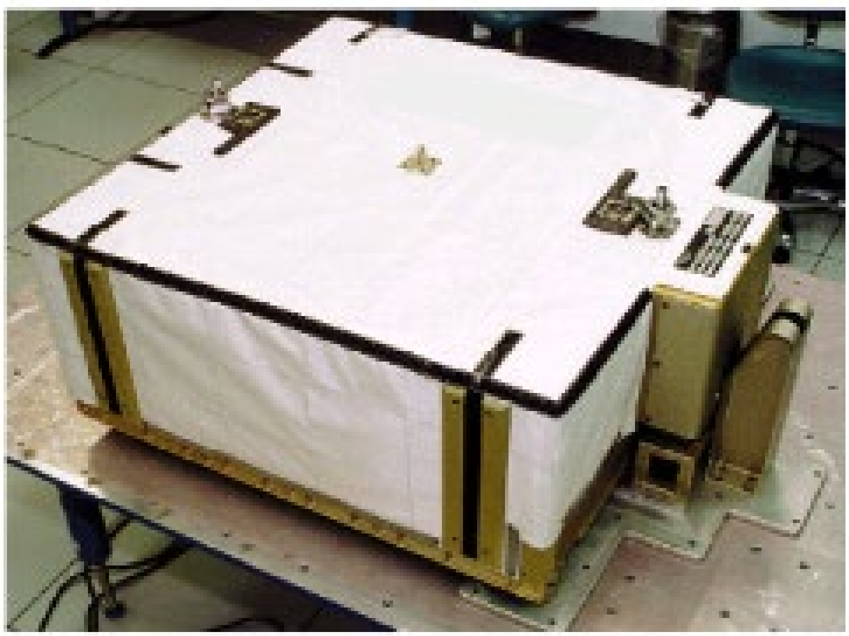


Figure 8. Battery ORU. Source: [12].

In addition to maintenance, the MSS is responsible for unloading external cargo from resupply vehicles. Cargo, which includes replacement ORUs, will be moved from the external compartment of a resupply vehicle and relocating it to an external storage location aboard the ISS. Figure 9 shows a rendering of Canadarm2 unloading cargo from a Cargo Dragon 2 during a commercial resupply mission.

Figure 9. Canadarm2 conducting external cargo offload. Source: [17].

There is also an additional robotic system attached to the Japanese Experimental Module (JEM) known as the JEM Robot Manipulator System (JEMRMS). The JEMRMS consists of two robot arms; the Main Arm (MA) and the small fine arm which each have six degrees of freedom. The main task of the JEMRMS is to exchange payloads aboard the JEM's exposed facility (EF). The EF provides a non-pressurized, exposed environment for conducting experiments. The MA has a length of 10m and a mass of 780 kg. It is capable of handling payloads up to 500 kg. The MA has a fixed base but is capable of rotating its arm about 60 millimeters per second [18]. The JEMRMS is capable of handling heavy masses quickly, but it executes a very specific set of tasks within a relatively limited workspace. It is also incapable of autonomous operation.

D. CATEGORIZING ROBOTICS ACTIVITIES

A method for categorizing and defining the range of FFR activities is necessary to the development of a comprehensive mobility strategy because mobility options will change with the specific activity. The first characteristic that should be identified is the broad location of the activity. I suggest that the activities be divided into extravehicular and intravehicular because of the drastic design differences required of a robot to operate in either environment. A robot conducting intravehicular activities will be less limited by on board propellant since it can use the space station's air to propel itself with onboard fans. An extravehicular FFR will be limited by the available propellant on board, requiring the robot to stop to refuel or replace propellant as it runs low. Intravehicular robots will require less robust thermal control systems since they operate at temperatures like those found terrestrially. Extravehicular robots will require more robust thermal control systems and must be designed to operate in an environment that does not benefit from the radiation shielding of the ISS' hull. Intravehicular robots have more options for crewmember interaction and control than extravehicular robots. IVRs can be operated directly with voice commands as well as remotely. Since EVRs don't have the benefit of the ISS' atmosphere, voice commands are not an option. Additionally, they will not be able to conduct acoustic monitoring from the exterior of the space station since there is no air for soundwaves to propagate through.

Each activity can be further defined by the complexity of the activity. I have chosen to define complexity using the following two levels: Simple and complex. Simple refers to tasks which are often repetitive and require little dexterous manipulation. In general, an FFR can complete simple tasks by using onboard sensors and moving from location to location. The simple categorization does not consider processing required to analyze and utilize collected information. Instead, it refers to the robot's interaction with the physical environment and assumes that processing will be handled by onboard or offboard computers. Simple activities include those related to mapping and simple object retrieval. Complex tasks are those that require precise positioning, extensive dexterous manipulation, or activities which are novel and require problem solving. An example of a complex task could be the replacement of an ORU since the task requires precise positioning, manipulation of tools, and differs with each type of ORU.

FFR activities will also be defined their autonomy requirements. Autonomy is defined at three different levels. Full autonomy refers to a task that the robot can complete without any human involvement in the control loop. This includes problem identification and resolution without prompting. Augmented refers to tasks that are partially automated but may still require a human in the loop. Augmented tasks are common because the robot can move from one location to another autonomously but often requires human assistance to complete a task at the new location. An example of an augmented activity would be the retrieval of a tool. A remote operator can define the FFRs goal location as a tool storage box, allow the FFR to transit autonomously, and then take over remote control to control the manipulator arm to grab the tool. The FFR could then return to its original location autonomously. Fully remote refers to activities which require a human in the loop for the duration of the activity. A fully remote activity could include ORU replacement since it will likely require a human to remotely move the FFR from an initial location to the location of the repair, require the human operator to control the FFR as it conducts the repair, and then require the human operator to control the FFR as it returns to its original position.

Criticality is the importance of a subsystem to the overall operation of the space station and time to criticality will impact how quickly on-board robotic systems need to respond to an anomaly. Critical subsystems will be prioritized for repair and maintenance activities because they have the greatest effect on overall system operability. Time to criticality refers to the amount of time that a subsystem can remain inoperable before it has cascading impacts to overall operations that may or may not be reversible. An example of a critical subsystem during full operations would be the oxygen generation subsystem. If this system becomes inoperable the crew will eventually become unable to survive. Time to criticality in this situation would depend on how much oxygen remains in the station and how quickly the crew consumes it. Time to criticality would be a few hours in this situation but could be as long as a few days depending on how many crewmembers are onboard and their consumption rates.

Table 1 provides a full breakdown of intravehicular activities which FFRs could support or are currently supporting. Each task is grouped according to activity type. For each task complexity, autonomy, criticality, and time limit to complete (TLTC) are defined.

Table 1. Intravehicular activities

Intravehicular Activities				
Task	**Complexity**	**Autonomy**	**Criticality**	**TLTC**
Preventive Maintenance/ Inspections				
Acoustic Monitoring	Complex	Fully Autonomous	None	None
Visual Inspection of door seals	Simple	Augmented	Low - Conducted 2x/yr	Months to Years
Atmospheric Monitoring	Simple	Fully Autonomous	Low to High	Hours to Days
Mapping	Simple	Augmented	None	None
Reactive Maintenance (repair)				
Air Filter Replacement	Complex	Operator Required	Low to High	Days to Weeks
Atmospheric Anomaly Correction	Simple to Complex	Augmented	High	Hours to Days
React to Depressurization Event	Complex	Augmented	High	Hours
Crew Assistance				
Inventory via RFID	Simple	Fully Autonomous	None	None
Cargo Retrieval and Stowing	Simple to Complex	Remotely Operated	None	None
Tool Retrieval	Simple	Augmented	None	None
Information Support	Simple	Fully Autonomous	None	None
Imaging Support	Simple	Fully Autonomous	None	None
Mapping Activities				
Identify Lighting Anomalies	Simple	Fully Autonomous	None	None
Obstacle and Obstruction detection	Simple	Fully Autonomous	None	None
Item Locations and Inventory Database Updates	Simple	Fully Autonomous	None	None
Identify available storage areas	Simple	Fully Autonomous	None	None
Acoustic Mapping and anomaly Detection	Simple	Fully Autonomous Detection Augmented Response to Anomalies	None	None

Table 2. Extravehicular robot activities

Extravehicular Activities				
Task	**Complexity**	**Autonomy**	**Criticality**	**TLTC**
Preventive Maintenance/ Inspections				
Routine Hull Inspection	Moderate	Augmented	High	
Hull Repair	Complex	Fully Remote	High	Minutes to Weeks
ORU Replacement	Complex	Augmented	Low to High	Hours to Days
Support to Manned EVA				
Workspace Imaging and Inspection in Preparation For EVA	Simple	Augmented	Low	Hours
Replacement Part Retrieval	Simple	Augmented	Low	None
Augmented Lighting	Simple	Autonomous	Low	Hours
Astronaut Imaging	Simple	Augmented	Low	Hours
Tool Retrieval	Simple	Autonomous	Low	Minutes to Hours
Support to Rendezvous, Proximity Operations, and Docking				
Spacecraft Docking Assistance (“Cosmic Capture”)	Complex	Fully Remote	Low	None
Docking Imagery and Video Support	Simple	Autonomous	Low	None
Cargo or Experimental Sample Retrieval or From Resupply Spacecraft While Docked	Moderate	Augmented	Low	None
Cargo or Experimental Sample Retrieval or From Resupply Spacecraft Without Docking	Complex	Fully Remote	Low	None
External Situational Awareness				
Environmental Sensing	Simple	Autonomous	Low	None
Object Detection Using Camera	Simple	Augmented	Low to High	Minutes to Days

Robotic activities which require movement from the interior to exterior of a space station have not been considered because of the complex engineering and design requirements for a dual environment FFR and the currently limited number of tasks that may require the capability. An extravehicular FFR will require a more robust thermal control subsystem, radiation shielding, propellant storage, and cold gas thrusters. Adding these capabilities to an intravehicular FFR would make it too large, complex, and impractical for regular intravehicular use. Although there is potential that a dual-environment FFR could retrieve externally mounted cargo to store inside a space station, current cargo delivery systems have been engineered so that extravehicular cargo is environmentally segregated aboard the delivery craft and never requires movement from the outside of the resupply craft to the inside of the space station. Intravehicular cargo is delivered from within the pressurized portion of the resupply craft to the space station through the airlock. Extravehicular cargo is removed from unpressurized external storage spaces and transported directly to external space station storage locations.

III. PREVIOUS WORK

Space robots can use a variety of locomotion methods and controls to increase their available workspace, conduct tasks, and respond to critical space station anomalies. Many methods of locomotion exist at varying technology readiness levels (TRLs). Extensive research and demonstration of locomotion using thrusters has been demonstrated on-orbit, as shown by Astrobee and a variety of other FFRs. Some thrusterless methods of locomotion are being actively used on orbit, such as those employed by Canadarm2 [13]. Other methods have only been demonstrated on free floating spacecraft simulators. Finally, some methods are still only conceptual. Research into individual robotic designs and specific methods of locomotion is extensive. Research into combined methods of locomotion and robot designs which employ multiple methods of locomotion is limited. Overarching strategies which consider locomotion for the whole of tasks that space station robots may conduct are nonexistent.

Naval Postgraduate Schools Spacecraft Robotics Laboratory (SRL) is responsible for much of the research done towards thrusterless locomotion of FFRs. In 2017, Andrew Bradstreet demonstrated a thrusterless, planar, self-toss maneuver using a robot with two manipulators [19]. Bradstreet's maneuver used the robot's two manipulators to push itself off one handrail, coast, and then grab another handrail. His experimentation would lay the groundwork for further SRL research into self-tossing maneuvers using Astrobees, as part of the Astrobatics program.

Alsup first suggested the use of Astrobee's perching arm to conduct a thrusterless self-toss maneuver from one hand railing to another [20]. Figure 10 is a diagram showing how the proposed maneuver would be conducted. Safbom demonstrated the self-toss maneuver on the SRL's and NASA Ames' free floating space simulators [21].

Initial research conducted by Safbom utilized a fixed handrail to demonstrate a hopping maneuver. This research was taken a step further by Watanabe et al. [22] when they demonstrated a hopping maneuver between two Astrobees while holding a free floating handrail. This laid the foundations for a more complex, propellantless maneuver strategy where an FFR could jump from both fixed objects as well as other free-floating objects of similar mass. Kwok-Choon et al. [23] suggest employing Watanabe's maneuver to save propellant during the conduct intersatellite servicing.

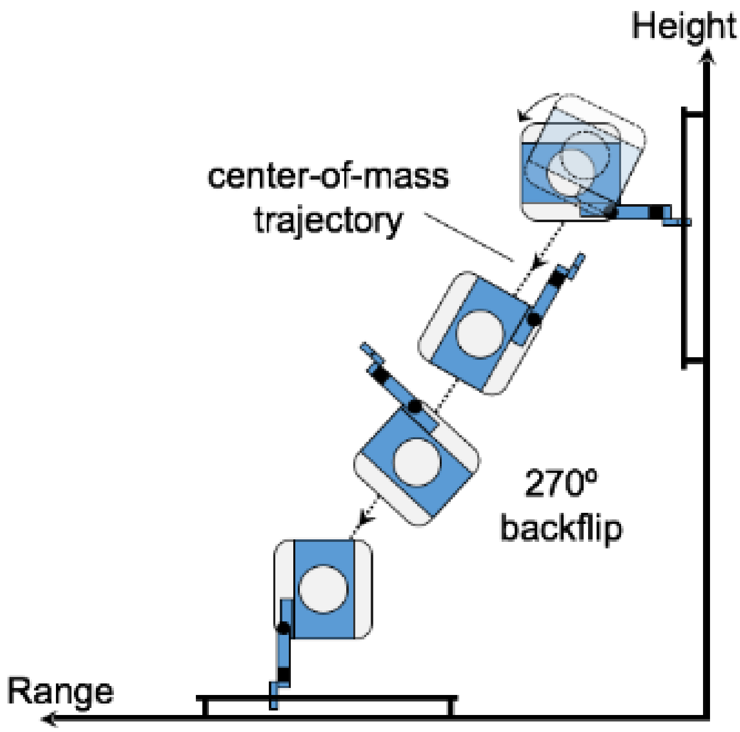


Figure 10. Schematic of Astrobee self-toss maneuver. Source: [20].

There is limited literature on the distinct types, advantages, and disadvantages of different controllers implemented on FFRs. This is due to so few FFRs being in orbit. Most of the controller modeling, implementation, and testing has been conducted toward rendezvous and proximity operations of satellite servicing robots. This research, although seminal to the area of in-orbit satellite servicing, has limited specific applicability to FFRs operating on board space stations. In general the problem of rendezvous is complicated and requires extensive consideration of additional factors such as the independent orbits of a target and chaser satellite [24].

IV. LOCOMOTION METHODS AND STRATEGY

A variety of locomotion methods are available to choose from when designing a space robot. In general, these methods can be categorized as thrusterless or propulsive maneuvers. Thrusterless methods include self-toss maneuvers, push-fly-park maneuvers, zero-gravity climbing, and tether-based locomotion. Each of these methods will be examined in greater detail in Section B. Propulsive maneuvers require the use of an onboard thruster to move the robot. In the context of FFRs, thrusters will employ a cold-gas thruster design which requires propellant, or a fan driven thruster which takes advantage of a space station's internal atmosphere to propel itself. AERcam and SPHERES both utilized cold-gas thrusters [1], [3]. Astrobee and Int-Ball are examples of FFRs which use propellantless, fan-driven propulsion [6], [5].

A. CHALLENGES TO LOCOMOTION

Locomotion aboard and in vicinity of space stations presents a variety of challenges. Intravehicular and Extravehicular locomotion also present a variety of different advantages and challenges due to their drastically different operating environments.

Intravehicular locomotion can take advantage of the air present inside the space station to move a robot using impeller and electric fan driven thrusters. This also means that FFRs are subject to disturbances caused by the movement of air within the space station. It is likely that they will need to be able to react to unexpected disturbances such as air drafts. The internal environment is maintained at a consistent temperature and more shielded from radiation than externally. This means that Intravehicular FFRs do not require extensive radiation shielding or thermal regulation. An Intravehicular FFR has a higher error tolerance since it can push directly off a bulkhead without inadvertently flying off into space. Intravehicular FFRs can also take advantage of the various handrails positioned throughout the ISS to allow astronauts themselves to move around or hold themselves in place while working.

The ISS has 388 cubic meters of habitable volume, as much as a Boeing 747. For comparison, it has the same internal size as a 6-bedroom house [25]. That is a massive amount of area for an FFR to cover. Furthermore, intravehicular locomotion is complicated by the presence of clutter around the space station. This clutter is often intended since there is little space for storage and many of the internal components of the ISS are exposed in the interior. Examples of clutter include internal wiring, unstowed cargo, or potentially astronauts themselves. Figure 11 shows an internal view of the JEM, where on-orbit Astrobee experimentation is conducted. The figure shows an area cluttered with wires, computers, cameras, and experimentation equipment. The figure also shows an internal handrail and foot clasps which are used to hold astronauts in place while they conduct experiments in the JEM.

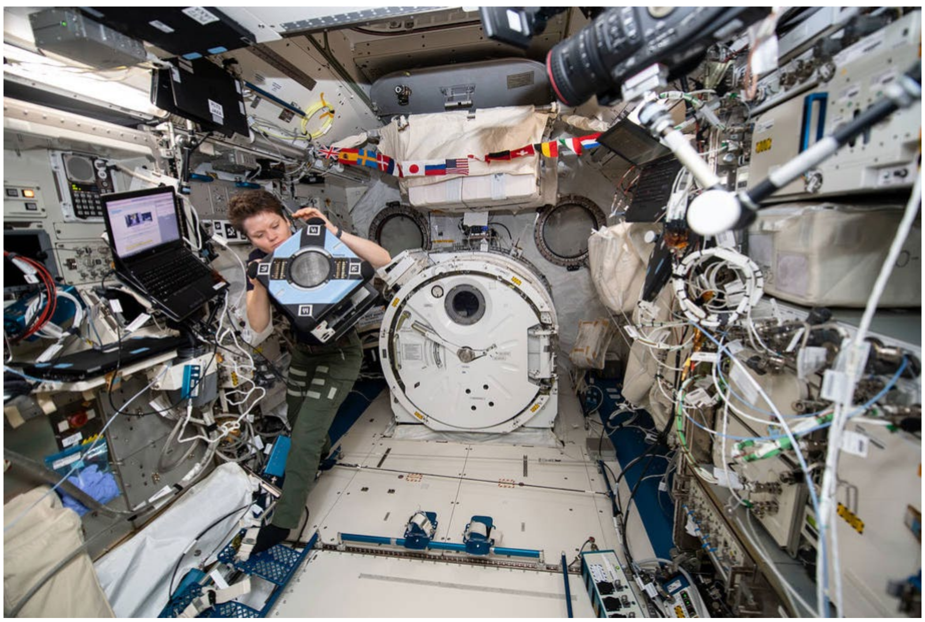


Figure 11. Internal JEM environment. Source: [26]

The extravehicular environment of the ISS presents vastly different challenges. Since there is no radiation shielding or thermal protection, an extravehicular FFR must be designed with a robust capability to manage both. There are a variety of sensitive external structures such as solar arrays which are prone to damage and require an FFR to have the ability to maneuver around without causing damage. In total, the ISS has 8 solar arrays which are 73 meters long if laid side by side [25]. At 109 meters end to end, the space station is almost as long as a football field. This is a huge amount of area to traverse. Figure

12 shows a map of the ISS and its various modules. It is apparent that an FFR would need to be able to avoid and navigate a variety of complex structures to move from one end to another.

