Paper No: 2024021

7th International Conference on Tethers in Space

June 2-5, 2024, Toronto, ON, Canada

Design and Applications of Tethered Spacecraft Simulators

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Conference Topic: Subsystem Technologies to Enable Space Tether Missions

Abstract:

Small, tethered spacecraft, or space tugs, are a promising space capability. They can be deployed on tethers and used for a wide variety of in-space activities; a large portion of which fall under in-space servicing, assembly, manufacturing (ISAM) functions. This includes functions such as structural mating and assembly, servicing, proximity operations, capture, docking, mating, and relocation. However, there is a great deal of work to be done to raise the Technology Readiness Level (TRL) of the capabilities needed to fully realize these capabilities.
The Flat Floor Robotics Lab (FFRL) at NASA's Marshall Spaceflight Center (MSFC) has been working on space tug development for several years. The eponymous floor is 44 by 86 feet, made from a self-leveling epoxy. This creates an extremely smooth surface that air bearings can float on with very little friction, creating a simulation of zero gravity in a two-dimensional plane. The lab has several platforms of various sizes that act as vehicle simulators for testing sensors, control algorithms, mechanisms, etc. One of these platforms is a small spacecraft simulator, which can be tethered to simulate a space tug.

In the last several months, the FFRL team has been working with MSFC's welding group to conduct a laser beam welding demonstration on air bearing platforms. This demo is utilizing a space tug simulator to fly up to a floating weld platform, where two parts are clamped together and laser welded. The space tug simulator has an air bearing to provide float, as well as several actuated air thrusters to provide propulsion and make the simulator maneuverable. Currently, flights of this simulator are completed by a human operator. A Radio Frequency (RF) hand controller sends signals to both actuate and fire three sets of thrusters on the simulator. This makes any maneuvers of the space tug highly subject to human error, and operators must have dedicated practice time before being able to perform maneuvers with any sufficient reliability. For the current laser welding demonstration, human operated performance is sufficient, but future implementations of in-space welding and other ISAM efforts will require higher precision, reliability, and autonomy.

MSFC has funded a project that will allow a small team in the FFRL to develop the next generation of space tug simulator, which will be automated. Closed loop control will allow a user to command a position, or set of positions, that the simulator will be able to "fly" to on its own. This Maneuverable Automated Tethered Spacecraft (MATS) simulator will have configurable design, to allow a variety of payloads and mission configurations to be demonstrated on the air bearing floor. This will be an invaluable test bed for low and mid TRL advancement for space tether mission subsystems, such as more advanced demonstrations of in-space welding. Once one MATS simulator is constructed and demonstrated effectively, several more can be built, enabling more advanced tether missions; Electric Sail test beds, sensor arrays, and other science-enabling missions.

This paper will detail the design and test of the FFRL's MATS simulator, including efforts to establish closed loop control and autonomous capabilities. It will also detail use cases for this technology, and how it will further develop both develop science and exploration missions.

1. Introduction

Space tugs are small spacecraft typically used to transfer satellites and other cargo into higher orbits. A tethered space tug – a small vehicle attached to a larger one via a mechanical tether – has several key applications for space operations. In-Space Servicing, Assembly, and Manufacturing (ISAM) covers a wide range of activities that are and will be necessary for enabling long-lasting and high performing spacecraft and payloads. This includes, but isn't limited to, construction and maintenance of large space structures and stations; crewed Moon and Mars missions and surface operations; and satellite extension missions. Tethered vehicles are a promising tool for enabling ISAM activities. These vehicles would be housed on larger spacecraft, such as the International Space Station (ISS) or NASA's Lunar Gateway, and deployed for a variety of purposes, depending on how the vehicle is outfitted. When these activities are complete, the space tug can be reeled back to its host spacecraft via electrical power. These vehicles would have more maneuverability and flexibility in motion, and in application, than larger spacecraft.

The Flat Floor Robotics Lab (FFRL) at NASA's Marshall Space Flight Center (MSFC) contains a 44 by 86-foot air bearing epoxy floor. By supplying air to bearings placed on the floor, spacecraft simulators, test beds, and other platforms can be floated across the floor with minimal friction. This allows these platforms to experience partial microgravity dynamics, without the high cost and complexity of a flight experiment. The FFRL is able to machine air bearings in-house, which gives the team high flexibility in the design of air bearing platforms.

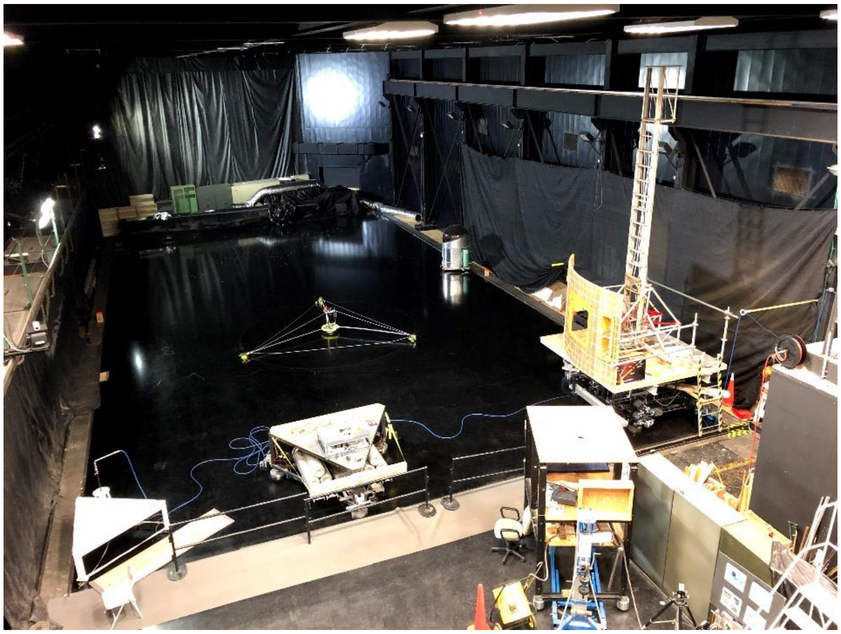

Figure 1. The Flat Floor Robotics Lab, featuring a 44 x 86' air bearing epoxy floor.

The FFRL has worked on tethered space tugs for many years through the development of small spacecraft simulators, referred to as 'microbases.' As spacecraft have gotten smaller over decades of space development, so have the simulators needed to test them. Microbases developed in the FFRL have two main characteristics – air bearing capability and thruster capability. Previous microbase iterations, such as the one shown in Figure 2, have an air bearing base (1), powered by Ryobi air compressors (2). These are commercial off the shelf (COTS) battery powered air pumps that can run for 90 minutes on a single charge. Two Ryobi compressors are enough to float a 40-pound microbase. The microbases also use 24V solenoid valves (3) with COTS high purity air (HPA) paintball tanks (4) for thrust capability. The facility contains an HPA fill station that can fill tanks up to 3000 PSI.

