

Autonomous Cargo Management & Distribution for Surface Logistics

M2M X-Hab Academic Innovation Challenge FY23 Final Report



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Abstract

The BLISS: Cargo Management and Retrieval project is a submission to the NASA X-Hab challenge for an autonomous system of cargo storage and retrieval for use on the Lunar Gateway system. The system is designed to stow 5 tonnes of cargo within a capsule that has an internal diameter of 3.2 meters and height of 6 meters for cargo that will be up to 0.8 meters in any one dimension. The system will inventory all cargo items placed in each cargo container and then track the containers using RFID chips for autonomous stowage and retrieval upon request by on-station crew.

Team Breakdown

The Bioastronautics and Life Support System (BLiSS): Cargo team consists of four sub-teams concerned with dedicated tasks integral to mission success. Each sub-team maintains constant communication in the form of weekly meetings focusing on tracking weekly activities and progress for all assigned tasks. The four sub-teams are as follows:

Human Factors – responsible for all aspects of the project regarding crew operations and interactions with the system, such as the user interface and cargo organization design.

Robotics – responsible for all actuators within the system as well as the parts that are actuated, such as motors and the chain/gear system.

Sensors & Software – responsible for all sensors and their corresponding software for safety interfaces as well as actuator programming.

Structures & Manufacturing – responsible for all structural components of the system, such as the central support system and cargo container exterior design.

As a student organization, BLiSS teams consist of a broad range of students. For those projects which were part of the X-Hab program, BLiSS partnered with 2 systems engineering classes at the University of Michigan. As in years past, BLiSS was part of the 582/583 course progression for graduate students learning to apply systems engineering principles of space based applications. BLiSS also partnered with undergraduate students in the x88 classes: a course series within the Aerospace Engineering department focused on model-based systems engineering with an emphasis on delivering a manufactured final product at the end of the year. Additionally, BLiSS performed outreach at the start of each semester to recruit more members that were not affiliated with these classes. A full list of team members is provided in Table 1.

Table 1: Full List of Team Members.

Project Leads			
Kieana Fana	Jessica Fisher	Luke McFarling	
Human Factors	Robotics	Sensors & Software	Structures & Manufacturing
<i>Rohan Valluri</i>	<i>Christopher May</i>	<i>Adam Jones</i>	<i>Miles Irmer</i>
Maxwell Chappell	Sara Aldawood	Eleanor Haycock	Jackson Albright
Ryan Dick	Tobi Farbstein	Annie Li	Eric Chen
Yilin Fang	Owen Faulkner	George Lu	Jacob Kaspriak
Monica Kalique	Shashank Kalluri	Akashdeep Pawar	Benjamin Vilapanfo
Kasiheng Li	Andrew Stephenson	Cameron Sahagian-Crandall	Richard Andrew Wright
Ilyana Smith		Abraham Skoczylas	
		Mary Smirnova	

System Overview

Project Goal

BLISS: Cargo’s goal is to develop an autonomous system for the Lunar Gateway Logistics Module that will store and retrieve cargo for station crew while requiring less active crew time than the currently used methods on the International Space Station.

Project Objectives

1. Design a system that meets the requirements of the X-Hab Challenge.
2. Develop a functional prototype for the X-Hab Challenge.
3. Advance team members’ understanding of space systems engineering.

Project Deliverables

There are 7 required and 1 optional deliverables associated with this project, including this document as shown in Table 2 below. All of these are primarily for informational and feedback purposes. The one

optional deliverable is the Educational Outreach Report that BLiSS: Cargo has elected not to fulfill. A full breakdown and explanation of each of these deliverables is available in APPENDIX [C]: Data Item Descriptions.

Table 2: 14 Informational deliverables of the BLiSS: Cargo project.