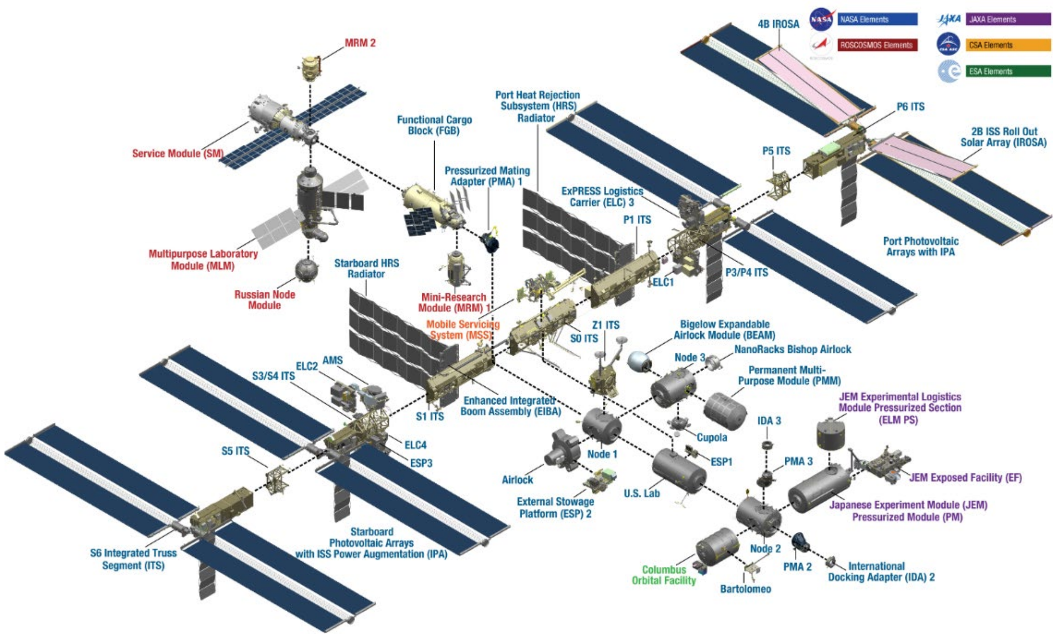


Figure 12. Map of ISS and its various modules. Source: [27].

Extravehicular movement is further complicated due to weightlessness experienced in orbit. There is usually no net force exerting a normal force between an extravehicular robot and the space station itself. On Earth, we rely on that normal force to create friction between our feet and the ground when we walk. The same motion on the exterior of the space station would send us flying off into space, instead of in our intended direction of travel. To compensate for this, Astronauts conducting EVAs must grip and move along handrails in a climbing motion or they must use portable foot restraints to hold themselves in contact with the space station while working [28]. This creates further challenges because climbing based locomotion will be limited to paths which have handrails. Figure 13 shows an example of a designed primary EVA translation pathway [28]. It provides handrails and tether points so that Astronauts can maintain constant attachment to the space station as they move around its exterior.

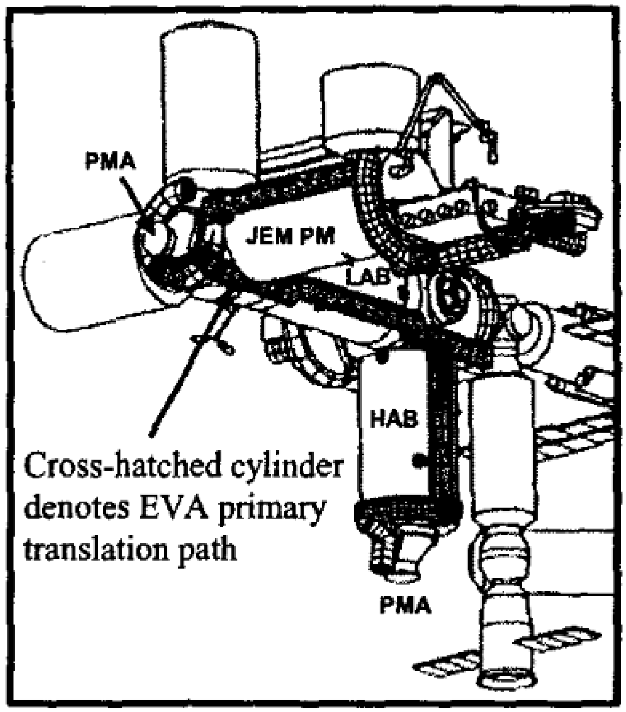


Figure 13. Primary EVA translation path. Source: [28].

The ISS has three types of external mobility areas. For reference, Figure 14 shows the exterior of the ISS with its overlaid coordinate system.

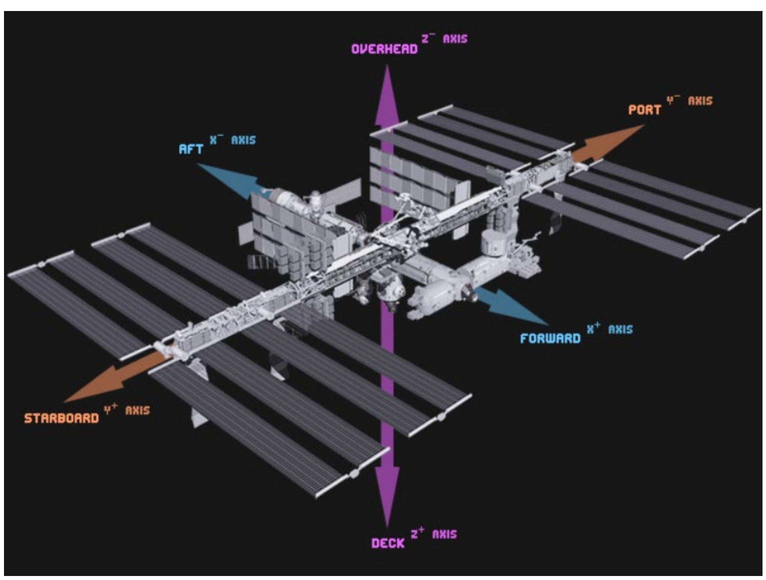
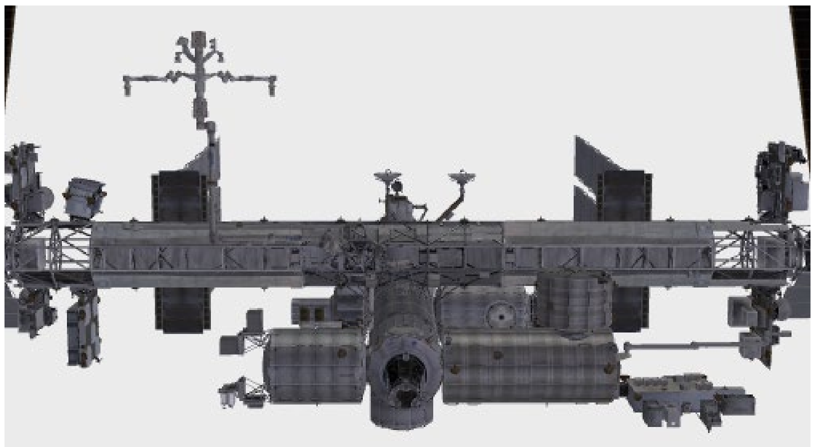


Figure 14. Coordinate system of the ISS. Source: [29].

The first area is the primary truss structure. The forward side of this truss structure has a rail system which allows the MBS to roll in a linear fashion between the port and starboard portions. Figure 15 shows the location of the primary truss at the center of the ISS.



This rendering also shows the SSRMS with Dextre attached.

Figure 15. View of main truss from the forward direction. Source: [30].

The aft section has a less uniform truss structure, solar arrays on either side, and various antenna. Most of the space station's ORU's are located on the port and starboard ends of the main truss structure. Figure 16 shows the ISS as viewed from the aft. Solar panels, ORU's, antennas, and Dextre are visible in the rendering.

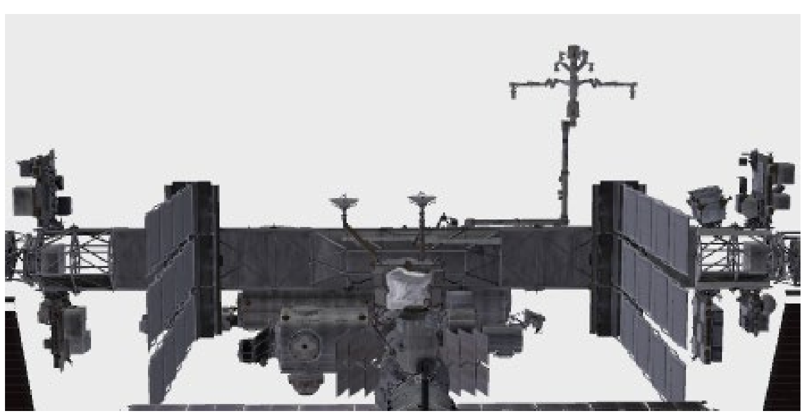


Figure 16. View of main truss from aft direction. Source: [30].

The second maneuver area is the port and starboard flanks of the main truss. This area is where the largest solar panels on ISS are located. The area lacks the uniform truss structure of the central truss and freedom of maneuver around the section is limited by the large solar panels. Figure 17 shows the large solar panel array located on the port side of the ISS.

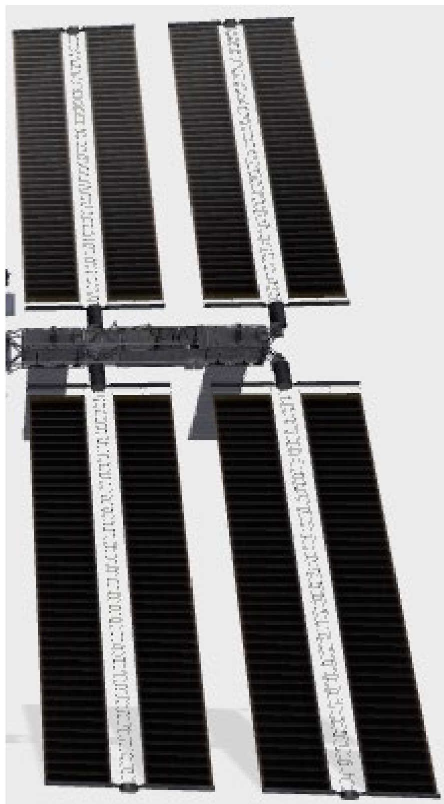


Figure 17. The port section of the second maneuver area viewed from the forward direction. Source: [30].

The third area is the pressurized modules where the astronauts live. The exterior of these modules has handrails that enable exterior movement as shown in Figure 18.

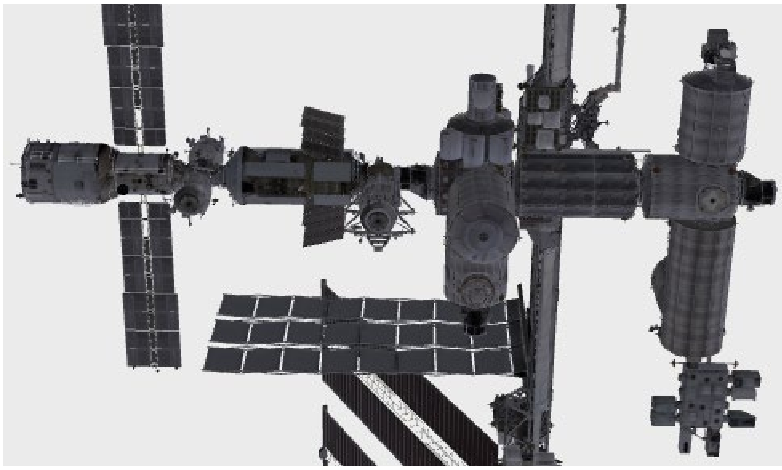


Figure 18. ISS main modules viewed from the deck direction. Source: [30].

An additional challenge to external locomotion for FFRs is the location of charging ports. With limited access to charging ports, an external FFR will be charge-limited as to how long it can remain at a worksite before it needs to return to a charging station.

A final challenge for FFR is the inherently complicated and unknown center of mass and inertia caused by moving an object of unknown weight, rigidity, and with loose linkages. This problem is compounded by the negligible friction and weight an FFR experiences while moving about a space station. In a situation where an FFR is grasping and moving an object with an unknown center of mass the entire center of mass of the system becomes unknown. In a frictionless and weightless environment, small disturbances caused by an unknown center of mass can challenge the ability of a controller to maneuver the robot. The disturbances can force the FFR to compensate by repeatedly firing its thrusters alternately in opposite directions, leading to inefficiencies in propellant usage. A great enough disturbance can even prevent an FFR from reaching a goal location or pose altogether.

B. THRUSTERLESS LOCOMOTION

Thrusterless locomotion methods are all the methods of locomotion which could be employed on a space station which do not require the use of a thruster. Each method has its own advantages and disadvantages, and some will require extensive redesign for implementation on an FFR. Astrobees have been used to demonstrate the use of thrusterless locomotion on orbit by utilizing the Astrobee's perching arm to conduct a "self-toss" maneuver [22]. As demonstrated, FFRs can take advantage of their own manipulators to use thrusterless locomotion. Future FFR designs could be purpose built with thrusterless locomotion capabilities.

1. Zero Gravity Climbing

Zero-gravity climbing is the first thrusterless method that will be examined. Zero-gravity climbing is the use of two manipulators to move from one fixed point to the next. Zero-gravity climbing is similar to how a human moves hand over hand as they climb a ladder, but it can be conducted in any direction. Also, since gravity on earth provides a normal force that allows us to move from one anchor point to the next, such as when we walk, zero-gravity climbing requires some other way to maintain force on each anchor point. This force can come from using an end effector to grip a hand railing, from gecko inspired designs which allow a robot to cling to a surface [31], or from other novel adhesion methods. When astronauts conduct space walks aboard the ISS, they will often move hand over hand from one hand railing to the next. This form of zero-gravity climbing is effective because the astronaut can maintain constant contact with the space station and does not risk pushing themselves off into space with no way to get back to a work site.

Space Station robots can use a similar method for climbing. Chung and Xu present two possible gaits that could be employed by a proposed truss climbing robot [32]. The mechanics of the inchworm gait are shown in Figure 19. and the turnaround gait is shown in Figure 20. Canadarm 2 currently utilizes the turnaround gait to move along the exterior of the ISS.

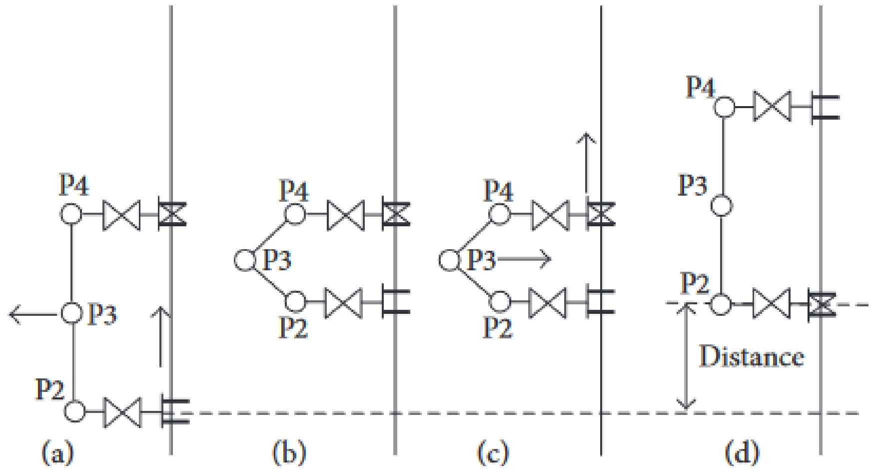


Figure 19. The inchworm gait. Source [32].

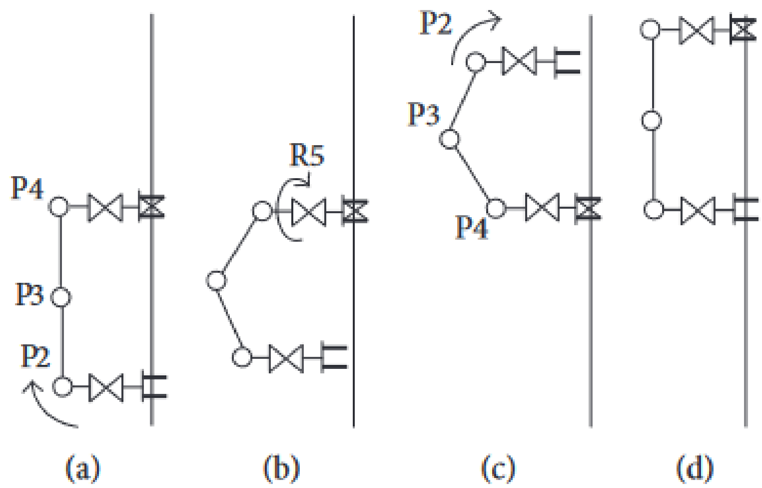


Figure 20. The turnaround gait. Source: [32].

A few novel bio-inspired robots have been proposed. Wang et al. proposed a climbing robot named "Monkey Bot" with four limbs [33]. Monkey Bot would utilize modified locomotion methods which are like what Chung and Xu propose but the extra limbs enable Monkey Bot to conduct tasks, such as debris removal, while maintaining contact with hand railings.

Rehnmark et al. proposes an arachnid inspired climbing robot which may be suitable for climbing across large sensitive structures such as solar panels. Figure 21 shows a concept of what such a robot would look like as it moves different solar panel elements in to place [34]. Rehnmark's arachnid inspired design maintains contact by conducting inward pressure with the robot's legs. Although it has been proposed that it could be used for traversing solar panels it is important to note that the robot is not walking directly on top of the solar arrays. Instead, the robot would need to be specifically designed to operate on solar panels within a certain range of widths and they cannot be mounted flush with the overall array.

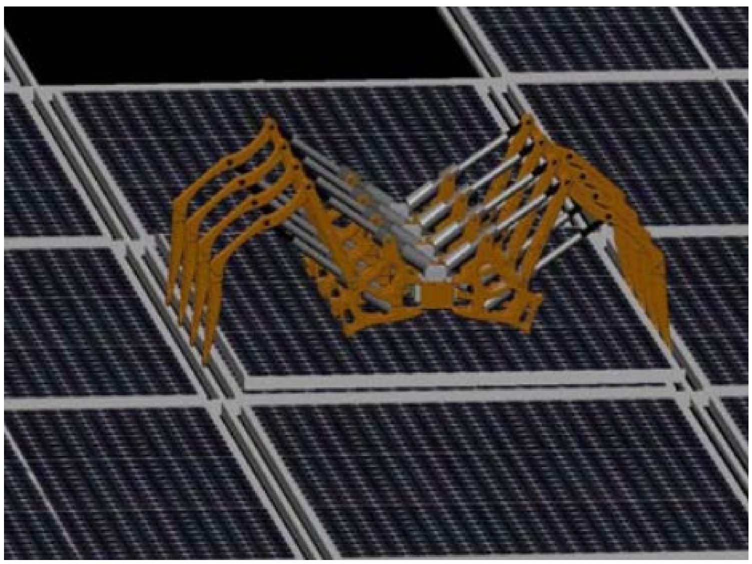


Figure 21. Conceptual arachnid robot moving across a solar array. Source: [34].