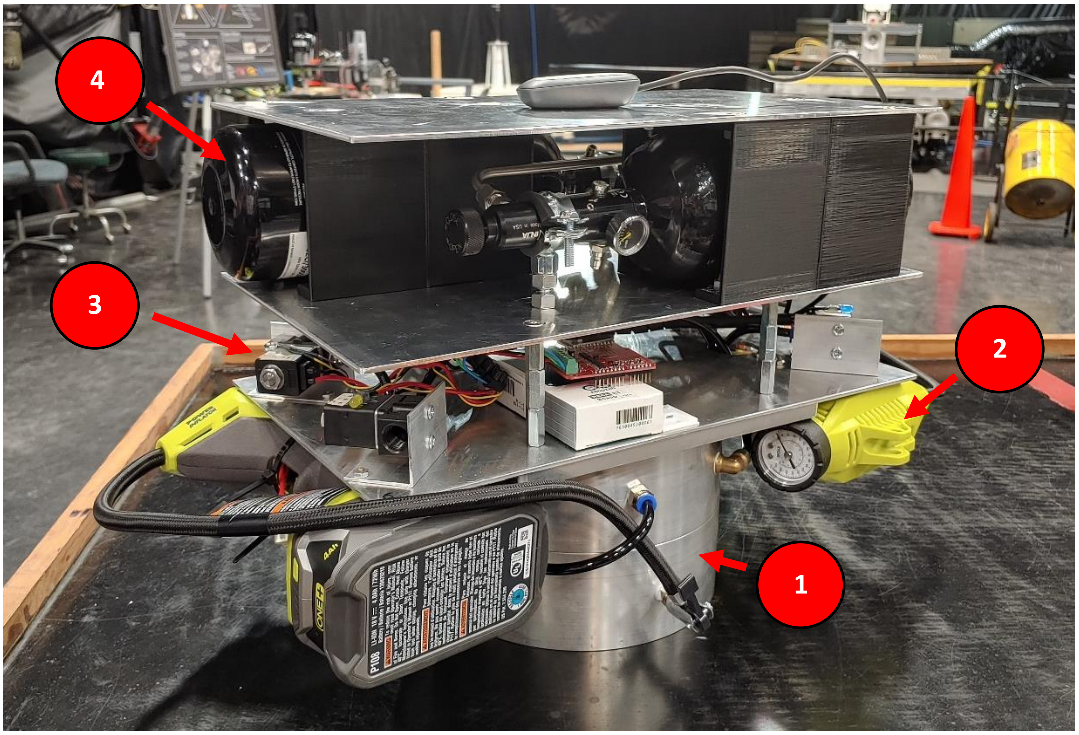

Figure 2. A fully constructed microbase in the FFRL.

Iterations of microbases have previously been deployed on tethers on the epoxy floor. Figure 3 shows the first generation microbase, with a tether reel located off of the floor. The microbase would be commanded via remote control (bottom center of figure), and deploy the tether attached to its center.

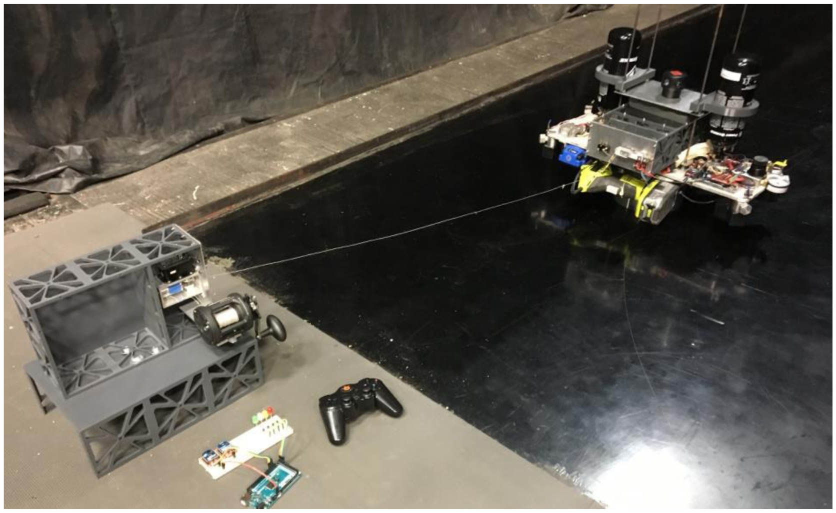

Figure 3. 1st generation tether deploying space tug simulator.

Microbases, both tethered and untethered, have been adapted for different tests and demonstrations in the FFRL. Most recently, a microbase was used to facilitate a demonstration of in-space laser beam welding. This was done using two air bearing platforms – one microbase, and one air-bearing mounted robotic arm, with a laser welder affixed to the end effector. To conduct a weld fully on air bearings, the microbase was flown to the laser welder platform, where two aluminum parts were mated together with a pneumatic clamp. With the platforms connected to each other via the clamp, and floating on air bearings, the robotic arm positioned the laser welder and performed a spot weld.

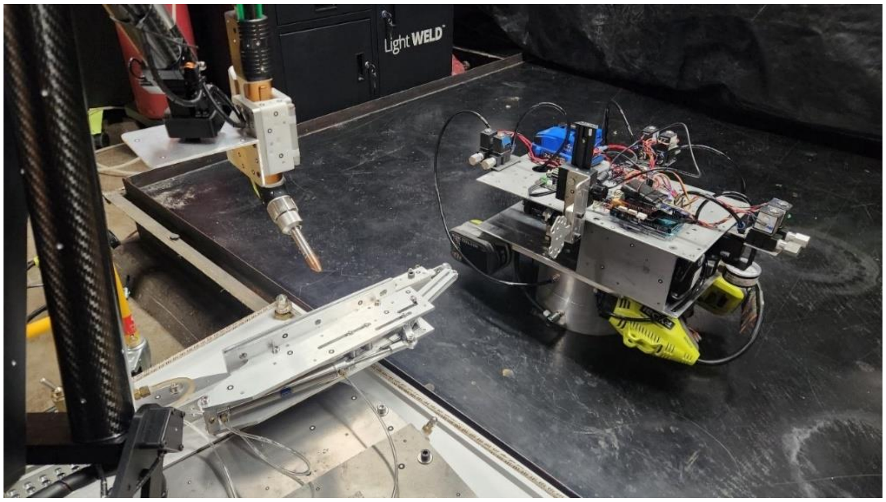

Figure 4. Air bearing laser welding demonstration.