Deliverable Title	Due Date
NASA SDR	October 11, 2022
NASA PDR	November 29, 2022
NASA CDR	February 16, 2023
NASA PCR	April 13, 2023
System Prototypes	May 3, 2023
NASA Final Presentation	May 4, 2023
Technical Final Report	May 31, 2023
Educational Outreach Report (Opt.)	Not Completed

Project Schedule

The project was broken down into a 10-month period beginning in August 2022 and ending in May 2023. The key milestones followed the standard NASA project timeline and included SDR, PDR, CDR, PCR, and a final review. On top of this, to satisfy the requirements for university credit, there were audited internal design reviews for the x88 course sequence and midterm and final presentations for the 582/583 course sequence. All milestones were successfully reached—most important among these being the NASA final review, which took place on May 4th at Kennedy Space Center in Florida. Though manufacturing and prototype testing fell behind schedule, the allotted contingency time allowed for on-time project completion, with prototype construction completed on April 29th with verification and validation testing finalized throughout the following days. A Gantt chart covering the final semester can be seen in Figure 1, and the entire project schedule is shown in APPENDIX [D].

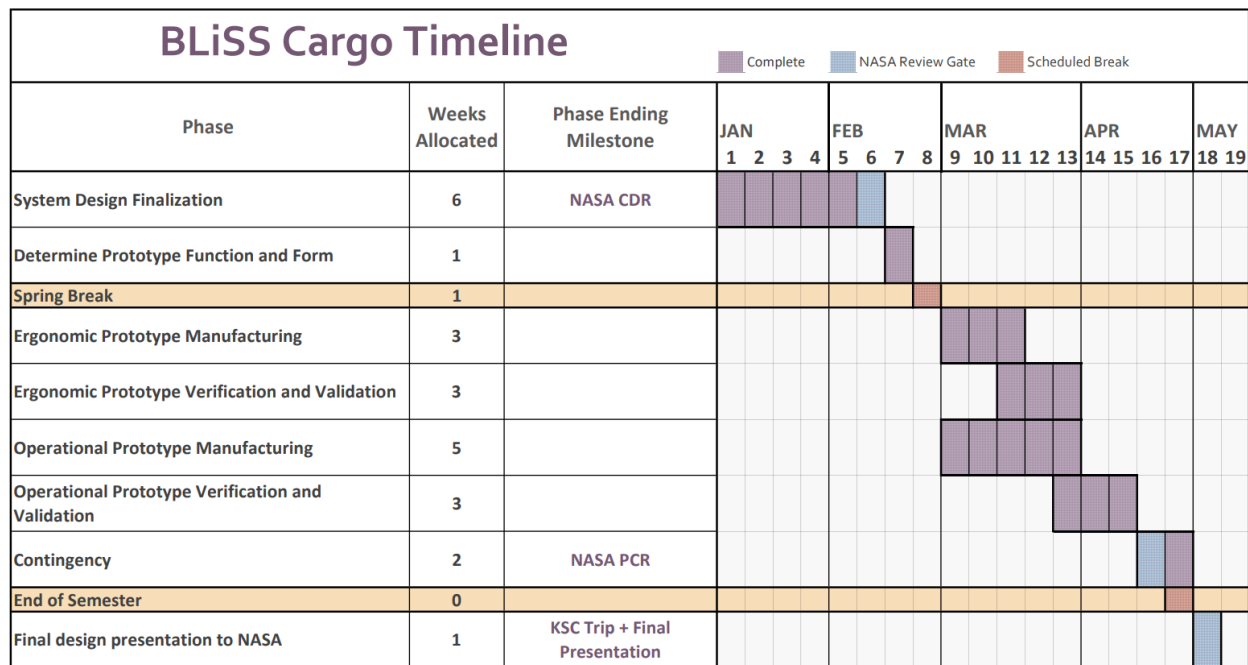


Figure 1: Project Gantt chart starting January 4th and ending on May 4th with the final presentation.

System Requirements

The system is described by a total of 135 requirements. These flow down into secondary, subsystem, and unit-level requirements from the ten top-level system requirements listed in Table 3. APPENDIX [A] contains the complete requirements traceability matrix. Verification plans were developed to confirm that all flowed-down requirements are satisfied by the system prototype. As the BLiSS: Cargo team is not constructing the final system, verification strategies that apply to only the top-level requirements were developed.

Table 3: List of ten top-level system requirements.