After Canadarm2, Robonaut 2 is the most technologically mature system that is using and experimenting with zero gravity climbing aboard the ISS. Robonaut 2 is a humanoid robot that can use its elongated legs to grasp and walk along hand railings on the interior of the ISS. While it has not demonstrated the ability to do so in-orbit, Robonaut 2 has maneuvered on the ground using both teleoperation and semi-autonomous control [35]. Notably, Robonaut 2's demonstrated movements are slow when compared to movement speeds of Astrobees. Badger et al. are working on NASA's Robonaut 2 project and have stated that precision tasks, such as holding on to a handrail, are difficult and time consuming for operators and that autonomous solutions need to be developed to create this capability [36]. Badger et al. also simulated Robonaut 2's movement on the ISS and encountered difficulties due to the cluttered and constrained environment inside the space station.

a. Advantages

Zero-gravity climbing can provide various advantages and suffer from disadvantages when compared to other methods of locomotion. Zero gravity climbing is advantageous because it can allow for precision movement as the robot moves from one anchor point to the next. Zero-gravity climbing is suited to situations where a robot is operating near fixed anchor points, will remain for an extended period, and will need to move heavy objects or conduct manipulations which require high torque. Zero gravity climbing is also advantageous because the anchor point created with the space station should enable the robot to grasp and move large loads when compared to a robot that is not anchored. The anchoring required for zero-gravity climbing requires low energy in comparison to a propulsive method. A robot on the exterior of the ISS could remain anchored with almost no energy expended whereas a propulsive robot would need to conduct constant station keeping maneuvers to remain in place. This ability to remain in place is advantageous for mapping work as well as tasks which will require the robot to remain for prolonged periods within a relatively small workspace. Finally, zero-gravity climbing has the potential to allow robots to maneuver on large fragile structures such as solar arrays while reducing the possibility of damage to those structures caused by a collision.

b. Disadvantages

Zero-gravity climbing has a set of disadvantages. It requires anchor points, so a robot must use some type of novel adhesion such as a gecko gripper, or the space station must be designed with a series of handrails along primary EVA pathways that allow the robot to move along. Many of these primary pathways are present on the main habitation modules of the ISS. Trusses on the ISS can fill a similar role as these primary pathways.

The need for pathways limits the workspace of the zero-gravity robot to those spaces nearest to anchor points.

Interior movement can be difficult due to the cluttered environment of the space station, making it difficult for the robot to avoid obstacles within its intended path. Finally, autonomous movement control of zero-gravity climbing robots is immature and has not been demonstrated in-orbit. This means that a human in the loop will be required to control the robot's movement until the technology is more mature.

2. Push-Fly-Park Locomotion

Push-Fly-Park (PFP) locomotion is a group of locomotion methods which involves the use of a mechanical actuator to push a robot off a wall or another object, coast through open space, and then grab a far handrail or wall, ceasing the movement and allowing the robot to dock. During the execution of this method of locomotion there are three phases. The first phase is the push phase. The second is the fly phase. And the final is the park phase. Zhang et al. utilize the PFP method of locomotion in the design of their humanoid space robot, Taikobot [37]. Figure 22 shows a simulation of the Taikobot conducting a PFP maneuver to move across the interior volume of a space station.

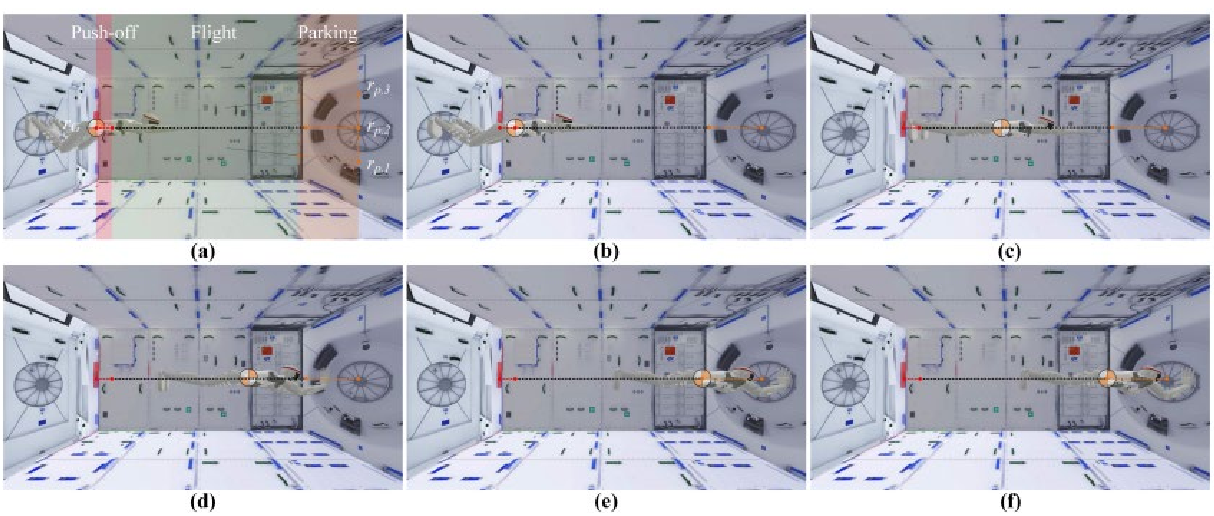


Figure 22. Simulation of Taikobot PFP maneuver. Source: [37].

As discussed in Chapter III, the NPS Astrobatics team used a variation of a PFP maneuver to move Astrobee. The SRL's Astrobee maneuver requires the same three phases of maneuver as Taikobot. The major difference between the maneuver demonstrated by Astrobatics and the Taikobot maneuver is that Astrobatics was able to execute an angled trajectory, which also imparted a rotation on the robot. The Taikobot team has only successfully simulated a perpendicular trajectory which does not impart a rotation.

Researchers have also examined the use of hopping mechanisms for the exploration of planets, moons, and other small celestial bodies. In 1967 Seifert proposed the use of a pogo-stick type hopping mechanism for locomotion on the lunar surface [38]. This type of mechanism relies on a piston-like actuator to impart force through the center of mass of the robot, allowing it to hop without imparting excessive rotational velocity to the system. Fiorni et al. used this same concept in their own hopping robot for planetary exploration [39]. It uses a piston actuator partly enclosed in a sphere to move. Figure 23 shows the actuator system enclosed in the robot body, with the spring actuator protruding from the bottom.

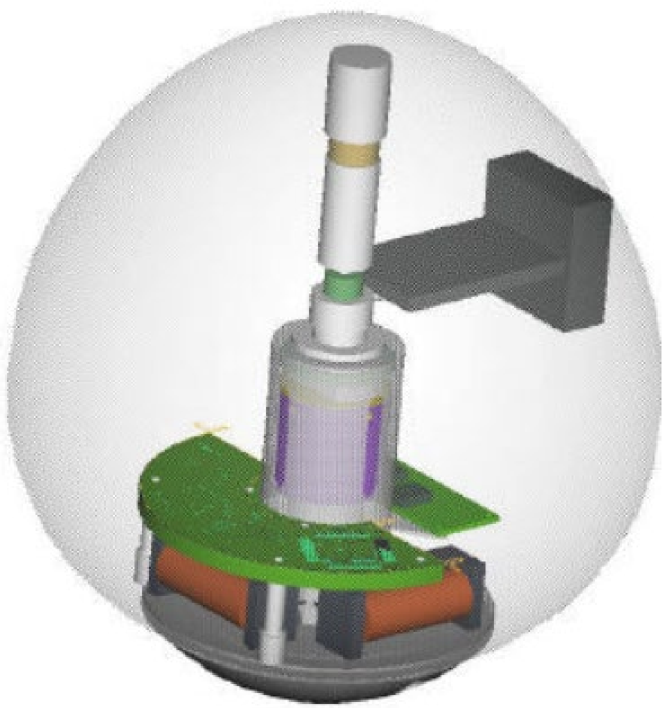


Figure 23. CAD rendering of Fiorini's hopping robot. Source: [39]

JAXA developed and deployed two small hopping robots, MINERVA II-A and MINERVA II-B, to the asteroid Ryguyu in September 2018. They used hopping locomotion to autonomously explore the asteroids surface for 10 days before their batteries failed [40]. The robots moved by using internal torquer mechanisms to create a reaction force against the surface to cause the robot to hop. Figure 24 shows a prototype conducting a torquer driven hopping maneuver [41].

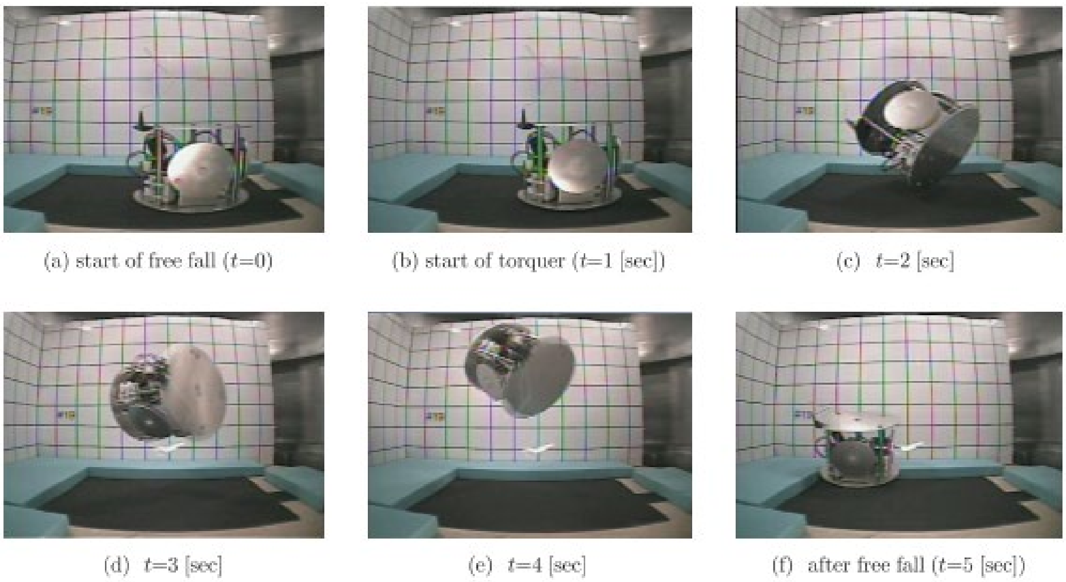
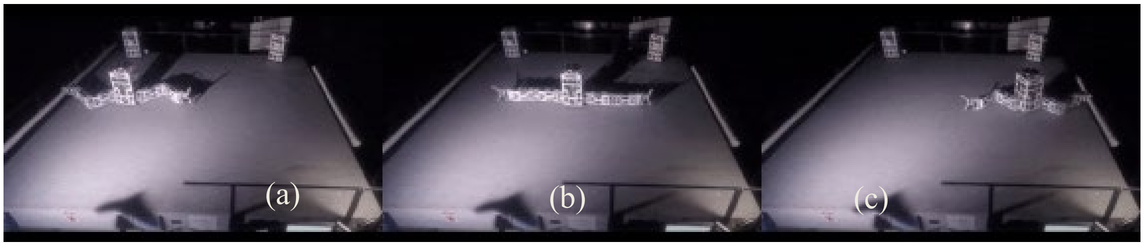


Figure 24. Robot Torquer hopping experiment. Source: [41]

Bradstreet et al. also demonstrated a planar hopping maneuver during ground-based experimentation, using a robot's manipulators to conduct a push fly park maneuver. Figure 19 shows Bradstreet's Manisat conducting the maneuver in the Naval Postgraduate School's Proximity Operation of Spacecraft: Experimental Hardware-In-the-Loop Dynamic Simulator (POSEIDYN) [19].



(a) shows the push phase. (b) shows the fly phase. (c) shows the park phase

Figure 25. Manisat push-fly-park maneuver on POSEIDYN. Adapted from [19].

Bradstreet’s design was advantageous because it would allow a robot to utilize its manipulators for dual uses, task completion and locomotion. This type of design reduces the need to design a robot with a standalone PFP maneuver device, such as Fiorni’s piston mechanism, to execute PFP locomotion.

a. Advantages

PFP maneuvers are advantageous because they potentially require little to no design alteration to conduct. A humanoid robot, like Taikobot for instance, can use the same manipulators to execute tasks and to conduct a PFP maneuver. Astrobee has likewise demonstrated the capability on orbit. PFP maneuvers are also advantageous because they require no propellant.

b. Disadvantages

PFP maneuvers require a fixed, and well characterized platform to push from. In the case of Astrobee, a handrail is required to conduct a PFP maneuver from. PFP maneuvers can be complicated by the presence of system components within a space station such as cargo bags, wires, or computer screens. If these are present it will be difficult for the robot to use them as a platform to push from.

PFP maneuvers also require a suitable fixture to conduct a parking maneuver, such as a handrail. The robot must be able to grasp the area and slowly reduce the translational and rotational movements imparted by the push portion of the PFP maneuver.

PFP maneuvers can also impart an uncontrolled rotation on the robot which must be arrested during the park phase by either a parking maneuver or with thrusters or reaction wheels.

Finally, PFP maneuvers can only be used to conduct linear translation. Multiple PFP maneuvers would be required for a robot to maneuver around an object or around a corner on a space station. Each of those maneuvers in turn requires a stable pushing platform.

3. Tether-Based Locomotion

Tether-based locomotion relies on the use of tethers to move a robot. Using multiple tethers, a robot can variably wind and unwind different tethers to change the relative lengths and tension between anchor points, allowing the robot to move. Tethers are an advantageous method of locomotion because they have long reach, are light and compact when wound up, and can support repeated movements between anchor points. Figure 26 shows the tether-based locomotion concept with an example of a robot utilizing a three-tether system. The robot's movable area is restricted to the plane between the anchor points, although out of plane movement is possible by reducing tether tension.

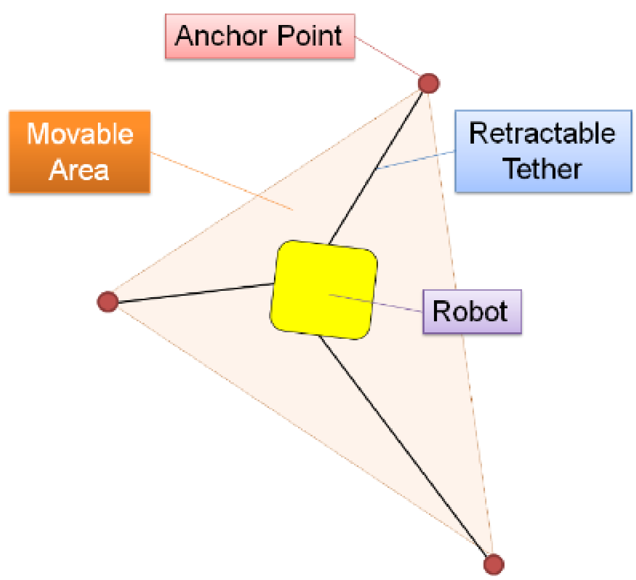


Figure 26. Tether-based locomotion concept. Source: [42].

Nakanishi et al. demonstrated tether-based locomotion on the ISS in 2013. Nakanishi's robot utilized an extendable arm to reconfigure its tethers, allowing it to change its movable area and making it suitable for use on large solar power structures. Figure 27 shows Nakanishi et al.'s concept.

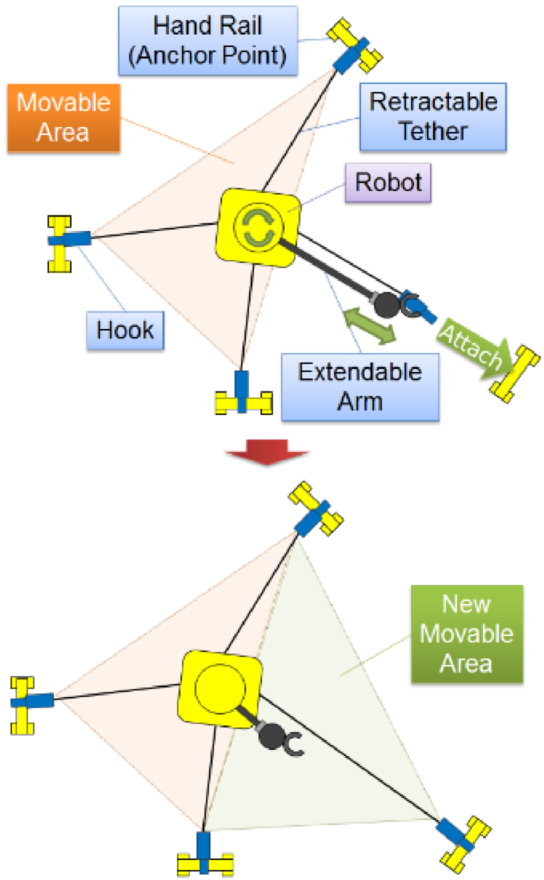


Figure 27. Self-reconfigurable tether-based locomotion concept. Source: [42].

Nakanishi et al. successfully showcased locomotion with positional accuracy within just a few millimeters from the intended target. Consequently, tether-based locomotion is well-suited for repetitive tasks that take place within a movable area and necessitate precision.

a. Advantages

Tether-based motion's greatest advantage is the precision and accuracy of its movements. It is well suited for tasks requiring repeated, precise trips within a defined area. The reconfigurable tether demonstrated by Nakanishi et al. will also allow a tether-based robot to utilize multiple anchor points with many different configurations to expand the robot's maneuver range. When used with a minimum of two anchor points, tether-based locomotion is also advantageous because it can be used to arrest the motion of the robot quickly. This is especially useful when transporting large cargo that will have high inertia when moved.

b. Disadvantages

Tether-based locomotion is disadvantageous because it is less flexible than other types of motion. This locomotion method also requires suitable anchor points, which may or not be available. Tether-based locomotion requires specific design changes for the robot. The robot must have a series of reels and tethers attached to it in order to actually use this method of locomotion. Tethers could also hinder the movement of other astronauts or external robotic arms.

V. PROPULSIVE LOCOMOTION EXPERIMENTATION WITH ASTROBEE

As part of the Astrobatics experiment campaign, the spacecraft research laboratory sought to compare the performance of tube based robust model predictive control (TRMPC) with standard model predictive control for a cargo retrieval task. Astrobatics experiment session 4 (S4) was designated to assess the experimental goals. As part of the Astrobatics S4 experiment, collaborators from New Mexico State University (NMSU) which included Dr. Hyeongjun Park, PhD candidate Isuru Basnayake, and M.S. candidate John Martinez designed and implemented the TRMPC controller on Astrobee. Astrobatics S4 would include Gazebo simulations of the TRMPC controller, ground testing at the NASA Ames Research Center's (ARC) Granite Lab, and a final test aboard the International Space Station in low earth orbit.

NMSU generated the TRMPC controller by using MATLAB and then converted the controller to C++ for integration with Astrobee. The goal of ground testing was to ensure proper functioning and implementation of the TRMPC controller, validate the experimental setup of a two Astrobee system, and to demonstrate the advantages of TRMPC for cargo movement in a planar environment. The goal of testing on board the ISS was to validate our experimental setup in a zero-gravity environment, demonstrate translational and rotational movement of a two Astrobee system, and to demonstrate the advantages of TRMPC over SMPC for cargo movement tasks in a three-dimensional, zero gravity environment.