Currently, all the microbases in the FFRL are piloted by a human operator, using an RF receiver and joystick controller. This makes control of the bases highly imprecise and dependent on the skill of the pilot, and the amount of experience they’ve had maneuvering the bases on the floor. For past activities, including the above laser welding, this level of control was sufficient, or the bases were used passively as air bearing platforms, with no need for control. However, implementation of in-space welding and other ISAM functions in future missions will require higher precision and autonomy. To enable this testing, the FFRL microbase is being upgraded to utilize a closed loop control scheme. By using indoor navigation systems and existing capabilities in the FFRL, the next iteration of the microbase, hereby referred to as the Maneuverable Autonomous Tethered Spacecraft (MATS) simulator, will be able to approach a user-defined location on the lab’s epoxy floor.

2. Methodology

2.1. Structure

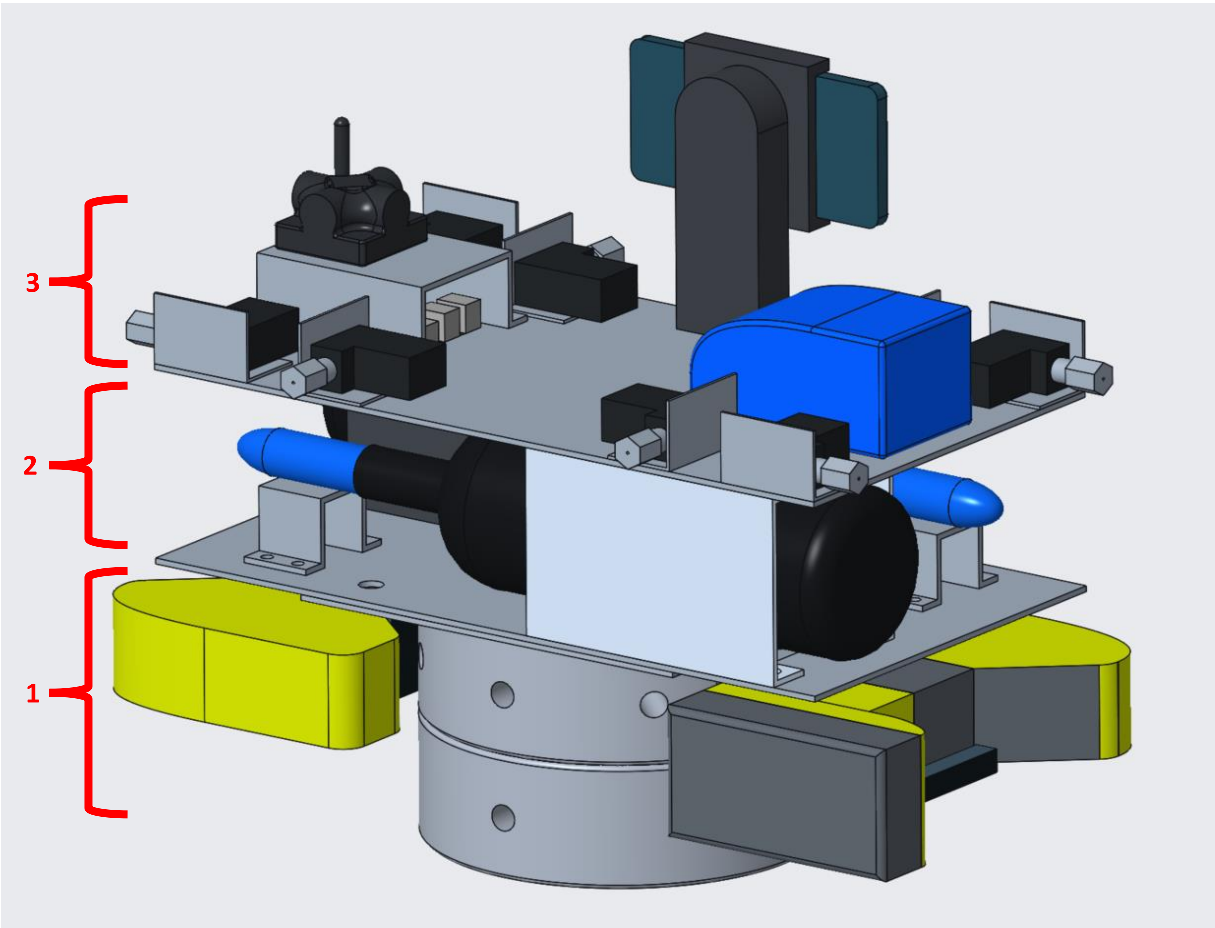

Figure 5. MATS Simulator Design.

The MATS simulator is best described in three levels, indicated in Figure 5.

1. **Air Bearing Deck:** The air bearing stack contains an 8-inch diameter air bearing, and the plenum. The HPA supply is first routed to the plenum for even distribution between the eight thrusters. The plenum is sealed with a close out plate and O-ring, on which the pneumatic deck is fastened. To save space and minimize hose distance, the Ryobi air inflators are mounted underneath the pneumatic deck and connected to valves on either side of the air bearing.

2. **Pneumatic Deck:** The pneumatic deck contains the HPA system for supplying the simulator's eight thrusters. HPA is supplied from two 62 cubic inch, 3000 PSIG paintball bottles. These tanks are COTS, meet reliable consumer safety standards, and contain built-in regulators that drop outlet pressure to 850 PSIG. These tanks screw into Universal Fill Adapters (UFAs) that allow the air tanks to be open and closed as needed. The 850 PSIG out of the tanks is routed to another regulator, which drops the pressure to 100 PSIG. Past this regulator is a pop off valve to prevent pressure over 110 PSIG from entering the thrusters, and a ball valve for opening and closing the air supply. Past the ball valve, the air is routed to the plenum and to each thruster, via flexible tubing. Figure 6 below details the pneumatic deck design and relevant air pressures.