Requirement No.	Title	Requirement Description
R1	Microgravity	The system shall function in microgravity
R2	Cargo Delivery	The system shall deliver desired cargo to the Gateway Logistics Module entry point
R3	Cargo Return Requirement	The system shall return various cargo containers from the entry point to a designated position
R4	System Anonymity	The system shall fulfill requests autonomously upon user input
R5	User Interface Accessibility	The system shall be controlled by a user interface(s) accessible from anywhere within the Lunar Gateway
R5	User Interface Accessibility	The system shall be controlled by a user interface(s) accessible from anywhere within the Lunar Gateway
R6	Wet Mass	The combined mass of the system and cargo shall be below 5.5 tons
R7	System Lifetime	The system shall operate for the entire on-station lifetime of 12 months
R8	System Integration With Gateway Module	The system shall be contained within the Gateway Logistics Module
R9	Structural Launch Conditions	The system shall withstand launch conditions
R10	System Fault Tolerance	The system shall have a one fault tolerance with regard to crew safety

Concept of Operations

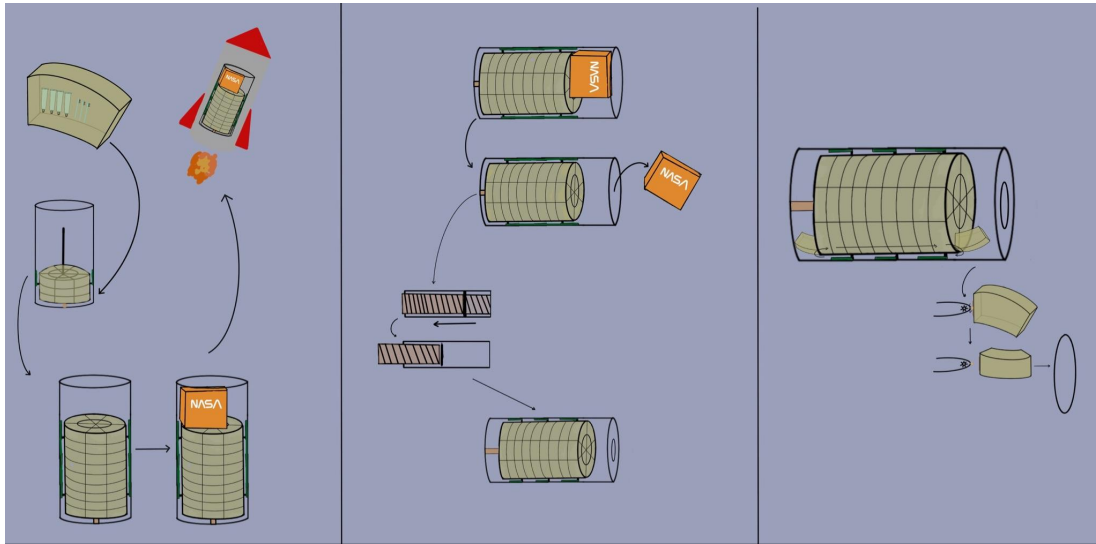


Figure 2: Launch and setup operations.

Figure 2 shows the operations for loading, launching, and, once the Gateway Logistics Module (GLM) is docked to the Lunar Gateway, setting up the system. On the ground, each cargo container is loaded with cargo and latched into its designated place. From this point until docking, the cargo stack rests on the bottom of the capsule. This offsets the weight of the cargo from the actuation system before and during launch. Additionally, this layout leaves space at the top of the capsule—above the cargo stack—to load extra cargo that is not part of the system. The capsule is then launched to the Lunar Gateway. Once the capsule is docked, the extra cargo is removed and the crew can use the user interface to move the cargo stack to its operational position via a leadscrew-actuated elevation system. This operational position allows for the cargo to circulate properly both above and below the main cargo stack.