A. ABOUT ASTROBEE

The Astrobee was designed to support guest research objectives in various areas. Three of the robots are available for experimentation onboard the ISS and can be used to accomplish research into the following subjects: motion control, advanced propulsion and mobility hardware, robotic manipulation, satellite inspection and rendezvous, and human-robot interaction. In support of those goals, the Astrobee design is modular and includes three different bays for payload integration. The robot also has six cameras, a two degree of freedom arm with gripper, and a propulsion system consisting of an impeller and 12 vent fans [6].

1. Astrobee Software

The Astrobee has three processors. A High-Level Processor (HLP), a Mid-Level Processor (MLP), and a Low-Level Processor (LLP). The HLP operates on an Android operating system and is dedicated to the use of guest science. The HLP enables ground station control of the Astrobee through the use of ROS messages, human-robot interaction through the onboard microphone and speaker, and payload communication [6].

Astrobee's MLP and LLP operate using Ubuntu 16.04 with ROS Kinetic. Astrobee Flight Software (AFS) is encoded with C++ and contains various ROS nodes for functionality. The AFS runs on both the MLP and LLP. Processes on the LLP are mainly related to hardware functionality [43].

The Ground Data System (GDS) is the interface through which users can control Astrobee from a ground station. Using the Data Distribution Service (DDS), commands are sent through the ISS to Astrobee. Once received by the Astrobee, DDS commands are converted to ROS commands by Astrobee's onboard processor [43].

Astrobee's flight software relies on coordinate systems based on two worlds. The first world uses the coordinate system of the NASA Ames Granite Lab. The second world uses the coordinate system of the ISS [43]. It is important to note that the coordinate systems of both worlds are different, and as such implementation of a controller in the Granite Lab may not correlate exactly with movement aboard the ISS.

2. Simulating Astrobee

The AFS has been designed for use with the Gazebo simulator. Gazebo provides physics and visualization and works closely with ROS. NASA has made the ISS world available for simulation using in Gazebo. Guest scientists can use NASA's Gazebo simulation to spawn different Astrobees, command them, and test implementation of new software in a simulated environment.

B. GROUND EXPERIMENTATION

This section identifies the characteristics of the ground testing facilities and the experimentation plan for the ground testing portion of the thesis.

1. Facilities

The NASA ARC Granite Lab is a facility which is designed to simulate the same low friction and low gravity that systems experience aboard the ISS. The Granite Lab consists of four main components: The granite table, an ISS mockup, Astrobees on air bearing carriages, and associated ground control systems. Although it serves as an excellent test bed, the granite lab has a few main drawbacks when compared to actual on-orbit testing. Motion on the granite table is limited to a planar surface unlike the three-dimensional environment on orbit. Second, the use of air bearing carriages nearly triples the weight of the Astrobee system and makes it difficult to replicate the exact mass and inertia of any systems which will be used on-orbit.

The Granite Lab's granite table is a 2 meter by 2 meter, smoothly polished granite surface [21]. The granite table provides a small surface over which air bearing carriages can ride, nearly eliminating surface friction. The granite table is enclosed by walls on 3 sides. The walls are paneled so that they visually match portions of the JEM on the ISS. The 3 walls allow the Astrobee to use its Navigation Camera (NavCam) to conduct localization in the same manner it would aboard the ISS. The ARC Granite Lab uses replica Astrobees mounted atop air bearing carriages. The Astrobees operate in the same way as those aboard the ISS. They are mounted atop a carriage which uses replaceable, pressurized, carbon-dioxide canisters with air bearings to create nearly frictionless contact with the granite table. The final component of the ARC Granite Lab is the ground stations used to command Astrobees. The Granite Lab uses the same GDS as Astrobees aboard the ISS for commanding and receiving telemetry data. Experimental data for test sessions is downloaded by the ARC Granite Lab operator and posted to NASA's Confluence web page for access and parsing by experimenters. Figure 28 shows the Granite Lab with two Astrobees on air carriages. Figure 29 shows the Coordinate axes for the Ames Granite Lab.

It is notable that the origin of the granite lab coordinate system does not coincide with the origin of the coordinate system on the ISS.

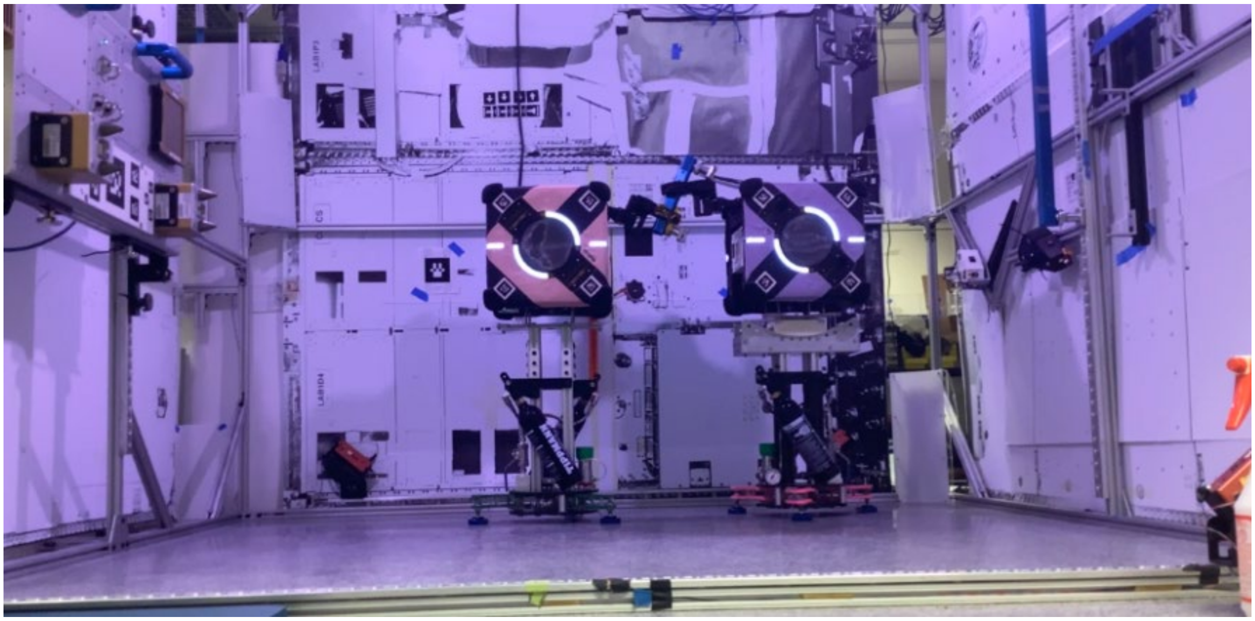


Figure 28. Granite lab with Astrobee simulators

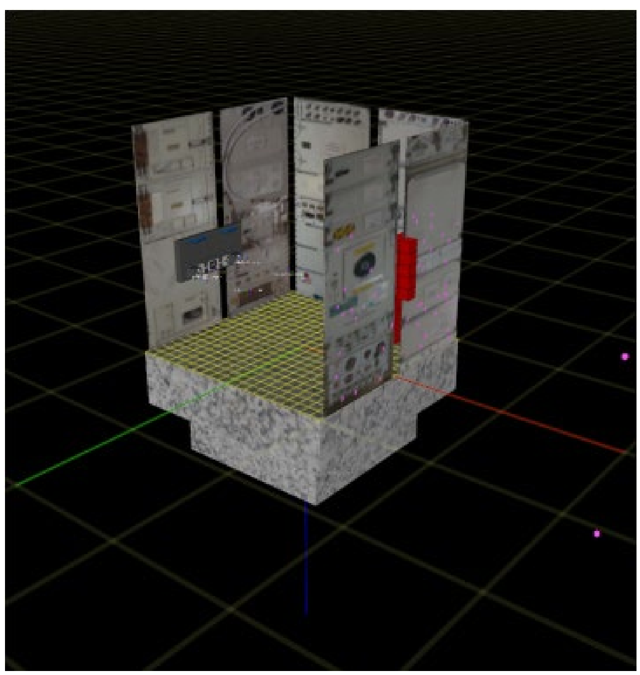


Figure 29. Coordinate system for Ames granite lab. RGB corresponds to XYZ axis Source: [43].

2. Ground Testing Plan

The Astrobatics S4 test plan included four ground tests conducted at the NASA Ames Research Center Granite lab. In preparation for those tests the NMSU team utilized a Gazebo simulation to test the implementation of their TRMPC on the Astrobee operating system. The goal of ground testing was to compare the performance of TRMPC to standard MPC while progressively increasing the mass estimation error of the system. It was postulated that the TRMPC would be more capable than standard MPC for moving from a start position to goal position in a smoother trajectory despite perturbations caused by increasingly poor mass estimates of the system. 6 test cases were proposed and tested at NASA ARC and are shown in Table 3. Three runs were to be repeated for each case.

Table 3. Test sequence for TRMPC and standard MPC comparison

Case	Tube Based MPC Algorithm	Standard MPC Algorithm
1	3 Runs	
2		3 Runs
3	3 Runs	
4		3 Runs
5	3 Runs	
6		3 Runs
* 3 Runs per case = 18 runs (~2.5 hours crew time including setup)		

Legend	
(green)	No Mass Estimation Error
(yellow)	%50 Mass Estimation Error
(red)	%90 Mass Estimation Error

For ground testing, two Astrobees were connected to a free-floating handrail to simulate a single Astrobee conducting transport of a cargo of unknown weight. The system consisted of one active Astrobee and one passive Astrobee. The active Astrobee was powered on and used its impeller system to move the system from a specified start location to a specified goal location. The passive Astrobee served as cargo. The passive Astrobee was powered on only to provide additional localization data to the system. The MPC controllers were not loaded onto the passive Astrobee, and its impellers remained powered off for the entire test. The perching arms of both Astrobees were fully deployed. The gripper of both Astrobees were wrapped around the free-floating handrail. Figure 30 shows the orientation of both Astrobee grippers on the free-floating handrail. Finally, the grippers were taped to the free-floating handrail using kapton tape to ensure the grippers remained closed and firmly affixed to the handrail through the conduct of all test cases.

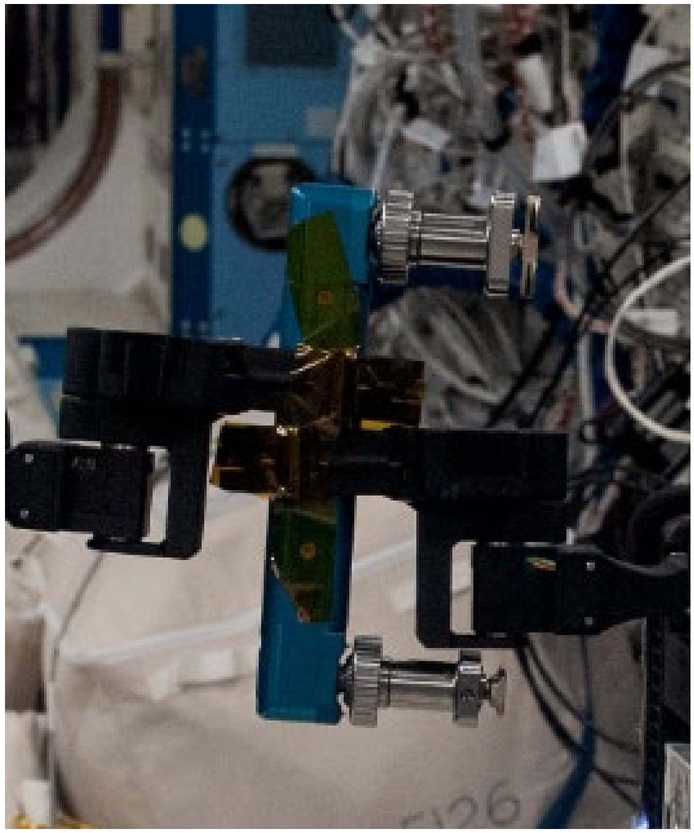
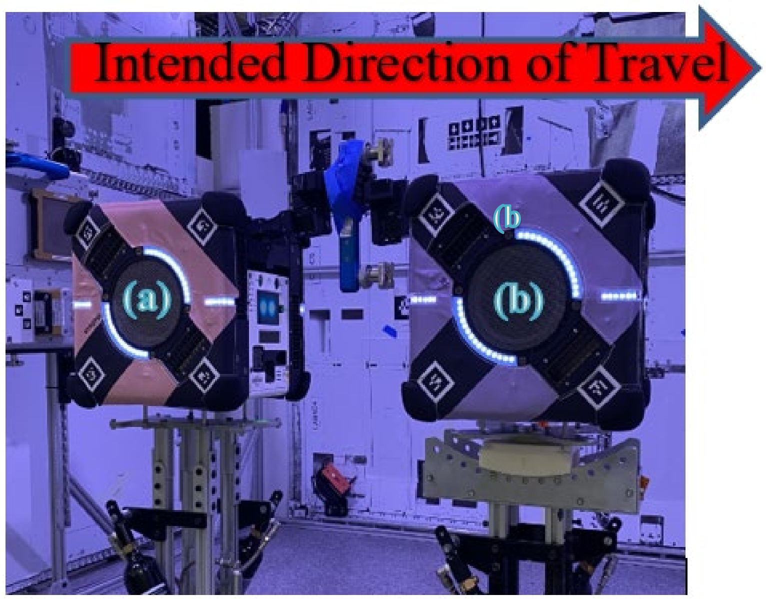


Figure 30. Orientation of perching arm grippers on free floating handrail

The Astrobee system was initially oriented so that the active astrobee was proximal to the goal location and the passive Astrobee was distant. The goal location was chosen so that the Astrobee system would have to execute both translational and rotational motion to reach the final goal. Figure 31 shows the two Astrobee system with the active Astrobee toward the direction of travel.



(a) is the passive Astrobee. (b) is the active Astrobee.

Figure 31. Orientation of two-Astrobee system at NASA ARC granite lab

During the first three sets of ground tests limited usable data was gained. During the first test, the system had difficulty moving from the start to the goal position. This is due to localization issues with the active Astrobee. The Astrobee relied on localization data from its navigation camera, which was located on the face of the Astrobee opposite the free-floating handrail. NASA ARC's Granite Lab has open walls on two sides which made it difficult for the active Astrobee to conduct localization since the navigation camera was facing out toward the open lab during the entire maneuver. To compensate for this, an initial position toward the +X and -Y axis was used, and the orientation of the system was rotated so that the active Astrobee was now distal from the goal position.

a. Ground Test 1 results

Figure 32 shows the Astrobee using TRMPC to move from an initial position to a goal position. Using a different initial position, we conducted another maneuver using SMPC. Figure 33 shows the trajectory of the active Astrobee as it moved from its initial position to a goal position.

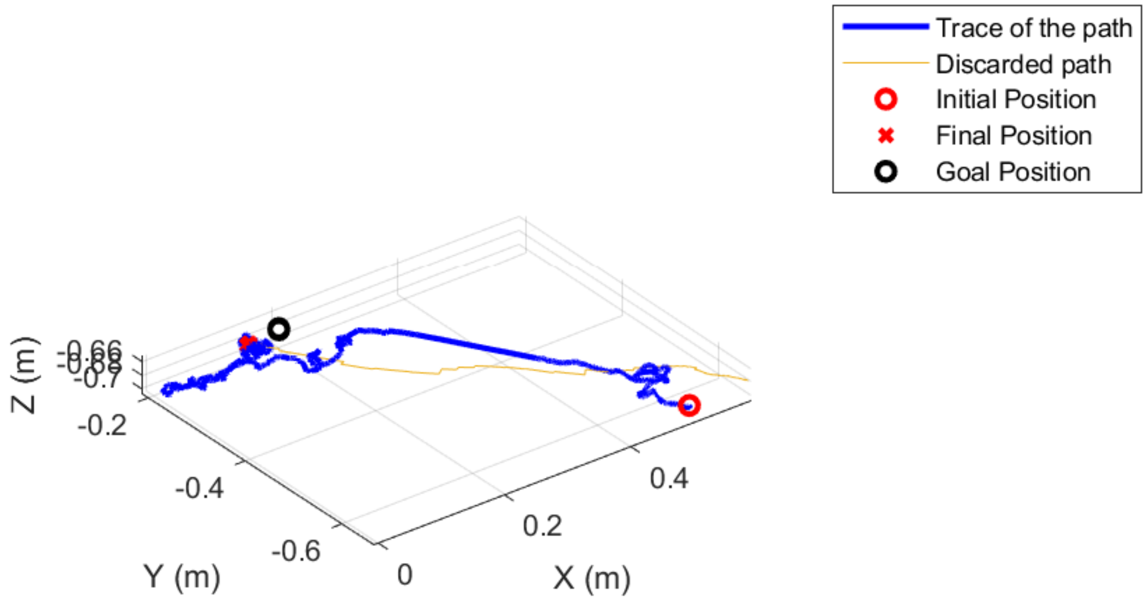


Figure 32. Trajectory of active Astrobee using TRMPC with correct mass estimation. Source: [44].

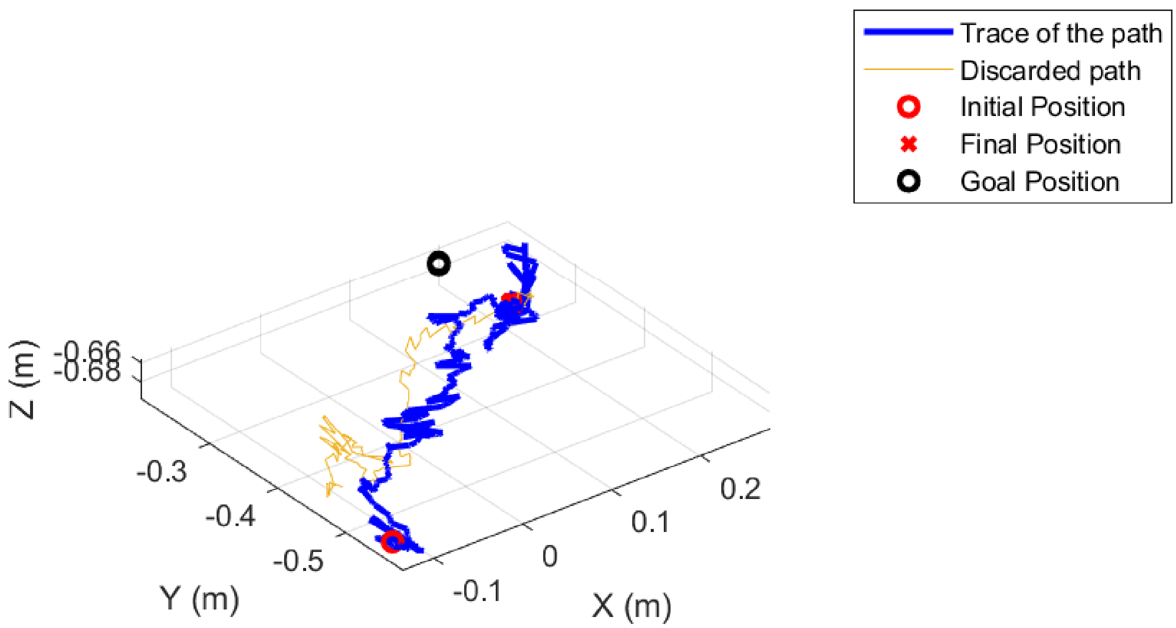


Figure 33. Trajectory of active Astrobee using SMPC with correct mass estimation. Source: [44].