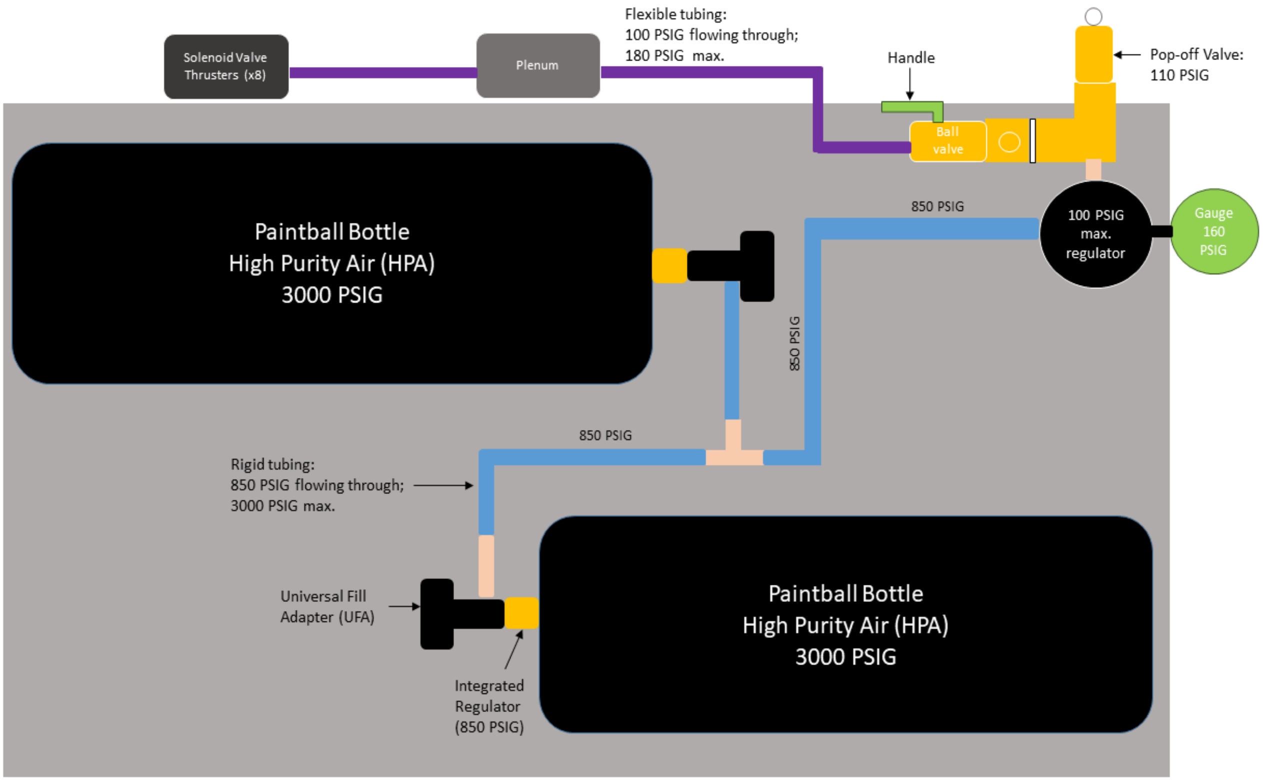

Figure 6. Pressure schematic for the MATS simulator pneumatic deck.

3. **Electronics Deck:** The electronics deck sits at the top of the MATS simulator. It holds the eight thrusters as well as the other electronics equipment necessary to operate the simulator, and a 24V battery. The components on this deck and their functions are elaborated on in Section 2.2.

Not shown in Figure 5 above is the tether attachment point. This will be a fixture mounted to the pneumatic deck, as this is closer to the center of gravity of the simulator. Previous tether work has shown that a flexible boom attached to the tether allows for an added element of control. By articulating this boom, the simulator can use the tension in the tether to achieve additional yaw control. This has been shown on a previous microbase design utilizing a flexible boom attached to a thruster pod articulated with a servo. This is shown in Figures 7 and 8 below.

Figure 7. Microbase with tether and boom attached to reel mechanism.

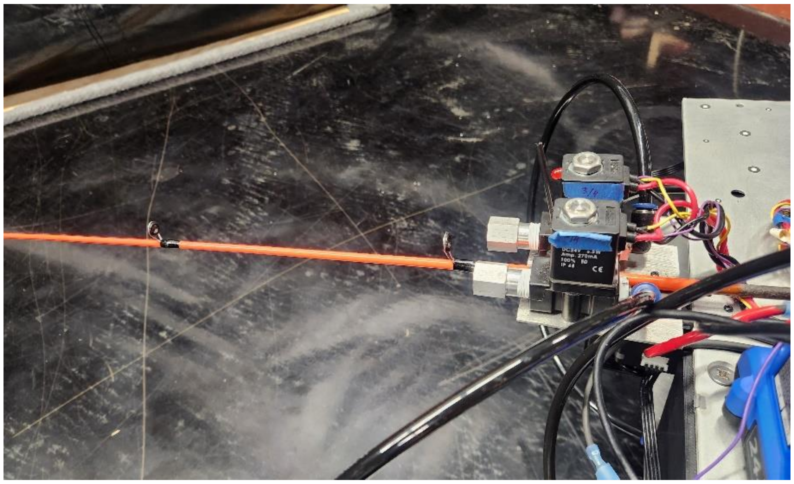

Figure 8. Close up on tether boom and articulated thruster pod.

The addition of this tether articulation is a goal for the MATS simulator, and is currently a work in progress. This is discussed more in Future Testing in Section 4.

2.2. Avionics

Previous microbase iterations that featured human-in-the-loop (HITL) control utilize an Arduino Mega microcontroller and RF receiver. The microbase design shown in Figures 7 and 8 also used servos to allow pods of thrusters to fire at different angles.

The MATS simulator design, due to higher demands for on-board computing, utilizes a Raspberry Pi Model 5 as the main flight computer. To allow for finer control of the microbase on the epoxy floor, eight fixed thrusters are used. This limits the electrical and computational load required by actuated thrusters to achieve fine adjustments. Having the electronics deck on top of the stack allows for easy access to connect cables, check wiring, replace batteries, etc. A high level schematic of the avionics is shown in Figure 9.