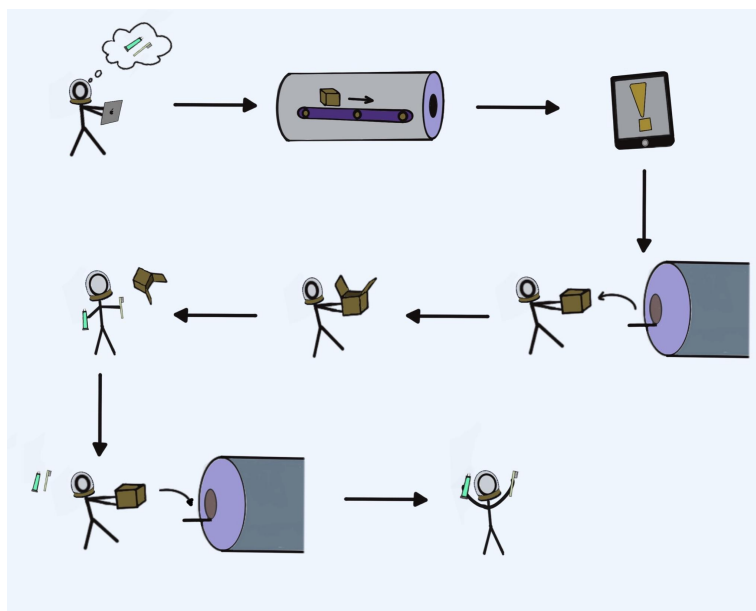


Figure 3: Concept of operations.

Figure 3 shows the overall concept of operations for the cargo delivery system. The process starts when a crew member wants a certain item of cargo. They use the user interface (contained within their personal tablets in the form of an app) to make a cargo request. The system then brings the cargo container that holds that specific cargo to the entrance of the GLM. Once this process is complete, the crew member receives a notification through the user interface saying that their cargo container has been delivered to the hatch of the GLM. The astronaut retrieves the cargo container, takes the cargo out of the container, and replaces the container back into the GLM, where the system then stores the container back in its designated spot. The crew member is left with the desired cargo.

When the GLM's mission is complete, the system will be filled with trash and the GLM will undock from the Lunar Gateway. The GLM will then be inserted into a heliocentric orbit for disposal.

System Architecture

The selected architecture is a system of radial conveyor belts that will transport cargo to the retrieval position at the top of the capsule. These conveyor belts are organized such that concentric wedges of cargo are broken into three sections along the radius of the capsule, providing small, medium, and large cargo sizes. There will be a total of six pairs of concentric wedges, each one with their own conveyor belt systems, for a total of eighteen conveyor belts (six wedges, with three belts each), as shown in Figure 4. This was done to minimize the amount of mass that each conveyor belt is responsible for, as well as to reduce the single points of failure; if one belt becomes inoperable, the crew can still access cargo on all other belts. In the case of belt failure, a crank will attach to the gears of the belt and a standard ratchet such that the crew can manually operate the failed belt. The full system is illustrated in Figure 5 below, with the manual crank and videos of operations found in APPENDIX [B].