The initial round of ground testing was successful in demonstrating the ability of TRMPC to conduct a smoother trajectory than SMPC. It was also useful in validating and troubleshooting the orientation of the two Astrobee system in the NASA ARC Granite Lab so that the Astrobees can effectively conduct localization throughout a maneuver.

Ground test sessions 2 and 3 were conducted with the goal of implementing the proper software configurations to allow for ISS testing of the TRMPC. Both sessions were used to identify discrepancies between the coordinate system of the controller, Astrobee flight software, and the ISS. The tests were also used to validate the method for quickly switching between test cases. The ability to rapidly switch between test cases was necessary to reduce setup time during ISS testing and maximize time conducting experimentation.

Ground test session 4 incorporated all the lessons gained from earlier experimentation in order to successfully implement the controller prior to testing aboard the ISS. In the interest of time and due to previous issues with controller implementation, this round of testing focused purely on verifying the implementation of software prior to ISS testing. Although test data was recorded, it does not yield experimental significance because it was not recorded to comparatively assess the capabilities of TRMPC over SMPC.

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VI. TESTING ABOARD THE INTERNATIONAL SPACE STATION

Testing on board the ISS occurred on 23 February 2023. The Astrobatics team coordinated and worked through the Astrobee team from NASA to utilize 2.5 hours of crew time to conduct experimentation. Japanese Astronaut, Dr. Koichi Wakata was responsible for experimental setup and execution aboard the ISS. In total, the Astrobatics team conducted nine different experimental runs during the allocated crew time.

Dr. Wakata sets up connected Astrobee system in the Japanese Experiment Module

Figure 34. Astrobee system initial on-orbit setup

The experiment was set up using the same configuration as demonstrated during ground testing. A Naval Postgraduate School skin was installed on the Active Astrobee. The dual-Astrobee system was centered in the fifth bay of the JEM, approximately 1.5 meters from the deck of the JEM and 1 meter from the wall where the docking station is mounted.

The Astrobee system was connected to a free-floating handrail and secured with Kapton tape, in a manner like ground testing. Figures 35 and 36 show the method used for connecting the Astrobees.

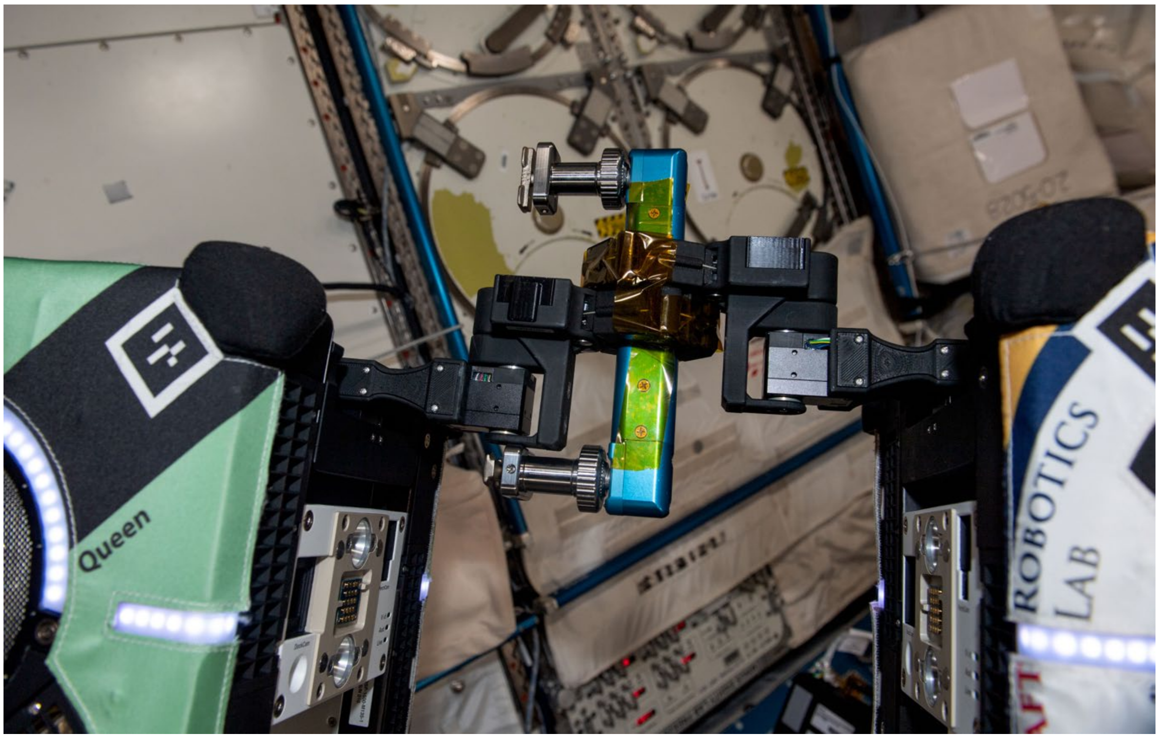

Figure 35. Side view of connected Astrobees

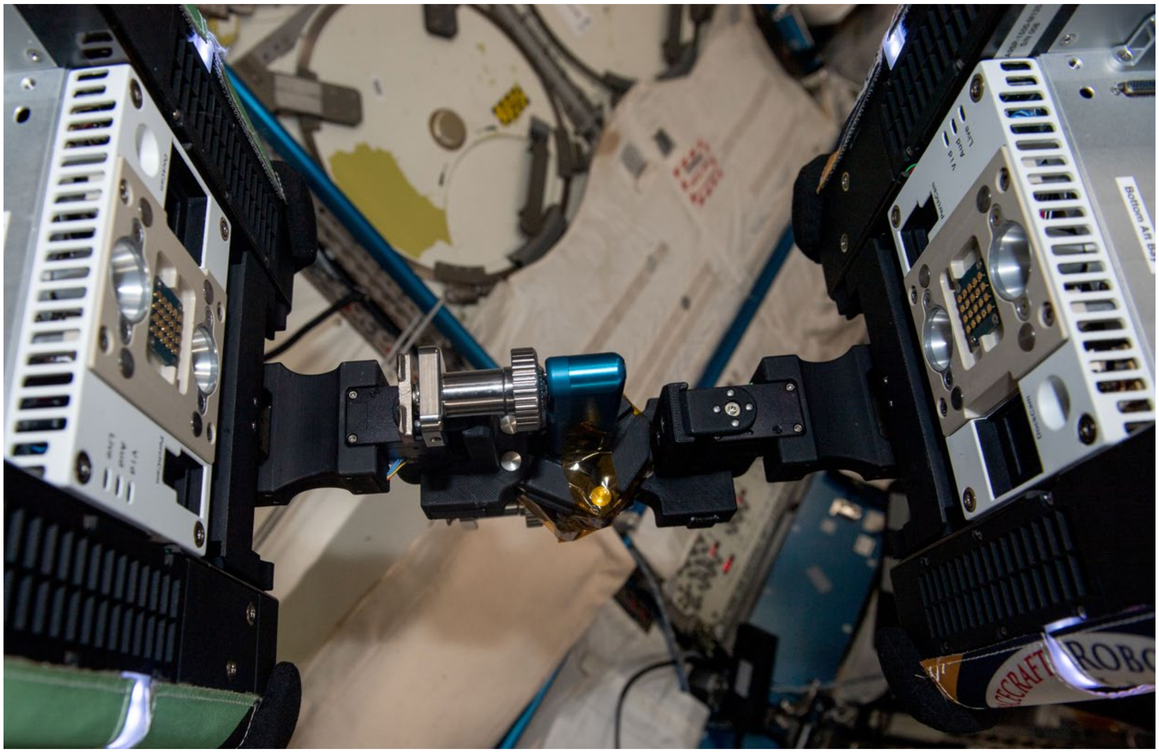

Figure 36. Bottom-up view of connected Astrobees

The Astrobatics team was geographically distributed during the conduct of the test and utilized various methods to access the experiment remotely. Aric Katterhagen from NASA Ames directly communicated with Koichi during the testing and provided directions on test set up as well as directing Koichi when the experiment could be reset. Another member of the Astrobee team, Jonathan Barlow, established a backroom on Microsoft Teams where he streamed video of the experiment and the active command terminal with the Astrobees. This was used to assist troubleshooting by the NMSU team. The NMSU team monitored the streams in the backroom and adjusted and updated the controller software as necessary. Dr. Hudson utilized NASA's Internet Voice Distribution System (IVoDS) to view the experiment stream and to provide directions to Aric Katterhagen.

A total of 9 tests were conducted. Data for each of the tests was recorded based on the ROS bag file produced by the active Astrobee. Video of the entire session was also recorded. For the first three tests, the TRMPC controller was not implemented correctly. This resulted in only 6 tests yielding usable data. The tests successfully demonstrated the ability of the connected Astrobee system to rotate and translate. The testing also showed that one Astrobee could successfully move the full system. In general, the system did not function as expected. The active Astrobee was expected to rotate and move towards a goal location in the +Y direction. Instead, the active Astrobee repeatedly tried to move the system in the -X direction. This resulted in the Astrobee system colliding with the bulkhead of the JEM. This also significantly reduced the translation distance of the maneuver, reducing the value of the collected data. The erroneous goal location also forced the active Astrobee to push the passive Astrobee, instead of conducting a towing maneuver as was originally intended.

The failure of the Astrobee to move to the desired goal location was a result of the incorrect goal location being uploaded with the controller software. The goal location from the ground testing was uploaded into Astrobee. Since the ISS uses a different coordinate frame, this resulted in the Astrobee system attempting to move to a goal location that was outside of the volume of the ISS. The goal location uploaded was [X = 0.2, Y = -0.2, Z = same as starting Z coordinate]. Coordinate frame issues could be mitigated in the future by conducting a ground test the day prior to ISS testing to ensure that the implemented controller is trying to move toward the ISS goal coordinate. Figure 37 shows the ISS coordinate system with the estimated initial and goal positions used for testing.

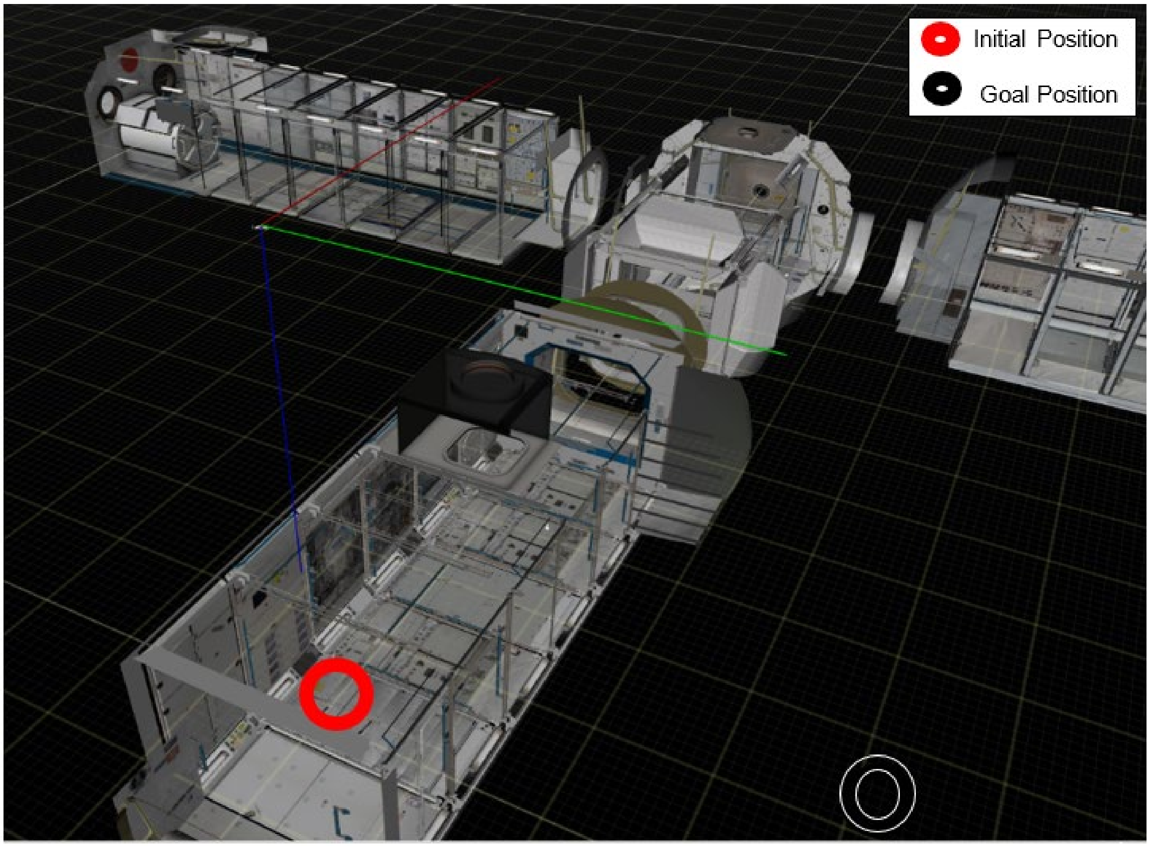

Figure 37. ISS coordinate system. RGB corresponds to XYZ axes. Adapted from [2].

Table 4 summarizes the tests which were conducted and identifies whether the data was usable or not.

Table 4. Summary of ISS testing

Test	Controller	Mass Estimate Used	Data Usable (Yes/ No)
1	TRMPC	Best Estimate	No
2	TRMPC	Best Estimate	No
3	TRMPC	Best Estimate	No
4	TRMPC	Best Estimate	Yes
5	TRMPC	Best Estimate	Yes
6	SMPC	Best Estimate	Yes
7	SMPC	Best Estimate	Yes
8	SMPC	Best Estimate	Yes
9	TRMPC	Good Estimate	Yes

A. RESULTS OF ON ORBIT TESTING

The trajectory was measured using the X, Y, and Z position data from the active Astrobee. Position data from the passive Astrobee was not used in the analysis of results. In general, there was a significant deviation between the desired trajectory and the observed trajectory of the system. The precise cause of this deviation is unknown but may have been caused by the inability of the active Astrobee's attitude determination and control system (ADCS) to overcome disturbances caused by towing a cargo load of equal mass and the error caused by utilizing a goal location from the wrong coordinate system.

It is also notable that the distance available for the maneuver was limited by our setup. Since the goal position was located outside of the ISS usable volume, the system had less than one meter of maneuver space before it collided with the ISS bulkhead during testing. The initial setup of the system which was repeated for all tests is shown in Figure 38.

Figure 38. Initial location of Astrobee system for all tests

This collision is visible as a bunching of positional data in the vicinity of the final position on each graph. The observed behavior at this point was that the system had collided with the bulkhead of the ISS and continued to attempt to maneuver towards the goal location until the ground station sent a command to cease that test run.

The behavior of individual test runs was compared to recorded video and images of the experiment in order to provide qualitative characterization of the observed behavior and recorded trajectories of the Astrobee.

1. Tests 1–3

Test 1, 2, and 3 have been omitted since they yielded no usable data. The results of tests 4–9 is included below.

2. Tests 4–9

a. Test 4. TRMPC with accurate mass estimate

(1) Observations

Test 4 tested TRMPC using a completely correct cargo mass estimate. Visual observation of the test shows that the system remains in the vicinity of the starting position for nearly 60 seconds until it moves towards the aft bulkhead. At one minute and 20 seconds, the system collides with the bulkhead and continues to push in place. Figure 39 shows the orientation of the system at collision. At approximately two minutes and 30 seconds, the passive Astrobee remains pinned against the bulkhead while the active Astrobee rotates towards the -Z direction.

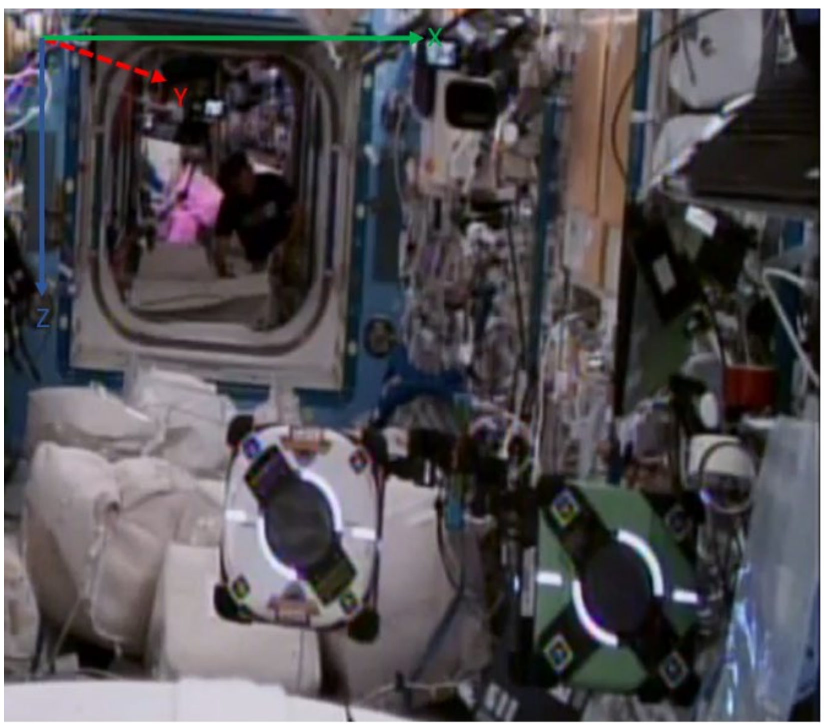

Figure 39. Orientation of system during initial collision during Test 4

(2) Data

Figure 40 shows the active Astrobee trajectory in relation to the goal location. Figure 41 shows the trajectory of the active Astrobee during the entire test run.