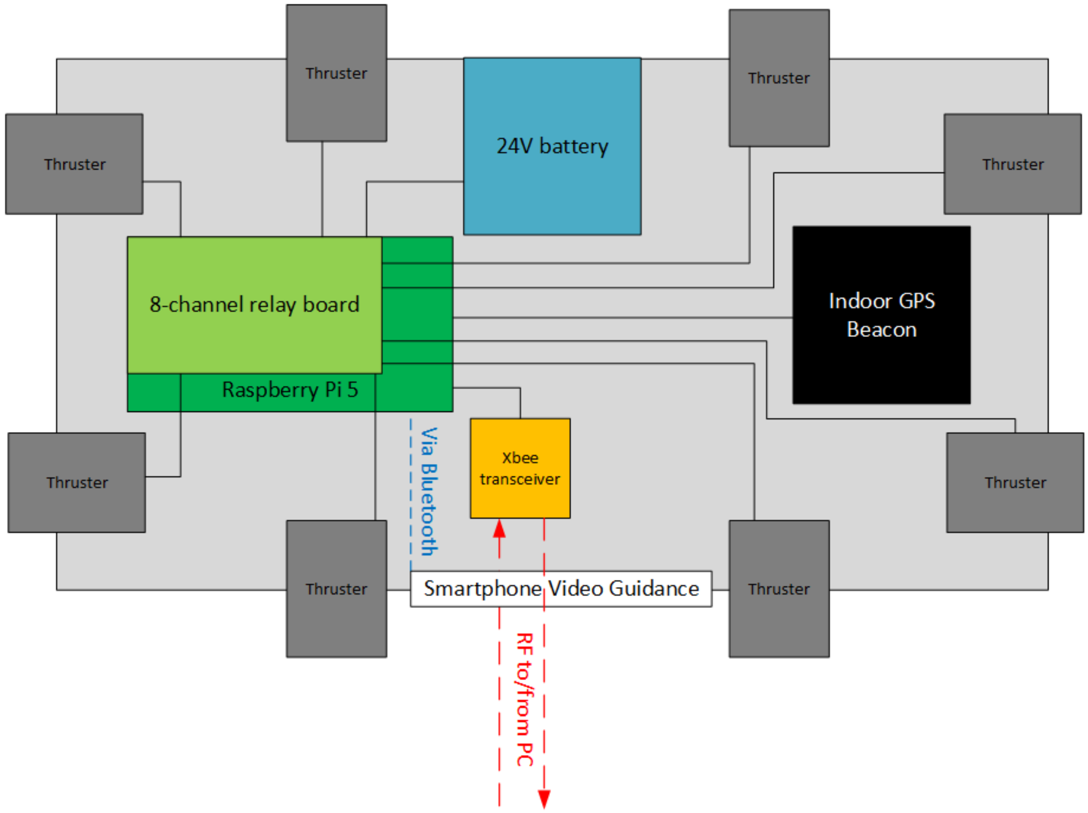

Figure 9. MATS simulator avionics schematic.

The MATS simulator utilizes two guidance, navigation, and control (GNC) sensors, both of which are located on the electronics deck:

2.2.1. Marvelmind Indoor GPS System

The Marvelmind Indoor Global Positioning System (GPS) is a COTS product that utilizes ultrasonic beacons to establish a positioning system. Stationary beacons are used to establish a perimeter, and mobile beacons within this perimeter can report their location within +/- 2 centimeters. This is calculated via trilateration, using the propagation delay of ultrasonic signals [1].

Marvelmind's GPS system can be used in different configurations, depending on the application. The FFRL needs the capability to support multiple mobile beacons on the epoxy floor without decreasing location update rate, which is achieved through Marvelmind's Inverse Architecture (IA). IA requires stationary beacons of unique frequencies that can maintain line of sight to the mobile beacons within their perimeter. The difference between stationary and mobile beacons is entirely software defined – any beacon can be used as a mobile or stationary beacon. As long as the stationary beacons can maintain unique frequencies, this is true of IA as well.

In the FFRL, six beacons have been mounted about the perimeter of the floor, 5.3 meters/17.5 feet above the surface of the epoxy floor. All mobile beacons used in IA can maintain an update rate of 40 Hz, which is not affected by the number of mobile beacons that are active.

The central controller of the system is a USB modem that connects to a computer. Any computer that can run Marvelmind's GPS Dashboard software can interface directly with the system using the modem.

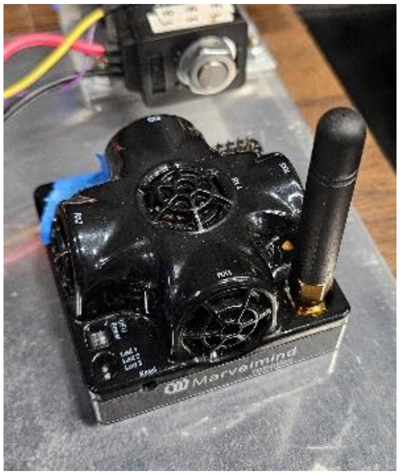

Figure 10. Indoor GPS beacon from Marvelmind.

In many space applications, +/- 2 cm positioning accuracy will not be precise enough. For autonomous maneuvering of the MATS simulator, the indoor GPS system will be used for coarser location information. For more accurate approach and positioning to a specified target, an additional Smart Video Guidance Sensor will be used.

2.2.2. Smart Video Guidance Sensor

To conduct more precise maneuvering relative to a target, MATS utilizes the Smart Video Guidance Sensor or SVGS for relative positioning information. SVGS has an extensive heritage dating back to the Video Guidance Sensor which was tested as part of a couple space shuttle missions [2]. The basic design of SVGS consists of two components: a target and a smartphone. The target consists of LED lights arranged in a known pattern which is then processed by the smartphone using collinearity equations to determine relative position and attitude information.

Figures 11 and 12 show what a SVGS target looks like. The LED targets are customizable and can be changed to fit different form factors. SVGS has been used as a part of several projects including proximity operations on ISS. The smartphone then can talk to the MATS controller utilizing a Bluetooth connection.

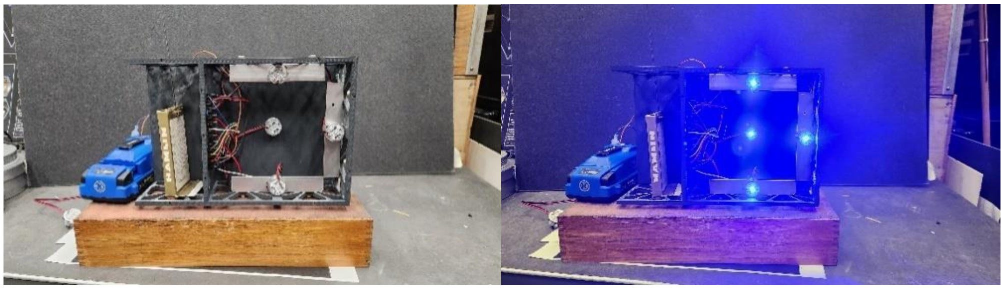

Figure 11 and 12. LED target assembly, powered by a 24V battery to light four high-intensity blue LEDs.

Figure 13. Ruggedized Samsung smartphone in adjustable mount attached to the electronics deck.

2.3. Software

2.3.1. Methods and Methodology

The guidance, navigation, and controls software was first developed in Simulink with C++ and MATLAB blocks, and then adapted into a usable format for the Raspberry Pi. This software was broken up into three subsystems: guidance, navigation, and controls. The navigation system estimates the current state of MATS, in two degrees of translation (XY) and one degree of rotation (yaw). The guidance system takes this estimate of states and compares them to the desired position, and determines what direction and rotation steps to take. The control system takes these direction and rotational commands and determines what thrusters to fire as part of MATS system. MATS can be controlled in two modes: manual and automatic. For manual mode, it takes direct commands from a connected computer in combinations of the two axis of translation and one axis of rotation. Automatic mode takes input for a position and attitude on the FFRL and has a software flag for whether to utilize SVGS and SVGS's current position and rotation.

The navigation information for MATS is provided by the GNC sensors described in Section 2.2. Utilizing a pair of indoor GPS beacons, MATS can get an estimated state and an estimated rotation based on the location of the two beacons on the floor. This gives MATS general enough information to be able to navigate to any position on the flat floor. SVGS is then triggered if the software flag is active for SVGS used and it reaches the cone of vision for the SVGS target. SVGS enables MATS to conduct much more precise maneuvering relative to a fixed target and could be used for various proximity operations such as sample docking between a chaser and target spacecraft, inspection operations, and more.