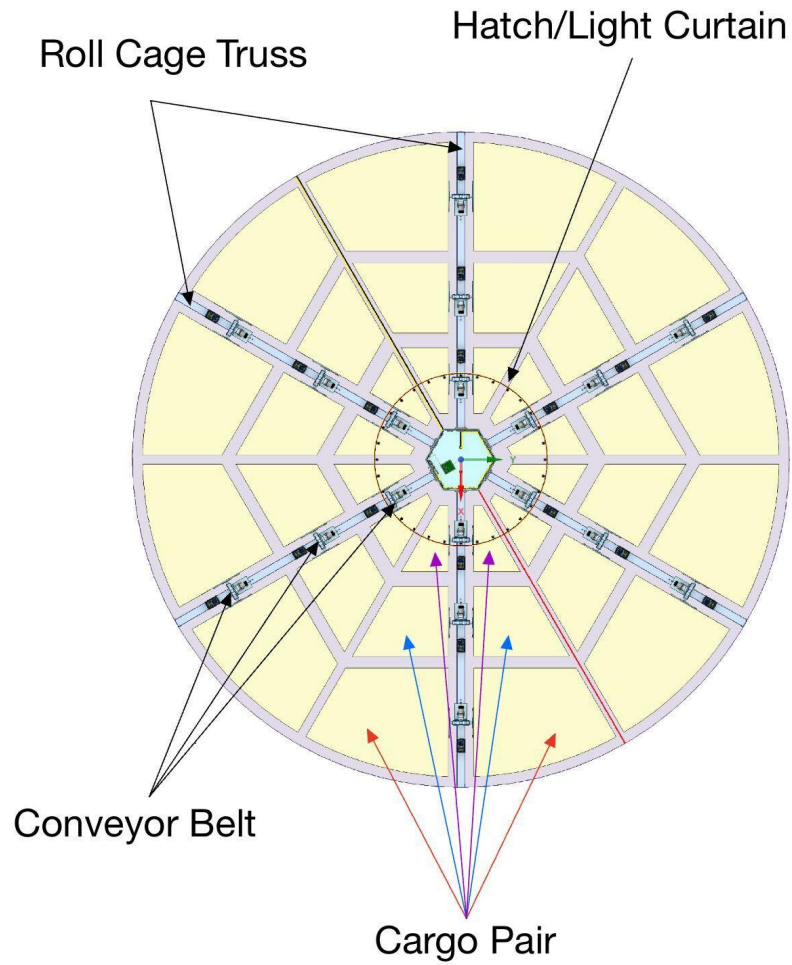


Figure 4: View from hatch side showing all separate cargo pairs and structural components.

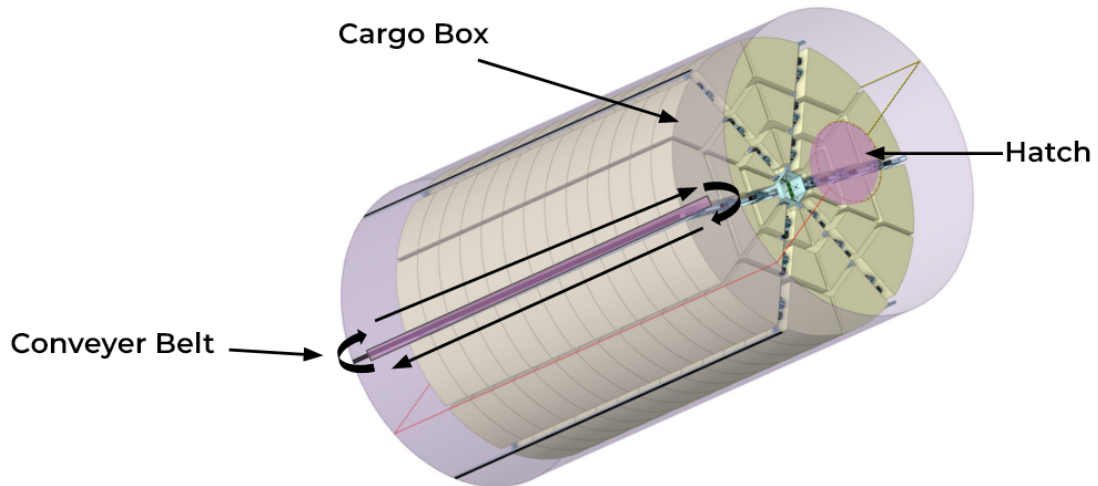


Figure 5: An illustration of the system showing the layout of cargo within the capsule, the direction of cargo travel, and the hatch where cargo is retrieved. There are a total of 18 belts of cargo which each move 28 cargo containers.

The entire system is designed for a capsule that has an internal diameter of 3.2 meters and height of 6 meters. In the launch configuration, the system is able to achieve greater than 75% volume efficiency, with miscellaneous cargo being stored on top of the cargo containers to take up additional space. Once that miscellaneous cargo is unloaded and the system is in its operational state, the system is able to use 55% of the capsule volume for cargo storage.

To counter any rotational forces exerted onto the Lunar Gateway station, the cargo directly opposite of the desired cargo will cycle in the opposite direction of motion. While any imbalances in mass between the two belts will cause imperfect force balancing, the overall reduction in torque applied to the station is still preferable to no mitigation.

Project Budgets

Cost Analysis

BLISS: Cargo budgeted \$ for the prototyping of the system. As shown below in Table 4, all but \$ (5.7%) was spent. All expenses have gone to prototype materials and manufacturing, as expected. The largest costs have come from the ball bearing assemblies and the motors.