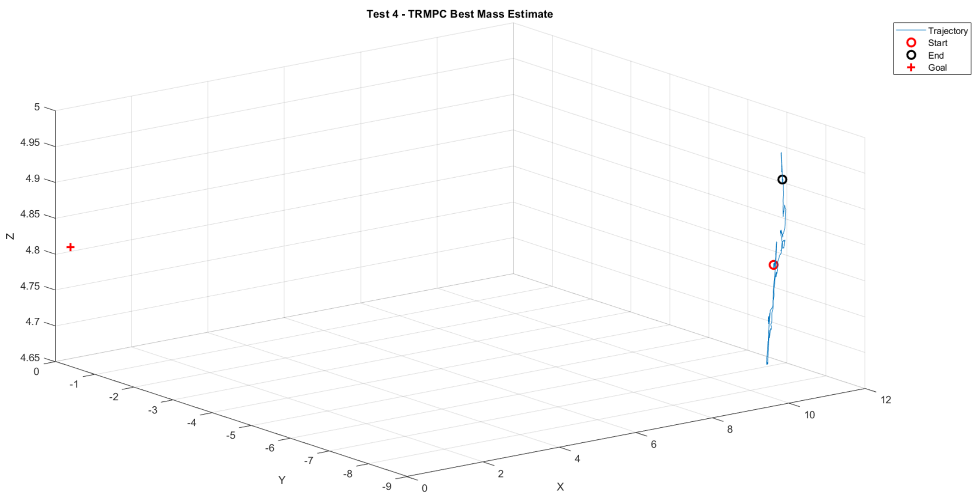

Figure 40. Trajectory of active Astrobee during Test 4

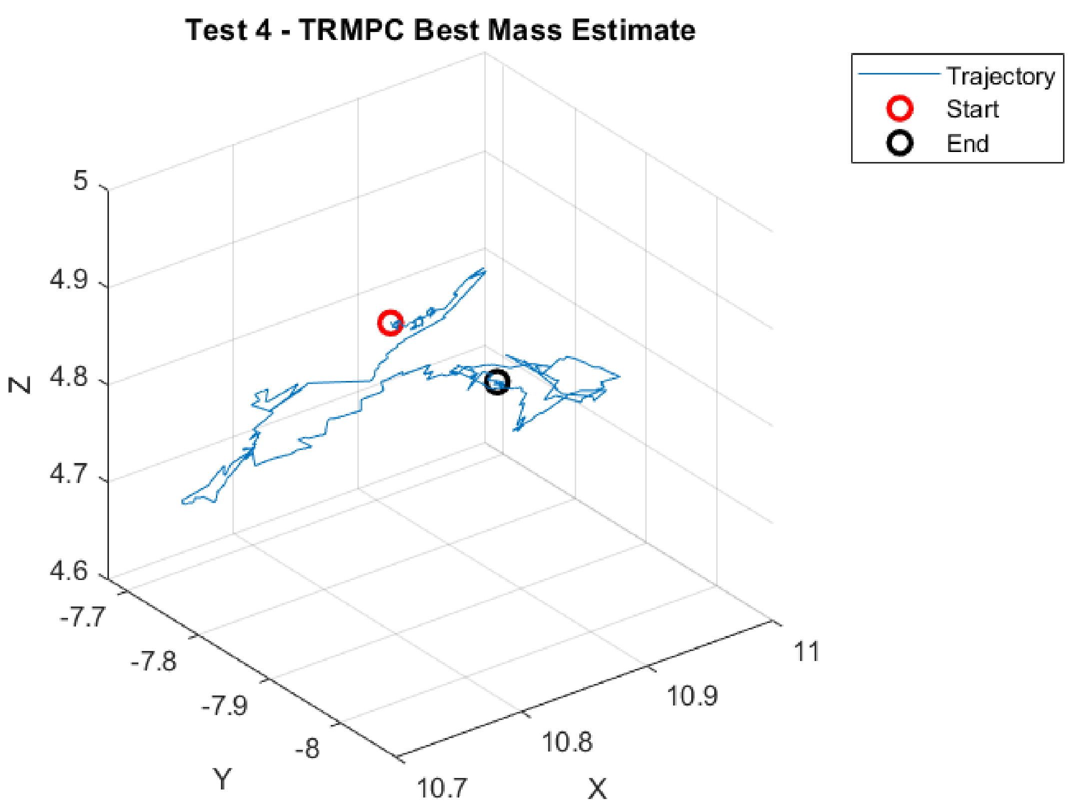

Figure 41. Trajectory of active Astrobee during Test 4

b. Test 5. TRMPC with accurate mass estimate

(1) Observations

During the first 35 seconds the Astrobee makes a slight rotation while the active Astrobee pushes. Initial movement from the starting position is in the +X, -Z direction. At approximately 1:05 into the experiment, the active Astrobee arrested the movement of the system. At 1:10, the Active Astrobee begins pushing again in the +X, -Z direction causing the passive Astrobee to collide with the overhead. Figure 42 shows the orientation of the system during the initial collision. Both Astrobees end up pinned against the aft bulkhead with the active Astrobee in the +Z direction in relation to the passive Astrobee.

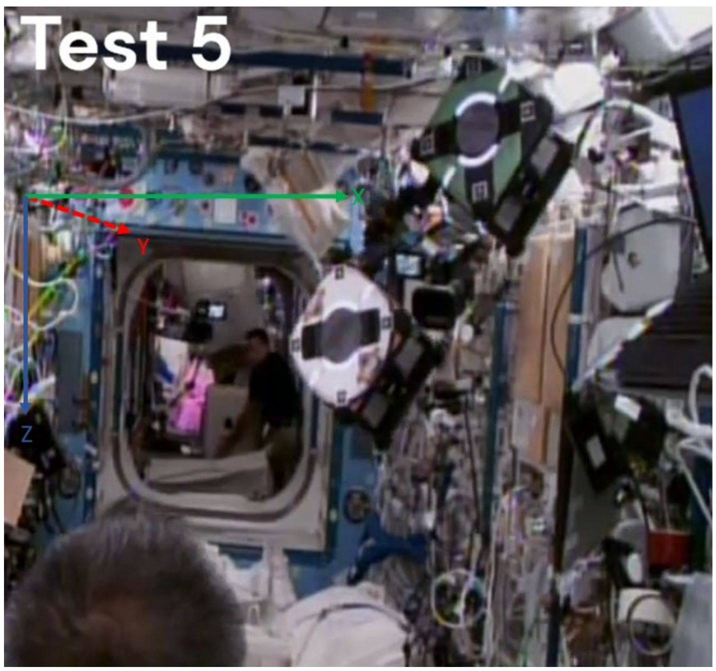

Figure 42. Orientation of system during initial collision during Test 5

(2) Data

Test 5 utilized TRMPC with the best mass estimate and yielded usable data. Visual observation of the Astrobee system shows the system first moves towards the goal position before reversing direction and arriving at the final location, most likely as a result of Koichi retrieving the system and returning it to the initial location. The result is extraneous location data. Figure 43 shows the active Astrobee trajectory in relation to the goal location. Figure 44 shows the trajectory of the active Astrobee during the entire test run. Unfortunately, it is difficult to parse out the extraneous data using telemetry information alone, since the telemetry does not show whether an external actor is moving the system or not. The most relevant portion of the trajectory, prior to reversing direction, shows a smooth movement towards the bulkhead.

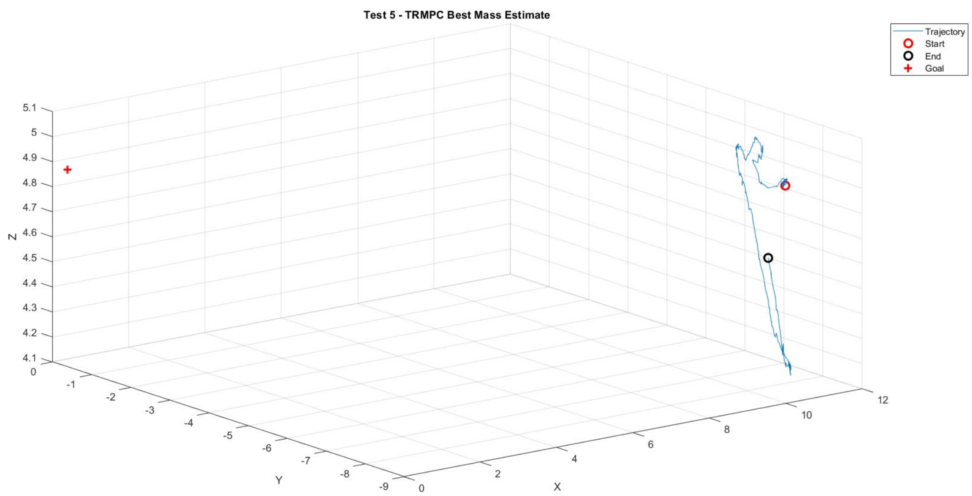

Figure 43. Trajectory of active Astrobee during Test 5

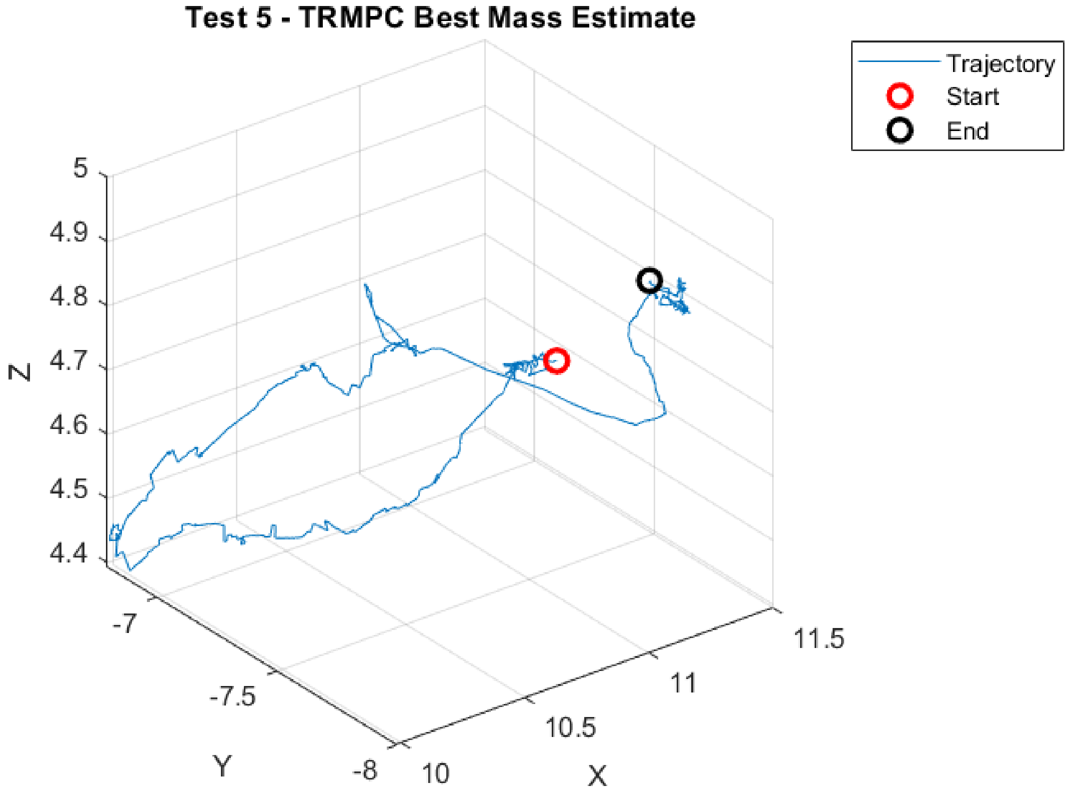

Figure 44. Trajectory of active Astrobee during Test 5

c. *Test 6. TRMPC with accurate mass estimate*

(1) Observations

The active Astrobee immediately moves towards the +X direction, causing the passive Astrobee to collide with the aft bulkhead. Figure 45 shows the orientation of the system during initial collision. The active Astrobee continues to push into the bulkhead for approximately 40 seconds, before the entire system moves in the -X, -Z direction and collides with the overhead.

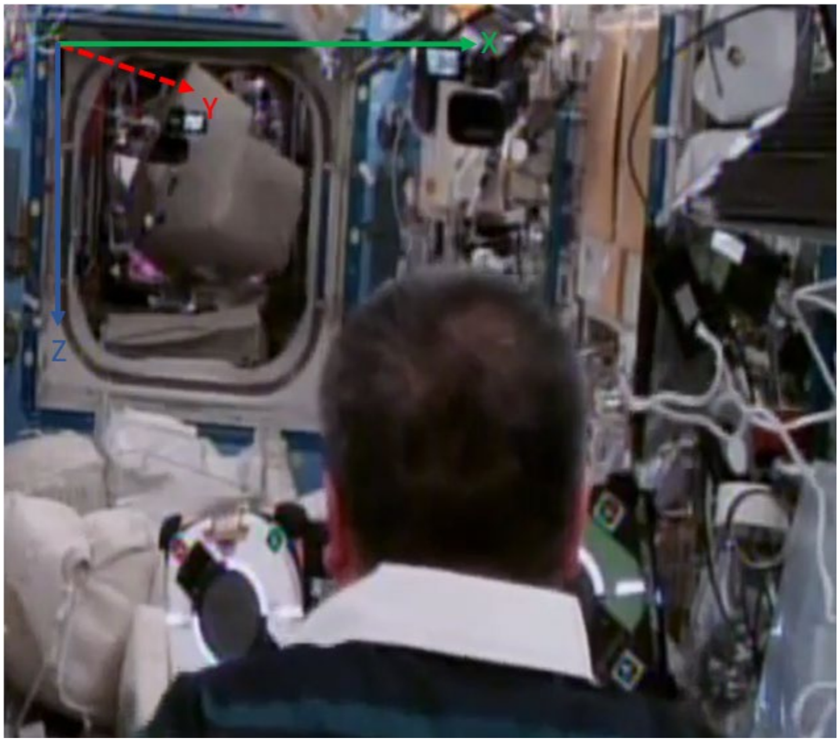

Figure 45. Orientation of system during initial collision during Test 6

(2) Data

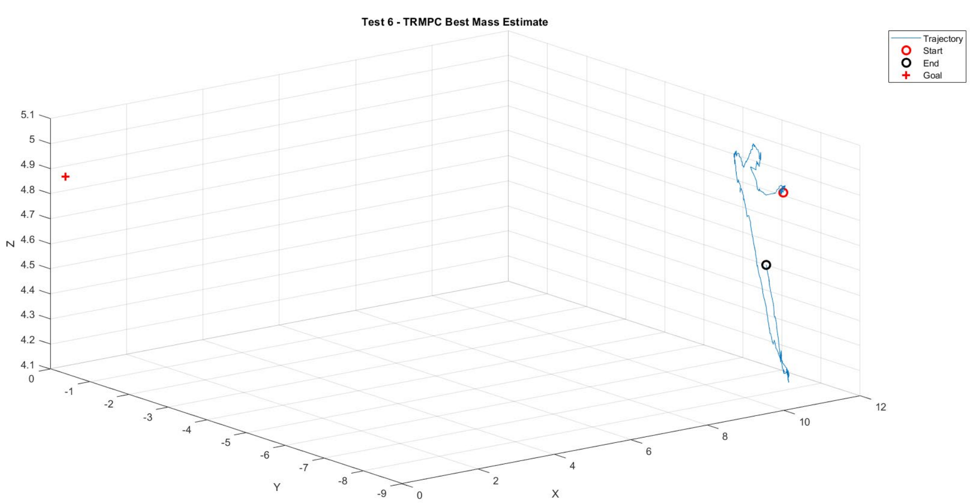

Figure 46. Trajectory of active Astrobee during Test 6

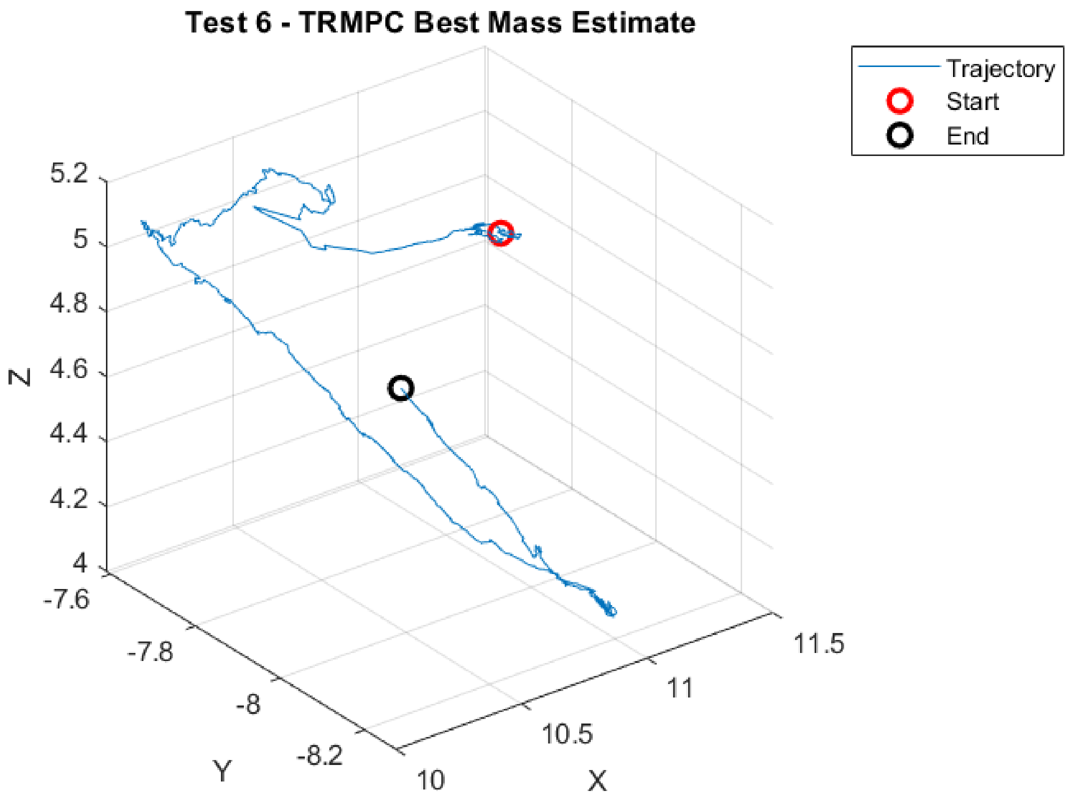

Figure 47. Trajectory of active Astrobee during Test 6

d. Test 7. SMPC with accurate mass estimate

(1) Observations

The active Astrobee immediately moves towards the +X direction, causing the passive Astrobee to collide with the aft bulkhead. Figure 48 shows the orientation of the system when it initially collides. The active Astrobee rotates completely around the passive astrobee before the experiment is reset.