The guidance system of MATS is further broken into two separate parts: the path creation portion and the path following program. In automatic mode, MATS takes in a desired end point and rotation. The end point is then processed utilizing two algorithms in the following order: nearest node algorithm then A star path planning. The nearest node algorithm takes the current position and the desired position and determine the closest node to each of those points. These nodes are then a part of a larger grid system that encompasses the entire FFRL. This enables the team to have dedicated keep out areas of the FFRL that are dedicated to other use cases such as other large microbases. Once the end and start node are determined, MATS utilizes the A star algorithm to find the shortest path between its present location and the final location. An example of these two algorithms working in tandem can be seen in Figure 14.

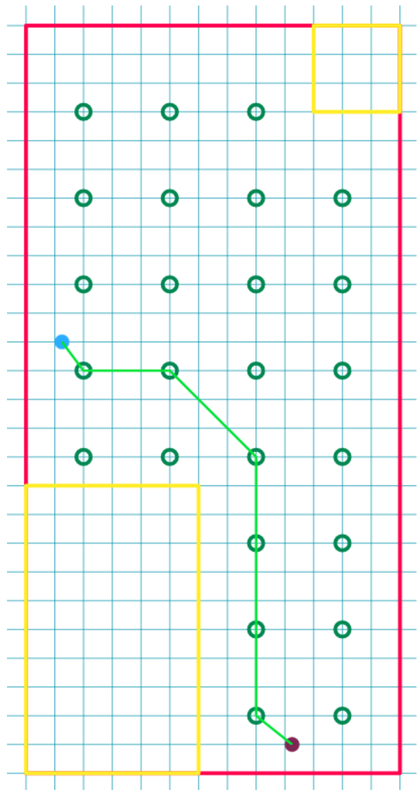

Figure 14. A* Pathfinding and Nearest Node Algorithm Example

After the path is created, the guidance system focuses on updating the current waypoint to iterate it through each of nodes until the final destination is reached. This updating system is run continuously while the more processor intensive pathfinding is only run once at the beginning of the initialization of automatic mode. This enables the guidance subsystem to be running continuously along with the navigation and control system. The guidance system then takes the current position and outputs a position error which is then passed on to the control system.

The control system takes in the guidance errors and utilizes position and velocity errors to create a thruster command through the use of a phase plane controller. Phase plane controllers are common on spacecraft and are used to command the thrusters in order to meet the guidance solution. A sample phase plane controller can be seen in Figure 15.

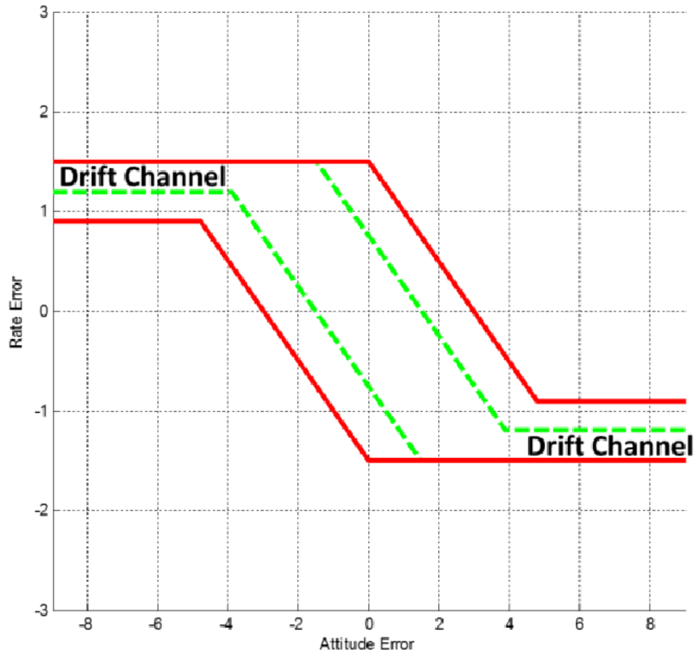

Figure 15. Example Phase Plane Controller

The phase plane controller is tuned to ensure the microbase doesn't travel too fast across the FFRL to prevent damage to other objects on the floor and traverse at safe velocities. The microbase controller features twenty-seven thruster mappings in order to meet all possible commands received to the system.

2.3.2. Ground Station GUI

MATS has a purpose-built Graphical User Interface (GUI) for commanding the simulator from a PC, crafted using Python and the tkinter library.

The GUI serves as a centralized control hub, enabling users to oversee and direct the microbase's movements and operations with ease. It includes several key features aimed at enhancing user experience and operational efficiency.

- **Position and Orientation Display**: Real-time display shows the simulator's current position in XY coordinates (meters) and its yaw angle in degrees. These XY coordinates, and those of the target position, are defined by the map generated by the Indoor GPS system.
- **Target Position Input**: Users can input desired target positions for the simulator, specifying XY coordinates and yaw angle in degrees. This functionality empowers users to set precise navigation goals for the microbase, facilitating autonomous or directed movement towards designated locations.
- **Manual and Automatic Control Modes**: The GUI allows toggling between manual and automatic control modes. In manual mode, users have individual control over the simulator's thrusters, with the ability to toggle individual thrusters on/off for troubleshooting purposes.
- **Keyboard-based Maneuvering**: For maneuverability in manual mode, the GUI allows users to execute basic direction inputs from the laptop keyboard. This is achieved using arrow keys for translation and <> keys for rotation.

- **Tethered/Untethered Mode Toggle**: A toggle switch is provided to indicate whether the microbase is tethered or untethered. This distinction will influence the implementation of tether-based control.
- **Return to Stowed Position Command**: A dedicated command is included to initiate the simulator's return to its stowed position. This will be a defined location on the edge of the epoxy floor, that can be moved as needed.

The GUI is designed with a user-centric approach, prioritizing intuitive navigation, and comprehensive control options.

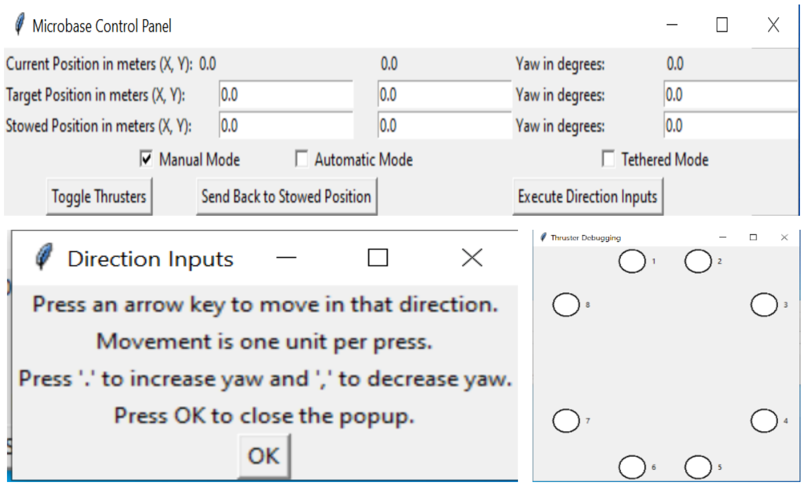

Figure 16. GUI for MATS simulator program

Figure 16 above shows a breakdown of the different GUI windows. These windows have each of the different functionalities described above. As MATS matures, this GUI will be developed to more seamlessly represent a control panel for various ISAM demonstrations utilizing MATS simulator.