Table 4: Detailed cost breakdown by subteam. Total amount spent to date remains under budget.

Robotics	
Component	Total Spent
Fastener	\$
Chain	
Gear	
Lubricant	
Brake	
Cam Latch	
Raw Materials	
Tensioner	
Tools	
Motor	
Motor mount	
Subtotal, Robotics	\$

Sensors and Software	
Component	Total Spent
Microcontroller	\$
Breadboard	
IR Sensor	
RFID	
Connectivity	
Storage	
Motor Control	
Button	
Wire	
Clock	
Power Supply	
Subtotal, Sensors and Software	\$

Structures and Manufacturing	
Component	Total Spent
Ball Bearing Carriage	\$
Ball Bearing Guide	\$
Ribcage Strut/Truss	\$
Lead Screw	\$
Lead Screw Nut	\$
Canvas	\$
Acrylic	\$
Rods	\$
Sheet Metal	\$
Misc.	\$
Subtotal, Structures	\$

Human Factors	
Component	Total Spent
N/A	\$
Subtotal, Human Factors	\$

	Actual	Budget
System Subtotal: \$		
Performance to Budget: \$		

Mass Budget

The total mass of the system without cargo is limited to 500 kg by requirement R6.1 (All non-cargo mass shall be at most 500 kg), with the individual subsystems being further limited from the lower levels of this same requirement as shown below in Table 5. The greatest single-item mass allowance was given to the cargo support cage, with 150 kg, by R6.1.2.2.

Table 5: Mass allocations prescribed by sublevels of requirement R6.1.

ID #	Requirement Text
R6.1.1	The mobility system mass shall be at most 200 kg
R6.1.1.2	The total mass of all actuators shall be no more than 60 kg
R6.1.1.3	The total mass of all cargo interface mechanisms will be no more than 50 kg
R6.1.1.4	Cargo dynamic mechanisms (chain/pulley system components) shall be less than 75[TBR] kg total
R6.1.2	The rigid structural mass shall be at most 255 kg
R6.1.2.1	Cargo partitions structures shall be less than 105[TBR] kg total
R6.1.2.2	Cargo support cage shall be less than 150[TBR] kg
R6.1.3	The sensing/software suite shall be at most 15 kg

Mass budgeting required a different breakdown in components than cost, as shown below in Table 6. Also shown are the current actual design masses for the different system components, which notably shows non-compliance with R6.1.2 with the total actual structural mass coming to 261 kg: 6 kg (2%) over the requirement. The other two subsystems satisfy their respective mass limit requirements, allowing the total actual mass to come to 461 kg: 39 kg (8%) under the overarching 500 kg limit. At this stage of the project, no mass changes are anticipated and the total mass is expected to remain compliant with requirement R6.1.

Table 6: Detailed mass breakdown by subteam. Total mass to date remains under budget.

Robotics			
Component	Budget (kg)	Spent (kg)	Available (kg)
Actuators	20.0	5.9	14.1
Chain	60.0	35.4	24.6
Cargo Latches	55.0	86.2	(31.2)
Cargo Linkage	50.0	46.0	4.0
Motor Controllers	0.5	0.50	0.0
Microcontroller (Actuators)	1.0	0.0	1.0
Actuator Mounting	10.0	4.2	5.8
Tensioner	8.5	12.0	(3.5)
Subtotal, Robotics	205.0	190.2	14.8
Robotics Budget Available			14.8

Structures			
Component	Budget (kg)	Spent (kg)	Available (kg)
Cargo Packing Device	75.0	79.0	(4.0)
Truss Structure	80.0	77.2	2.8
Pillar	80.0	76.6	3.4
Mount to Capsule	30.0	22.0	8.0
Fasteners	10.0	5.8	4.2
Subtotal, Structures	275.0	260.6	14.4
Structures Budget Available			14.4