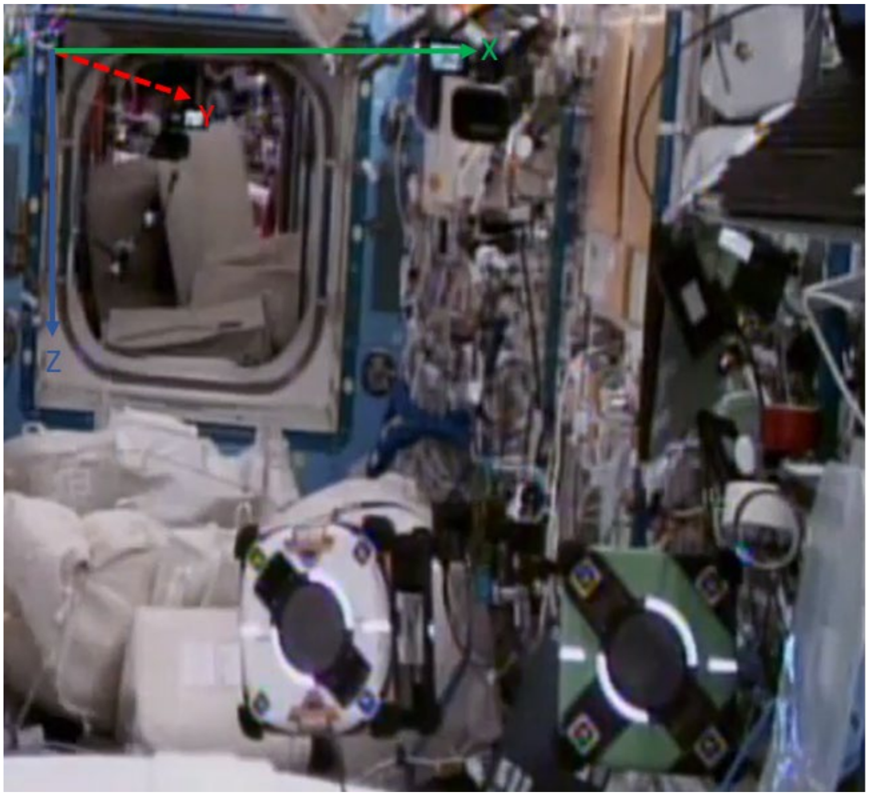

Figure 48. Orientation of system during initial collision during Test 7

(2) Data

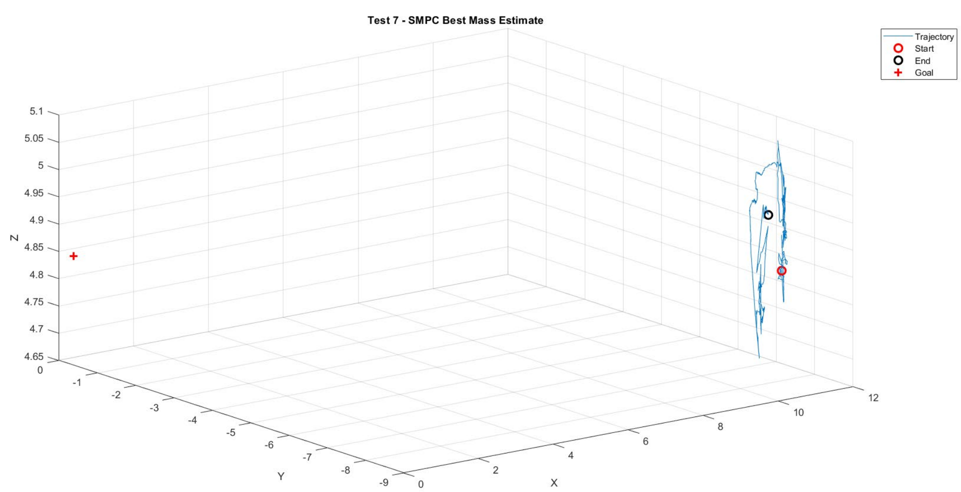

Figure 49. Trajectory of active Astrobee during Test 7

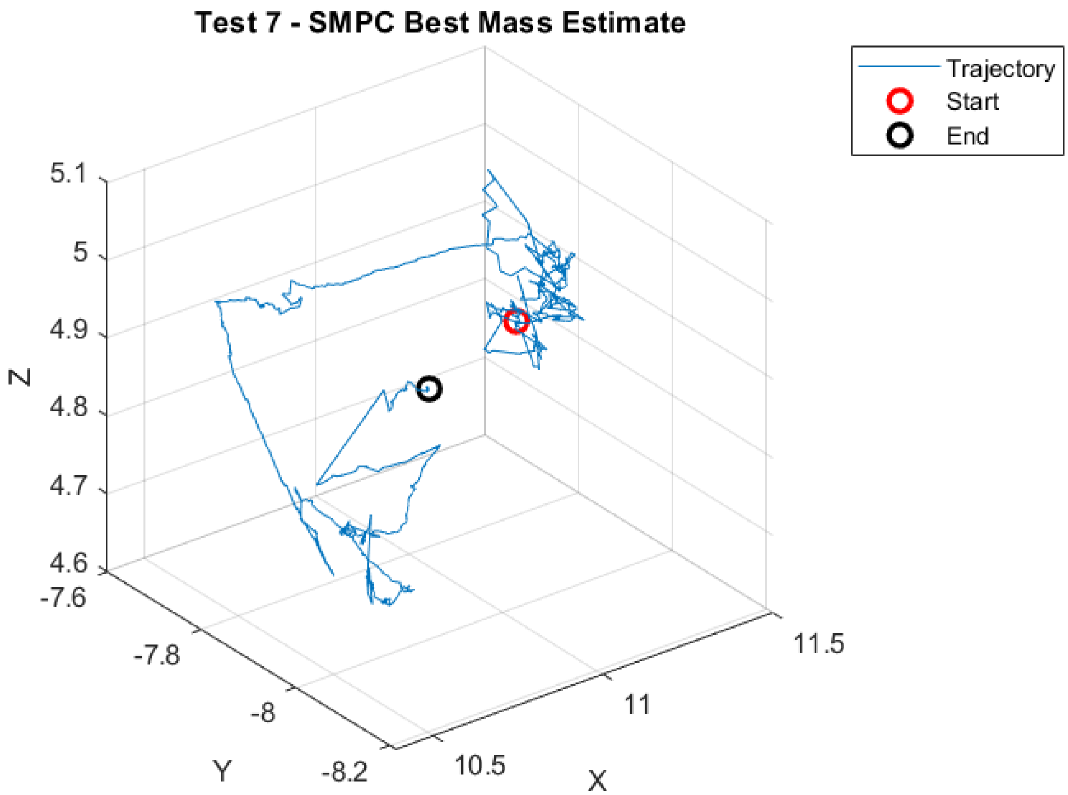

Figure 50. Trajectory of active Astrobee during Test 7

e. Test 8. SMPC with accurate mass estimate

(1) Observations

The active Astrobee immediately moves towards the +X, +Y, +Z direction. The system rotates slightly and both Astrobees collide with the aft bulkhead simultaneously. Figure 51 shows the orientation of the system when it collides with the aft bulkhead.

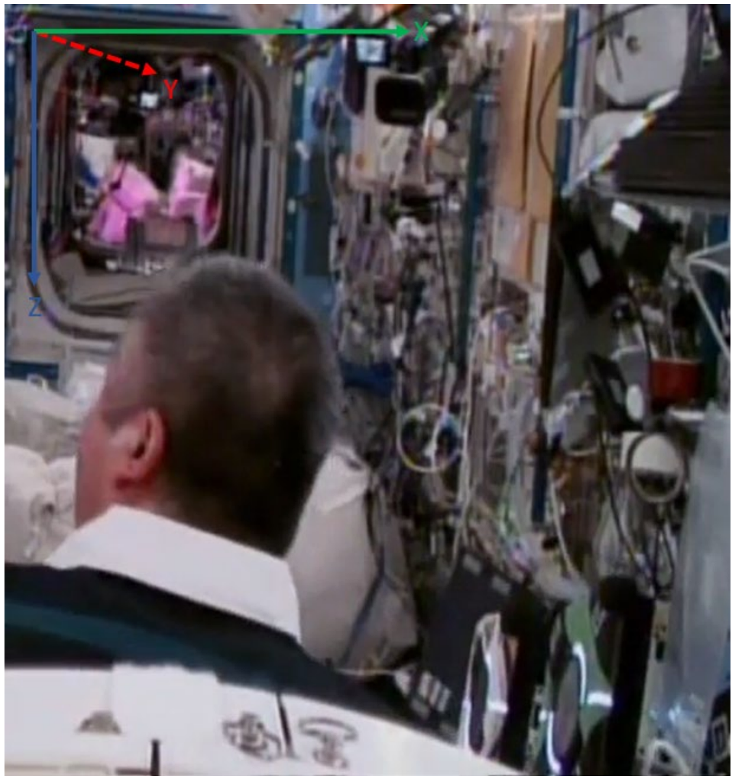

Figure 51. Orientation of system during initial collision during Test 8

(2) Data

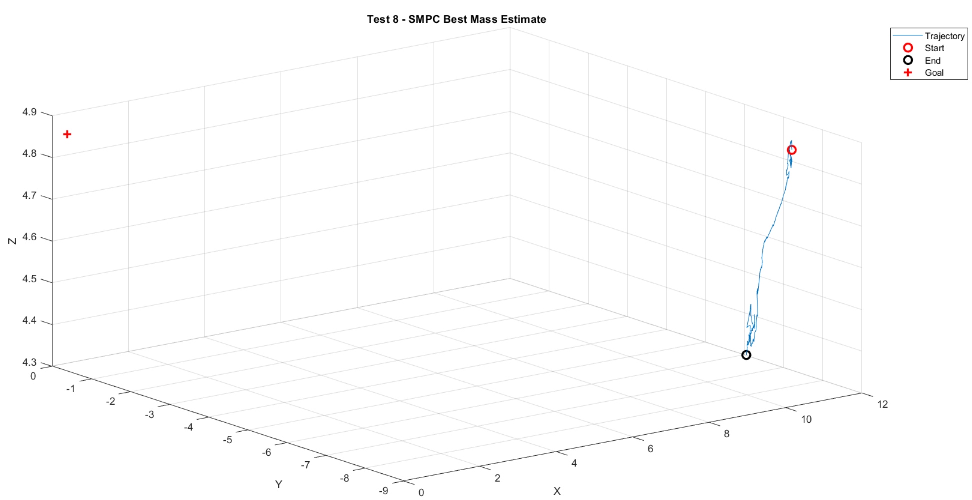

Figure 52. Trajectory of active Astrobee during Test 7

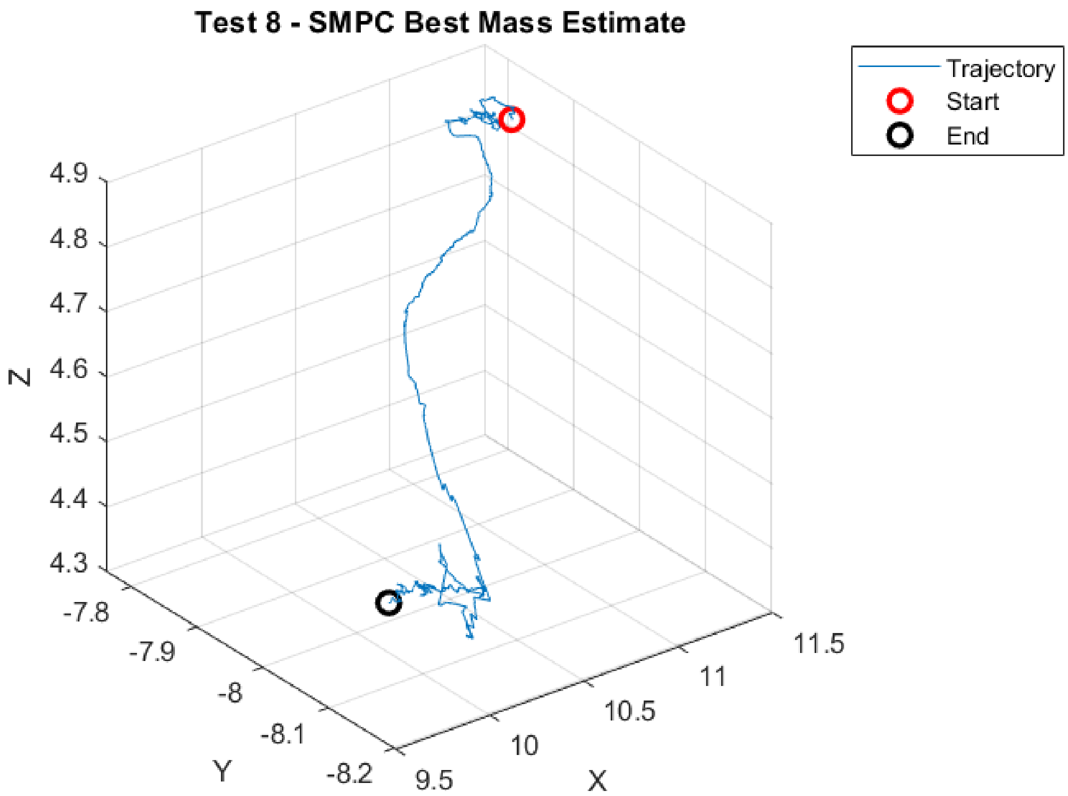

Figure 53. Trajectory of active Astrobee during Test 7

f. Test 9. TRMPC with moderately accurate mass estimate

(1) Observations

The active Astrobee immediately moves towards the +X, +Y, +Z direction. The system rotates slightly and both Astrobees collide with the aft bulkhead near simultaneously.

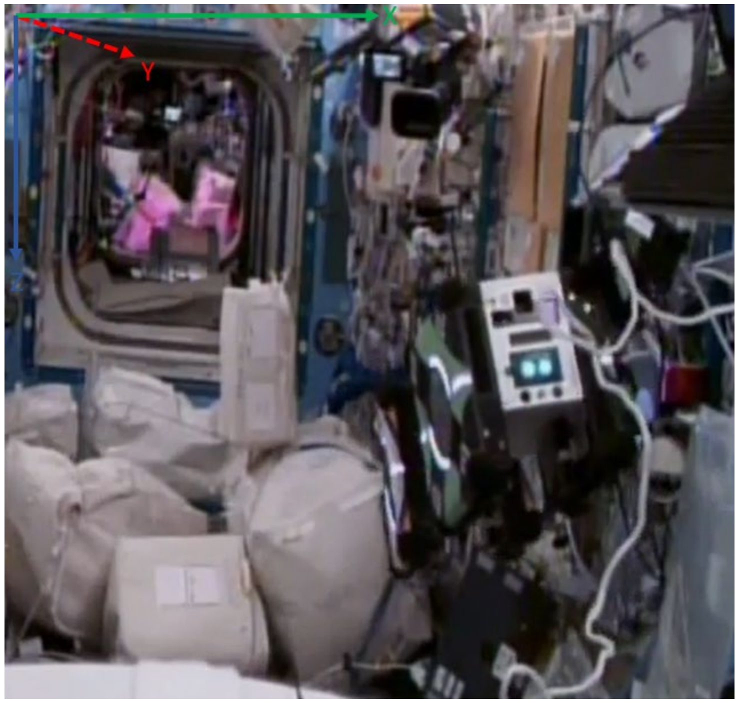

Figure 54. Orientation of system during initial collision during Test 9

(2) Data

The trajectory data includes an erroneous portion after collision, likely due to a result of the controller not being stopped before Koichi physically reset the system.

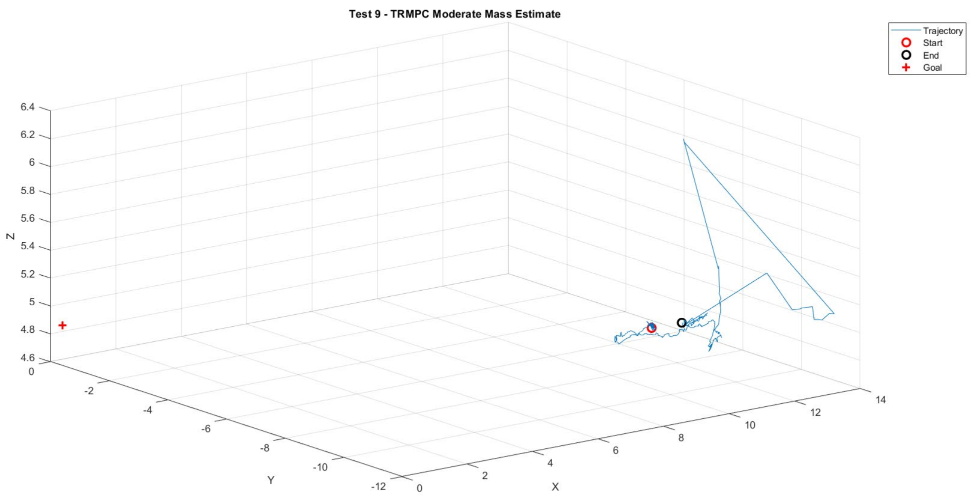

Figure 55. Trajectory of active Astrobee during Test 8

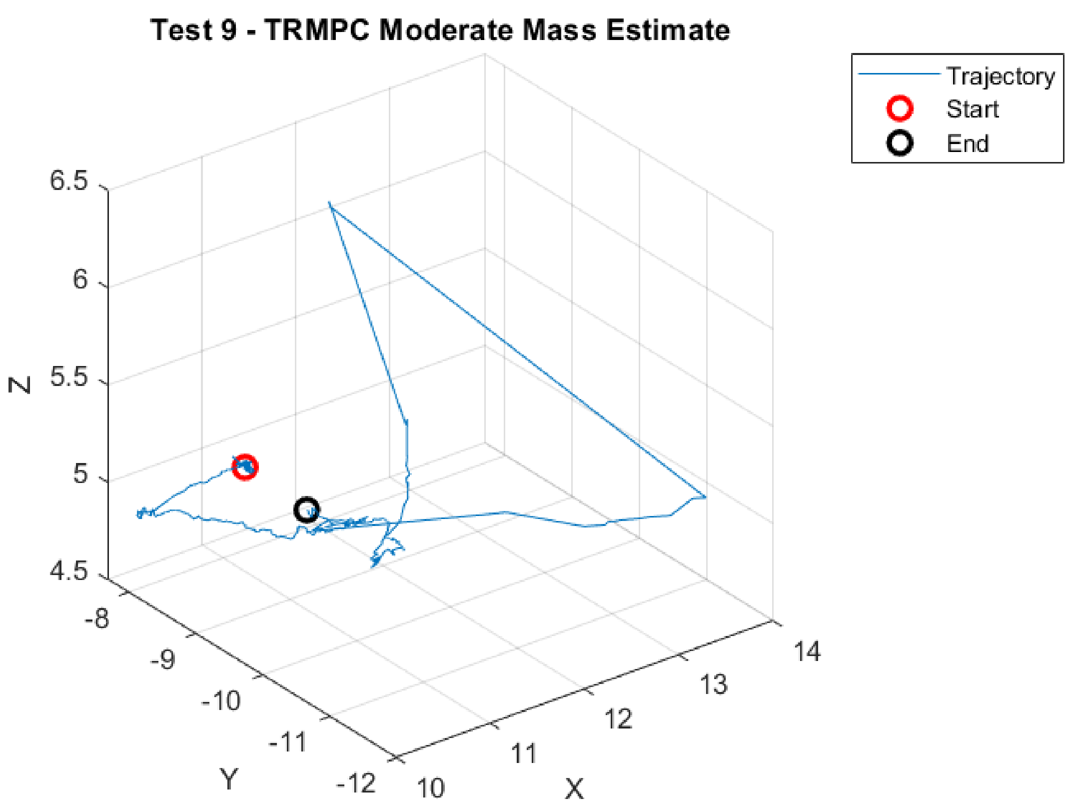

Figure 56. Trajectory of active Astrobee during Test 8

B. SUMMARY OF RESULTS

The data from our on-orbit testing is not sufficient to draw meaningful conclusions on the performance of TRMPC over SMPC control algorithms. The testing was successful at verifying our method for integrating a TRMPC into an Astrobee for in-orbit testing. The experiment validated our connected two-Astrobee setup, which demonstrated negligible slippage of the connection through multiple tests. The testing successfully demonstrated a free-flying robot's ability to move a cargo of comparable size over a short distance.

C. FAILURE ANALYSIS

Our experimental design and execution failed to yield a meaningful comparison of the performance of TRMPC and SMPC due to a variety of factors which can be controlled and adjusted in future testing.

The primary issue with our experimental set up was the inadvertent use of the goal location from ground testing in our on-orbit experiments. Three major factors contributed to this major error. First, the coordinate system used for ground testing was different than the coordinate system used during testing aboard the ISS. This is a result of NASA ARC's granite lab using a different coordinate system than the ISS. Figure 29 shows the XYZ axis of the ARC granite lab and Figure 37 shows the ISS XYZ axis. The longitudinal direction of the module in the ARC granite lab corresponds to the y axis. The longitudinal direction of the module in the ISS corresponds to the x axis. This means that even though ARC's granite lab contains a mockup of the ISS, any controller tested in that lab will need to be modified prior to on-orbit testing. The transition from ground testing to on-orbit testing could be greatly simplified if NASA were to adjust the coordinate system of the ARC granite lab to match the coordinate system of the ISS.