3. Results

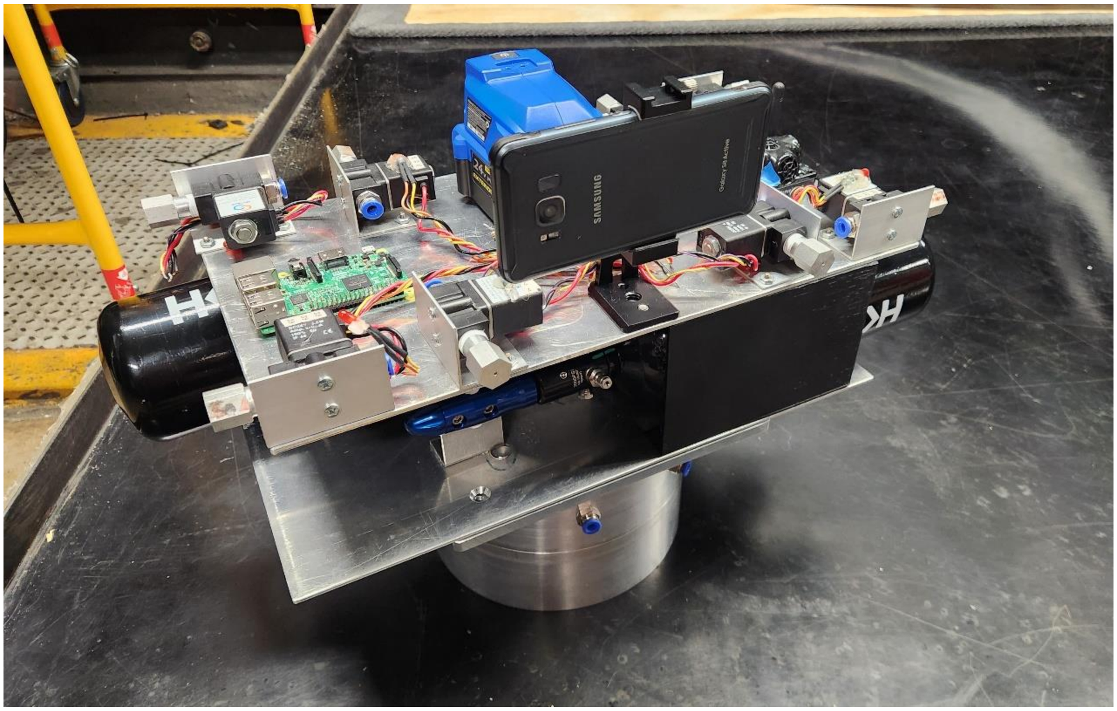

Figure 17. Constructed MATS simulator.

As of April 2024, the MATS simulator is near full construction. The pneumatic deck and electronics were reconfigured to account for updated design, such as larger volume air tanks and new thruster configuration. The SVGS ruggedized smartphone is attached via an adjustable mount that leaves the camera unobstructed. The last component of the pneumatic system is installing the flexible tubing between the air tanks, plenum, and thrusters. The pneumatic fittings on the thrusters may be replaced with 90-degree elbows for easier routing of the tubing.

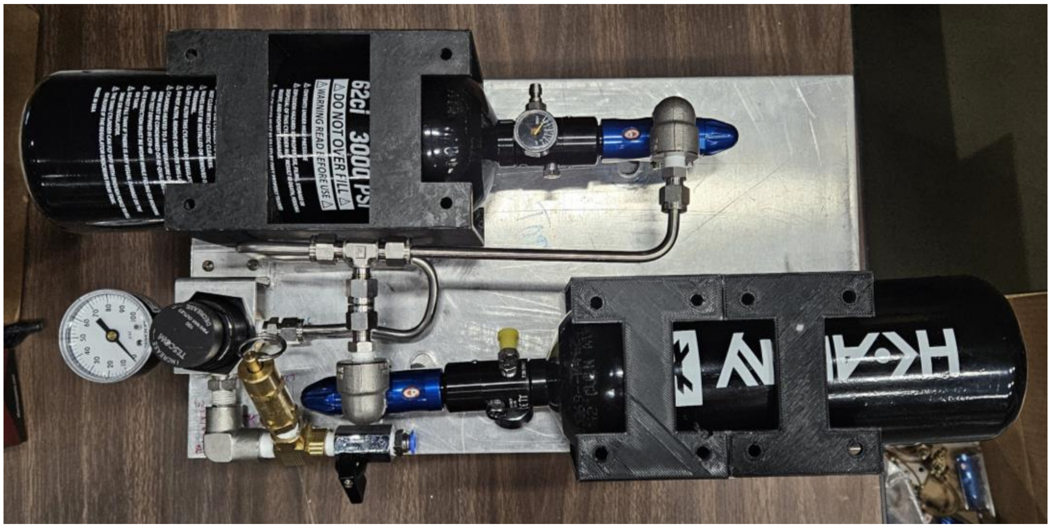

Figure 18. MATS simulator pneumatic deck.