Sensors & Software			
Component	Budget (kg)	Spent (kg)	Available (kg)
Obstruction (safety sensor)	1.5	0.8	0.7
Microcontroller (Arduino)	2.0	0.3	1.7
ID (RFID reader)	2.0	0.6	1.4
ID(cards)	2.0	0.2	1.8
Motion (rotary encoder)	1.5	1.0	0.5
Dataflow (wiring + bluetooth)	11.0	7.0	4.0
Subtotal, Sensors and Software	20.0	9.9	10.1
S/S Budget Available			10.1

	Budget (kg)	Spent (kg)	Available (kg)
Subtotal, System	500.0	460.7	39.3
Remaining Budget Available			39.3

Power Budget

The power consumption of the cargo system is limited by the available power from the Gateway Logistics Module, as denoted by requirement R8.2 and its sublevels shown below in Table 7. The largest power allowance was given to the actuators used to drive the chains of the cargo system.

Table 7: Requirement R8.2 and its sublevels limit power usage of the cargo system.

ID #	Requirement Text
R8.2	The system shall operate with power provided by Gateway Logistics Module
R8.2.1	The actuator shall operate on a power of no more than 230 W
R8.2.2	The cargo linkage shall operate on a power of no more than 10 W
R8.2.3	The microcontroller shall operate on a power of no more than 20W [TBR]

The power available to the system can be determined by the capsule in which the cargo system is launched. For design purposes, this was assumed to be the SpaceX Dragon XL capsule, with 1000 W of electrical power available. Two operating states of the cargo system were considered: nominal and Full Load Wattage (FLW). FLW considers all electrical systems operating at once. In practice, this would never be used, and it is only considered to show that the full system may operate within power available from the Dragon XL. The breakdown of each case by subsystem is reported below in Table 8. Under nominal operation, the system only uses 50 W (5%) of this budget. FLW shows the total power usage increases to 860 W (86%), 140 W below power available. Individual actuator, linkage, and microcontroller operation is within the above requirements. FLW is not covered by the requirements which only denote individual component power usage.

Table 8: If using Dragon XL power source, designed power costs to date are less than available power.

Robotics (Nominal)			
Component	Budget (W)	Spent (W)	Available (W)
Motor + Encoder (ea)	230.0	10.8	219.2
Brake	210.0	25.0	185.0
Elevation System	30.0	10.8	19.2
Motor Controller	10.0	1.2	8.8
Subtotal, Robotics	480.0	47.8	432.2
Robotics Provision	90%		450.0
Remaining Budget Available			882.2

Robotics (FLW)			
Component	Budget (W)	Spent (W)	Available (W)
Motor + Encoder (ea)	230.0	388.8	(158.8)
Brake	210.0	449.3	(239.3)
Elevation System	30.0	10.8	19.2
Motor Controller	10.0	2.4	7.6
Subtotal, Robotics	480.0	851.3	(371.3)
Robotics Provision	90%		450.0
Remaining Budget Available			78.7

Sensors & Software (Nominal)			
Component	Budget (W)	Spent (W)	Available (W)
Obstruction Sensors	10.0	0.4	9.6
RFID System	10.0	0.2	9.8
Subtotal, Sensors and Software	20.0	0.6	19.4
Sensors/Software Provision	10%		50.0
Remaining Budget Available			69.4

Sensors & Software (FLW)			
Component	Budget (W)	Spent (W)	Available (W)
Obstruction Sensors	10.0	6.4	3.6
RFID System	10.0	2.4	7.6
Subtotal, Sensors and Software	20.0	8.8	11.2
Sensors/Software Provision	10%		50.0
Remaining Budget Available			61.2

	Budget (W)	Spent (W)	Available (W)
Subtotal, System (ea.)	500.0	48.4	451.6
Subtotal, System (FLW)	500.0	860.1	(360.1)
Full System Provision	100%		500.0
Remaining Budget Available (Nominal)			951.6
Remaining Budget Available (FLW)			139.9

Subsystem Design, Analysis, and Trade Studies

Human Factors

Overview

The Human Factors subteam worked on various tasks related to optimizing the user experience of the crew members, ensuring ergonomic design, and enhancing safety within the cargo management system. The focus has been on designing an intuitive user interface, using a software called Figma, for the cargo management system, cargo box design—especially the interior and material selection—and implementing safety features that protect both the users and cargo. By combining the expertise in human factors, ergonomics, and systems engineering, Human Factors successfully developed a systematic approach to enhance the overall usability and efficiency of the cargo management system. Items prioritized included the well-being and time-saving of the crew member, as well as the safe transport of cargo.