Second, we did not confirm that the code provided to NASA for on-orbit testing was the correct version. We allowed nearly a month to lapse between our last ground test and the conduct of on-orbit testing which likely contributed to our assumption that the correct version of the controller code was provided to NASA. We were aware of the different coordinate systems between the ARC and ISS but if we had conducted one last dress rehearsal in the granite lab the day prior to on-orbit testing, we would likely have identified the erroneous goal location prior to executing our on-orbit test. The Astrobatics team has adjusted its internal procedures to account for this in the future and provided an after-action review to NASA to support the spreading of lessons learned to other Astrobee developers.

Finally, the team's dispersal in multiple locations and the use of a variety of multimedia platforms made it difficult to identify, troubleshoot, and correct the problem once an anomaly was detected during on-orbit testing. Our on-orbit testing was limited due to crew time constraints, so additional time could not be made available. Had the team been collocated with each other and their NASA counterparts, they may have been able to identify and correct the goal position early enough to reset the experiment and conduct additional test runs.

In addition to the goal position issue, we identified three corrections to our experimental setup which would have likely yielded clearer results. The Astrobee system should initially be positioned so that the active Astrobee is proximal to the direction of travel, instead of the whole system being perpendicular to the direction of travel. In our experiment, the perpendicular setup inadvertently forced the active Astrobee into a pushing motion, instead of our intended towing motion. A parallel set up would eliminate the need for the active Astrobee to rotate the system, ensure a towing motion, and ultimately yield more usable trajectory data for comparison. The parallel setup also has the added benefit of allowing a greater pathway for translation which would provide us with more complete trajectory data for the whole system.

The perpendicular setup resulted in poor initial localization data from the active Astrobee. This was likely caused by the difficulty of Astrobee's navigation camera in providing localization data while facing the aft or forward bulkheads. Localization data from the JEM airlock on the port side is usually much better, so orienting the system to allow the navigation camera to point in that direction would yield more accurate localization data.

Our experimental design only accounted for positional data from the active Astrobee. Although the passive Astrobee did collect positional data, it was not done in an intentional way to synchronize the information collected between both Astrobees. In the future, both Astrobees should begin and then cease localization data simultaneously. Time synchronized positional data for both Astrobees could be used to provide a more complete picture of the pose of the entire system instead of just the position of the Active Astrobee. This would allow us to better characterize and understand the movement of the towed cargo in relation to the active Astrobee throughout the maneuver.

A final factor that led to our poor results was the comparable size of our simulated cargo. We chose to use a passive Astrobee as cargo since similar dual Astrobee setups had been used in previous Astrobatics experiments and it did not require the use of actual cargo, which may not necessarily available to Astrobee developers for experimentation and would have required significant additional coordination with the Astrobee team. Since Astrobee was not designed as a cargo carrying platform, using a passive Astrobee of the same mass may have exceeded the capacity of Astrobee's attitude determination and control system (ADCS) especially as it's initial maneuver would have required large rotational movement. In the future, it is recommended that coordination for a cargo bag is conducted with the Astrobee team as early as possible to ensure approval prior to testing. A smaller cargo would have been less likely to exceed the capabilities of Astrobee's ADCS and would have enabled the collection of trajectory data that showed an actual comparison of controller performance, instead of showing each controller struggling to overcome the increased inertia from the passive Astrobee.

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VII. TASK-BASED LOCOMOTION STRATEGY FOR FFRS

Certain methods of locomotion are better suited to certain environments, activities, and operating constraints. If an FFR is required to conduct a variety of tasks, it may often be valuable to utilize a variety of locomotion methods to accomplish required tasks. Table 1 and 2 identified a variety of tasks, their corresponding environments, complexities, and times to criticality. Robotic designs can take advantage of the various methods of locomotion to create a combined strategy for locomotion based on the required tasks.

A. INTRAVEHICULAR STRATEGIES

The intravehicular environment of a space station allows an FFR access to an atmosphere providing unlimited propellant. It also typically allows an FFR better access to docking stations to enable charging. The constrained space of a space station, cluttered interior, and presence of sensitive items such as wiring lends itself to a robot designed in a smaller form factor to enable maneuverability with less chance of collision.

Due to these considerations, maneuvers using an onboard fan and impeller system, or thrusters are suitable for most tasks that an FFR may need to conduct. These tasks include preventive maintenance, inspections, crew assistance, and mapping activities.

There are a few cases where propellantless locomotion methods may not be preferable. When conducting acoustic mapping, the use of an impeller and fan system may create extraneous noise and interfere with mapping. A quieter method of locomotion such as tethers or zero-gravity climbing would be preferred.

Zero gravity climbing could be the preferred method of locomotion for certain types of inspection. For example, inspections of door seals may take over an hour, and the Astrobee may not have enough power to maintain station keeping without recharging. Zero gravity climbing could be used to anchor the Astrobee in place as it conducts a visual inspection.

Zero gravity climbing is also advantageous for tasks requiring dexterous manipulation, such as the use of tools like a powered drill or screwdriver. Since the

Astrobee needs to exert a torque through the tool it would be advantageous to anchor the robot in place.

Tether based locomotion could also be used to accomplish dexterous tasks with the advantage of its ability to conduct fine movements. This is especially helpful when the robot will be operating in a defined area conducting a more complicated repair that requires constant, accurate movement about a limited workspace.

The limited advantages of PFP locomotion are outweighed by the disadvantages in the intravehicular environment. The presence of clutter makes it difficult for the robot to find a clear even surface to push off of. As previous Astrobatics research has shown, the PFP method can make it difficult to control the location of the landing maneuver and the pose of the robot during the flight phase. Since the intravehicular environment is not limited by propellant availability there are few situations in which PFP should be used over thrusters, with few exceptions.

The main exception would be if the robot was designed without thrusters, or used thrusters that required propellant but was out of fuel and needed to conduct an impulsive maneuver from one location to another. PFP would be suitable in this situation. The use of PFP in robot design could also reduce the need for a propulsion system, allowing extra space for other payloads or functions. PFP could also be employed in a situation where the robot's propulsion system is not operating correctly. Although this doesn't constitute a primary strategy, PFP could be used to assist the robot in returning to a docking station for diagnosis.

Table 5. Suggested strategy, by task, for intravehicular activities

Task	Suggested Strategy
Preventive Maintenance/ Inspections	
Acoustic Monitoring	Utilize propulsive maneuvers to reach the area to be mapped. Once in the local area, utilize zero-gravity climbing for required maneuvers in order to reduce noise. Repeat this combination for as many required spaces as necessary.
Visual Inspection of door seals	Utilize propulsive maneuver or PFP to reach goal location. Use zero-gravity climbing to maneuver around the door frame to take required pictures.
Atmospheric Monitoring	Use propulsive maneuver or PFP to move to an anchor point in the area to be monitored.
Mapping	Use propulsive maneuvers to maneuver down the areas to be mapped. Use propulsive maneuvers for any necessary pose changes.
Reactive Maintenance (repair)	
Air Filter Replacement	Use zero-gravity climbing to maneuver around air filter replacement module. Use a propulsive maneuver to travel between the filter retrieval area, the workspace, and the filter disposal area.
Atmospheric Anomaly Correction	Since this is often a time-sensitive task, propulsive locomotion will be the most effective to conduct this task.
React to Depressurization Event	Since this is a time-sensitive task, propulsive locomotion will be the most effective to conduct this task.
Crew Assistance	
Inventory via RFID	This task will require the FFR to move throughout the entire space station. Because of the cluttered nature of the space station and no limitation on propellant, a propulsive maneuver alone will be the most effective way to conduct this task.
Cargo Retrieval and Stowing	For the retrieval of a few pieces of cargo with low mass, a propulsive maneuver will be effective. If the cargo is massive, zero-gravity climbing would be advantageous because the robot can exert forces on a fixed surface, whereas the propulsion system may have difficulty overcoming the disturbances caused by the uncertainty in mass distribution of the large cargo. Tether-based retrieval could be used in a situation such as offloading a cargo module where the robot will be conducting multiple trips from the docked spacecraft to a designated staging area.

Task	Suggested Strategy
Tool Retrieval	The suitability of locomotion methods for tool retrieval depends on the location of tools relative to the crew member and the number of trips required. Tether-based locomotion would work well in a situation where the tools and astronaut are in the same module and multiple retrieval trips are required over an extended period. PFP could be used but it will be slow and leave the crew members waiting on the robot, thus wasting time. Propulsive locomotion is suitable for all intravehicular tasks, is fast, and can conduct multiple trips as required.
Information Support	Locomotion to conduct information and imaging support requires the robot to remain in the vicinity of the Astronaut. Astronaut movements should not be constrained or slowed down by the robot's inability to follow along, and only propulsive locomotion allows the robot the freedom of movement throughout the space station that would be required.
Imaging Support	
Mapping Activities	
Identify Lighting Anomalies	The robot needs to be able to move throughout all modules without restriction. Propulsive locomotion can achieve this autonomously and more quickly than other locomotion methods. Zero-Gravity climbing is also an option but will cause an increase in time required for task completion.
Obstacle and Obstruction detection	
Item Locations and Inventory Database Updates	
Identify available storage areas	
Acoustic Mapping and anomaly Detection	Acoustic mapping and anomaly detection requires the robot to move to a particular area to be recorded and then remain in place for up to an hour to record a full acoustic profile. Propulsive locomotion can be used to autonomously move the robot to the goal location, but impellers and fans will interfere with data collection for the mapping portion, requiring the robot to either dock or switch to another locomotion method. Zero-gravity climbing and PFP are suitable if there is no time constraint for task completion and teleoperation is possible. Tether-based locomotion could be used if acoustic samples need to be collected in multiple areas within the same module or if proximity to a bulkhead will interfere with collection.

B. EXTRAVEHICULAR STRATEGIES

The extravehicular environment lends itself to combined maneuver strategies for a variety of reasons including the environment, the tasks required, and robot design factors.

Extravehicular locomotion strategies require consideration of the extravehicular environment. Typically, the exterior of a space station has limited anchor points, unless a robot is making use of some novel anchor method such as gecko grippers or magnets. The exterior is less cluttered and provides vastly more maneuver space. The exterior has no atmosphere so the robot must carry all its required propellant on board. The exterior also has limited docking stations that can enable charging. Finally, the exterior has much larger structures such as solar arrays which the robot will be required to maneuver on and around.

The extravehicular environment lends itself to a larger FFR design. The FFR operates in the open and does not need to maneuver in tight corridors. The FFR must carry its own propellant and will utilize some type of small propulsion system such as one using cold gas thrusters. The FFR must also have additional environmental shielding and a more robust thermal control system to cope with the space environment.

Extravehicular FFRs can conduct preventive maintenance, inspections, support manned EVA, support rendezvous and proximity operations (RPO), support docking, and provide external situational awareness.

Push-fly-park locomotion tends to lend itself to RPO and docking situations. An FFR could use PFP to maneuver towards an object during rendezvous and then provide additional situational awareness or thrust to assist with a docking maneuver. PFP could also be used to retrieve cargo from a nearby craft without requiring a docking maneuver at all, thus reducing the chance of collision, saving propellant in the craft attempting rendezvous, and reducing the time required for a docking maneuver. A PFP could also be used in conjunction with a tether for cargo retrieval. Figure 57 provides an example of how an FFR may use a tether to retrieve it from a rendezvous with a nearby spacecraft.

Figure 57. An FFR rendezvous with nearby spacecraft while tethered to a space station. This image was created with the assistance of generative AI, DALL-E

Zero-gravity climbing can be used extensively in the extravehicular environment, minimizing the FFR's requirement for propellant. Almost every category of tasks lends itself to the use of zero-gravity climbing if it is not time critical. Zero-gravity climbing enables a robot to remain anchored, which lends itself well to dexterous tasks and those requiring large objects, such as ORUs, to be removed or replaced. Zero-gravity climbing can also be utilized in certain situations to support manned EVAs to avoid the potential safety hazards of a free-floating object maneuvering around an astronaut. Finally, zero-gravity climbing is an excellent method of locomotion when conducting external situational awareness activities because the robot can move about multiple anchor points, with low power and low propellant use.

Tether-based locomotion could be used advantageously for multiple tasks. As discussed before, it can be used in combination with a propulsive or PFP maneuver to retrieve cargo from an un-docked spacecraft. Tether based locomotion could also be used with significant effect to conduct inspections and maintenance on large solar arrays. The accuracy of tether-based locomotion enables the robot to stay in place to replace solar panels, facilitate multiple trips from a staging area to a construction site, and ensure that the robot does not collide with the sensitive solar arrays. Tether based locomotion may also be useful in a situation that requires multiple trips between few points conducted quickly. This could include tool and supply retrieval for an astronaut conducting an external repair during a manned EVA.

Table 6. Suggested strategies for individual EVR tasks

Task	Suggested Strategy
Preventive Maintenance/ Inspections	
Routine Hull Inspection	Utilize zero-gravity climbing to the maximum extent possible to reduce fuel use. Utilize propulsive climbing as necessary to inspect areas which do not have features that support zero-gravity climbing.
Hull Repair	Utilize zero-gravity climbing if the repair is in the vicinity of appropriate anchor points. Utilize propulsive locomotion if the repair is time critical (such as a depressurization event) or if the repair is not in the vicinity of anchor points.
ORU Replacement	Utilize teleoperation to retrieve the ORU. Utilize autonomous propulsive maneuvers to move to replacement site. Utilize teleoperation to conduct the actual replacement. Zero-gravity climbing will be a suitable method if the robot is specifically designed with a minimum of three manipulators. One manipulator to grasp the ORU and two to execute zero-gravity climbing. Tether-based locomotion would be a suitable method if teleoperation is possible and if the replacement ORU and the worksite are within line of sight of eachother.
Support to Manned EVA	

Task	Suggested Strategy
Workspace Imaging and Inspection in Preparation For EVA	Propulsive maneuvers will be most effective because they can be conducted autonomously and quickly. They can also provide a distant vantage point of the worksite that other methods of locomotion cannot. Zero-gravity climbing is a feasible alternative and is best used in situations where the imager must be close to the worksite to capture more detail, but it does not provide a distant vantage point that propulsive maneuvers can.
Replacement Part Retrieval	Propulsive maneuvers will be most effective because they can be conducted autonomously and quickly without being restricted by anchor points or line of sight. Tether-based locomotion would be most effective in situations where multiple trips to retrieve parts are required, and where the retrieval site is within line of sight of the worksite. Zero-gravity climbing is a feasible method but requires teleoperation and will be slower.
Augmented Lighting	Tether-based locomotion is effective in specific situations where there are adequate tethers that provide an appropriate vantage point and lighting is required for longer duration. Zero-gravity climbing can also be effective if close-up lighting is required. Propulsive locomotion is the most effective method for accomplishing the task, but the robot will be severely limited by the amount of propellant on board.
Astronaut Imaging	Tether-based locomotion is effective in specific situations where there is an adequate tether that provides an appropriate vantage point and imagery support is required for longer duration. Zero-gravity climbing can also be effective if close-up imagery is required. Propulsive locomotion is the most effective method for accomplishing the task, but the robot will be severely limited by the amount of propellant on board.
Tool Retrieval	Propulsive locomotion will be most effective because it can accomplish the task quickly, autonomously, and the task is typically of short duration. Tether-based locomotion and zero-gravity climbing can be utilized to minimize propellant use at the expense of time.
Support to Rendezvous, Proximity Operations, and Docking	
Spacecraft Docking Assistance ("Cosmic Capture")	Establish a tether anchor on the space station. Utilize a PFP maneuver with the docking spacecraft. Reel in the tether to pull the docking craft toward the space station. Utilize a propulsive maneuver to stop the spacecraft's momentum just before docking.

Task	Suggested Strategy
Docking Imagery and Video Support	Utilize zero-gravity climbing to provide an additional vantage point from the space station to the nearby craft. Zero-gravity climbing is advantageous because it allows for some maneuverability of the vantage point while keeping a stable imaging platform and requiring no propellant.
Cargo or Experimental Sample Retrieval or From Resupply Spacecraft While Docked	Utilize PFP to maneuver to the cargo portion of the docked spacecraft. Utilize an autonomous propulsive maneuver to return the cargo from the docked spacecraft.
Cargo or Experimental Sample Retrieval or From Resupply Spacecraft Without Docking	Utilize a PFP to maneuver to rendezvous with the approaching spacecraft. Utilize manipulators to grab the sample or cargo and then utilize an autonomous propulsive maneuver to return the cargo to the appropriate airlock on the space station. Tether-based locomotion may also be used in a comparable manner as in Cosmic Capture.
External Situational Awareness	
Environmental Sensing	This task requires minimal movement so zero-gravity climbing is preferred to provide an anchor point for the robot while reducing propellant use. A propulsive maneuver may be used if the robot needs to quickly maneuver to a different part of the space station to conduct sensing.
Object Detection Using Camera	This task requires minimal movement so zero-gravity climbing is preferred to provide an anchor point for the robot while reducing propellant use. A propulsive maneuver may be used if the robot needs to quickly maneuver to a different part of the space station to take an image or continue tracking an object.

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VIII. CONCLUSION

The research delves into specific tasks for free-flying robots in space station operations and validates the use of different controllers for cargo retrieval through both ground and on-orbit testing. Despite ground testing suggesting potential advantages of TRMPC over standard MPC, the on-orbit experiments were inconclusive. The suggested strategies provide a starting place for additional research into specific FFR designs that could incorporate multimodal locomotion.

A. SUMMARY OF RESULTS

Free-flying robots hold immense promise for enhancing operations on future space stations. By employing combined locomotion techniques, more efficient utilization of propellant and energy can be achieved. Customizing mobility strategies to specific tasks will not only expand the array of supported tasks but also optimize designs to capitalize on the benefits of various locomotion methods.

This thesis pinpoints particular tasks that free-flying robots might undertake in support of space station operations and proposes strategies that would be beneficial for those tasks. Generally, incorporating Push-Fly-Park locomotion and zero-gravity climbing to complement propulsive maneuvers, particularly in extravehicular environments, can decrease propellant consumption and broaden the scope of feasible tasks for an FFR with minimal alterations to the robot's physical structure.

In executing a sophisticated cargo retrieval operation, both ground and on-orbit testing verified the practicality of applying different controller types on Astrobee for cargo retrieval. On-orbit testing confirmed the effectiveness of our dual-Astrobee experimental setup and contributed to the refinement of experimental procedures. Ground testing implies that TRMPC might offer some advantages over standard MPC, such as providing smoother system trajectories despite significant external disturbances. However, our on-orbit experiments failed to yield definitive proof of TRMPC's superiority over Standard MPC in on-orbit conditions due to the use of incorrect goal coordinates.

B. FUTURE WORK

Ongoing research is being conducted to investigate the dual-Astrobee system utilizing TRMPC in a simulated setting, with preliminary outcomes indicating TRMPC's advantages as evidenced in our terrestrial evaluations. Subsequent in-orbit experimentation, employing the appropriate coordinate system and incorporating knowledge gained from previous trials, is anticipated to generate more valuable data and definitive comparisons between TRMPC and Standard MPC. It is essential to explore the effectiveness of zero-gravity climbing for executing dexterous operations to ascertain the torque range and tasks that an FFR can perform while grasping an anchor point. Further investigation should focus on specific FFR configurations with at least two manipulators for zero-gravity climbing. Examining a PFP mechanism, such as Fiorini's proposed spring-driven system, might offer a means to implement PFP with minimal alterations to existing FFR designs.

Additionally, the findings of this research have relevance to other domains, including satellite servicing, in-orbit fabrication, and in-orbit assembly. In these areas, comprehensive approaches should be devised to leverage the diverse locomotion techniques accessible to space robotics.

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