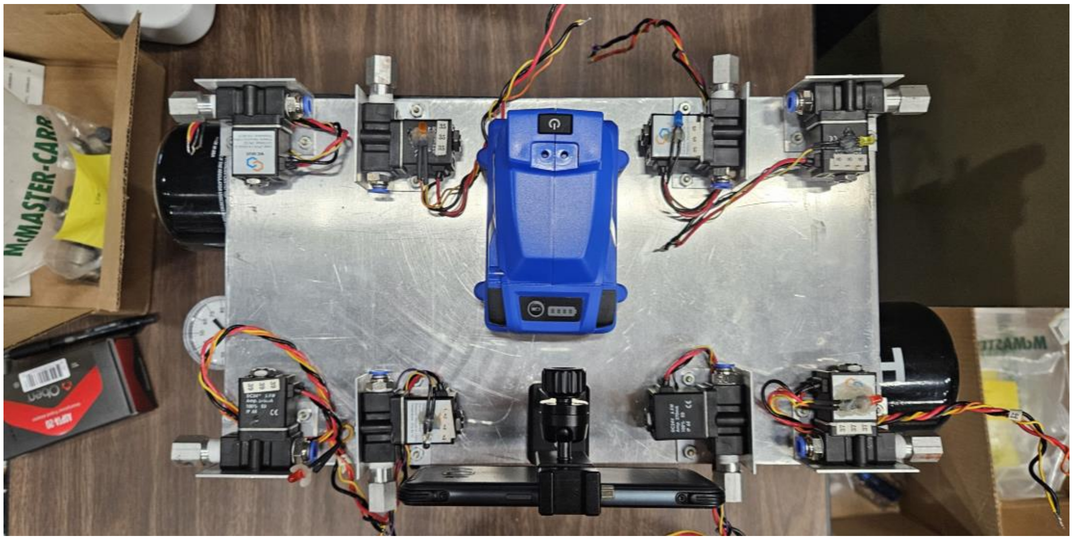

Figure 19. MATS simulator electronics deck

The major components that remain are avionics and tether implementation. The Raspberry Pi, 8-channel relay board, and Xbee transceiver, shown in Figure 20, will be programmed and wired into the electronics deck. The Indoor GPS beacon, which operates on its own battery, will also be added, and troubleshooting of the functionality of the communications system will be performed in the lab.

Figure 20. Raspberry Pi 5, 8-channel relay, and XBee Model 3

4. Future Testing

As this project was funded for US federal fiscal year 2024, the design and implementation stages of the project are still underway. Throughout the next several months, the Simulink algorithm will be adapted to function in the integrated avionics system on the MATS simulator. Iterative updates will be made to the control algorithm by conducting flight tests on the epoxy floor. First, commanding the simulator to navigate shorter distances, then increasingly further distances. The end goal is to have the MATS simulator traverse the length of the epoxy floor to an SVGS target mounted on the opposite side, totaling just shy of 86 feet. Distance between the target position and final position of the MATS simulator will be measured to accurately assess the accuracy of the simulator's positioning.

These tests of the simulator's performance will first be performed untethered. Then, the articulated tether will be integrated onto the microbase using a simple mount attached to the simulator's pneumatic deck. The tether will be articulated via a 12V Lynxmotion Smart Servo, which has been used on previous microbase designs. This servo will be integrated into the avionics system through either the Raspberry Pi directly, or through an Arduino that interfaces with the Pi. Interfacing with the Pi directly would save power and volume, but the Lynxmotion control boards are designed to integrate specifically with Arduino products. Alternatively, another servo will be used that can integrate more seamlessly into the Pi. This is an ongoing trade study.

5. Use Cases & Applications

NASA tracks several key technology gaps that need to be addressed to reach both short- and long-term space exploration goals. Tethered spacecraft address several of these gaps, particularly related to in-space manufacturing, maintenance, repair, construction, and microgravity robotic mobility. Some specific applications related to current NASA work are:

5.1. In-Space Servicing, Assembly, and Manufacturing

As detailed in Section 1, the previous microbase design has been used for demonstrations of in-space laser beam welding. Previous demos required trial and error for a human pilot to successfully control the microbase and fly it into the correct docking position. The ability of the MATS simulator to be commanded into place adds much higher precision and repeatability to continue conducting laser welding demonstrations on air bearings.

MSFC is currently working towards laser welding parabolic and suborbital flight experiments, and the FFRL is a proving ground for integrating and testing the mechanisms and procedures needed to make in-space laser welding a reality. With the high level of precision afforded by the SVGS, future tests could see the laser welder torch mounted to the MATS simulator itself, using the welder's umbilical as a tether to deploy and reel in the simulator. This capability has applications for on-orbit welding, which can be used for assembly or repair of metallic structures in the vicinity of a space station such as ISS or Gateway.

But components don't need to only be welded – for space applications, they must also be assembled into larger structures. With air bearing capability, on-orbit assembly technologies can be integrated and tested on floating platforms to achieve partial microgravity dynamics. This would be a stepping stone to a more complex flight demonstration.

5.2. Electric Sail Deployment

Electric sails or e-sails are a propulsion concept that utilize long positively charged tethers which exchange momentum with the solar wind to create a propulsive effort. In order to deploy the tethers, one proposed method to deploy these long tethers is to use booms to extend the end masses a set distance and then spin the system up. After the system spins up, the end masses can be released and utilizing conservation of momentum be extended to their full length. MATS can be used as part of a ground demonstration with multiple MATS forming the end masses utilized by the e-sail system.

MSFC has previously conducted an e-sail deployment demonstration on the FFRL utilizing the method described above, however, the end masses did not have active control features like MATS. MATS would offer a capability to control the end masses which would enable a complete end to end deployment demonstration utilizing a system that would more closely resemble a true e-sail system. Additionally, it would help serve as a basic proof of concept for formation control in a near frictionless environment.

MATS is an enabling technology that can help mature key e-sail systems and help bring it from its current state to flight.

5.3. Conductive Tether Integration

Tethered spacecraft can utilize electrified tethers to transfer power and communications between platforms. A larger host platform, such as ISS or Gateway, can house the power supply and flight computers, and a conductive tether can provide power and communicate commands directly to an umbilical vehicle, with only the necessary hardware on board to perform in-orbit operations. When the tethered vehicle needs to be returned, it can be reeled in entirely via electric power, greatly reducing fuel costs for the tethered vehicle. As described in Section 5.2, these conductive tethers are also the driving thrust mechanism behind Electric Sails.

The FFRL has done previous work into composite conductive tethers. AmberStrand is a composite conductive fiber originally funded by a NASA SBIR awarded to Syscom Technology Inc. AmberStrand is a hybrid metal-polymer cable, which is both light weight and high strength. Glenair, a connector and cable manufacturer, offers AmberStrand in custom shielded twisted pair conductors. The FFRL has purchased 95 feet of a three-conductor AmberStrand cable in order to develop a test bed for using this cable as a mechanical and electrical tether [3].

With the MATS simulator being developed simultaneously, this conductive tether can be integrated into a MATS simulator to demonstrate the ability to provide power and communications to thrusters, cameras, sensors, etc. to a tethered spacecraft.

5.4. Payload Capture/Debris Removal

An electric tether reel mechanism has potential as a payload capture or debris removal device. With an appropriate end effector installed on a spacecraft, payloads can be approached, captured, and reeled in to a host spacecraft.

6. Conclusion

Tethered spacecraft have many applications for in-space activities. Development of these capabilities is critical to closing key technology gaps that are standing between the space community and sustainable exploration goals. Having a ground-based test bed for tethered spacecraft simulators is a low-cost, high-reward way of further developing tethered spacecraft technology. The Maneuverable Automated Tethered Spacecraft simulator is the next step in the development of this capability. The size of MSFC’s epoxy floor, combined with rapid prototyping, machining capabilities, and experience with air bearing platforms, makes the Flat Floor Robotics Lab a premier facility for space tether development.

7. References

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