Trade Studies

The following section provides a summary of the most recent key subsystem and component-level trade studies conducted by the Human Factors team.

Interface Location

In order to determine where the location of the user interface should be, a trade study was conducted. The scores are shown in Table 9.

Table 9: Interface location trade study results.

Option	iPad/Tablet	Laptop	Fixed Screen near GLM Hatch	Fixed Screen in Crew Quarters
Score	10.3	9.5	5.6	5.6

The criteria used for this trade study were cost, ease of maintenance, and transportability; these had weightings of 3, 5, and 4, respectively. Based on these scores, the final choice for the interface location was an iOS app on an iPad. iPads are currently used for crew procedures aboard the ISS, which was an additional advantage of this selection. The iPad option also allows for portability and the ability to use the user interface app anywhere inside the Gateway station, which was a top-level requirement of the system. iPads also are very reliable, as they have many hours of usage on the ground by consumers. The multi-use nature of the iPad also made it favorable from a cost perspective (a brand new device would not have to be purchased specifically for the cargo management system).

Interface Input Method

The next trade study run by Human Factors was to determine the method of input for the system's user interface. The resulting scores are shown in Table 10.

Table 10: Interface input method trade study results.

Option	Graphical Interface	Voice Commands	Physical Buttons	Text Input
Score	13.5	9.9	8.5	9.3

The criteria used for this trade study were ease of implementation, ease of use, transportability, adaptability, aesthetics, and functionality; these had weightings of 3, 4, 2, 2, 2, and 5, respectively. Based on these scores, the final choice for input method was a graphical interface. This selection meshes well with the iPad app design, and allows for crew members to have a more intuitive interface within the system that will hopefully seem as familiar as conventional iOS apps. This method also seamlessly blends with the decision to use an iPad as the user interface device.

Safety Features

Finally, a trade study was conducted in order to determine what kind of safety feature would be best implemented within the system; resulting scores are shown in Table 11. For this trade, a light curtain consists of a series of light beam transmitters and receivers; when the connection between transmitter and receiver is broken—such as by an object crossing the curtain's plane into the GLM—the system ceases motion. The force sensor approach consists of the implementation of sensors that detect if more force than necessary is being used to move the belts—that is, if there is something impeding the motion of the system. If so, the system will cease motion. The optical recognition method consists of a machine vision system that identifies rogue objects in the area of motion for the system. Finally, the low force actuators method refers to the use of actuators with a low enough output force such that any astronauts could not actually be harmed by the system.

Table 11: Interface location trade study results.

Option	Light Curtain	Physical Barrier	Force Sensor	Optical Recognition	Low Force Actuators
Score	15.2	15.0	12.7	13.4	13.1

The criteria used for this trade study were cost, ease of implementation, efficiency, harm prevention, and maintenance; these had weightings of 2, 4, 2, 5, and 3, respectively. Based on these scores, the light curtain method was selected. This option was the most effective in detecting rogue objects or crew within the area of motion while also allowing for easy crew access into the GLM. The lack of physical barrier removes any risk of the safety system unintentionally encumbering crew members as they enter or leave the GLM.

User Interface

BLISS: Cargo developed a mock-up user interface designed to streamline and optimize the inventory and cargo handling and management processes using a design tool called Figma. Key features include intuitive inventory management (the ability for the crew member to view and edit cargo information, stock levels, and location data); easy and quick stowage and retrieval request submissions with QR code scanning capabilities; real-time queue monitoring for informed decision-making; estimated wait time calculations based on workload, resource availability, and historical data; and an emergency stop button to shut down the physical system for non-nominal operational situations. The user interface was thoroughly tested with more than 10 test subjects under various use cases and scenarios to ensure a seamless and intuitive experience. The overall feedback received was overwhelmingly positive, indicating that the UI system is well-designed to meet the diverse needs of its users, as well as the functional requirements, and to effectively streamline in-space cargo management.

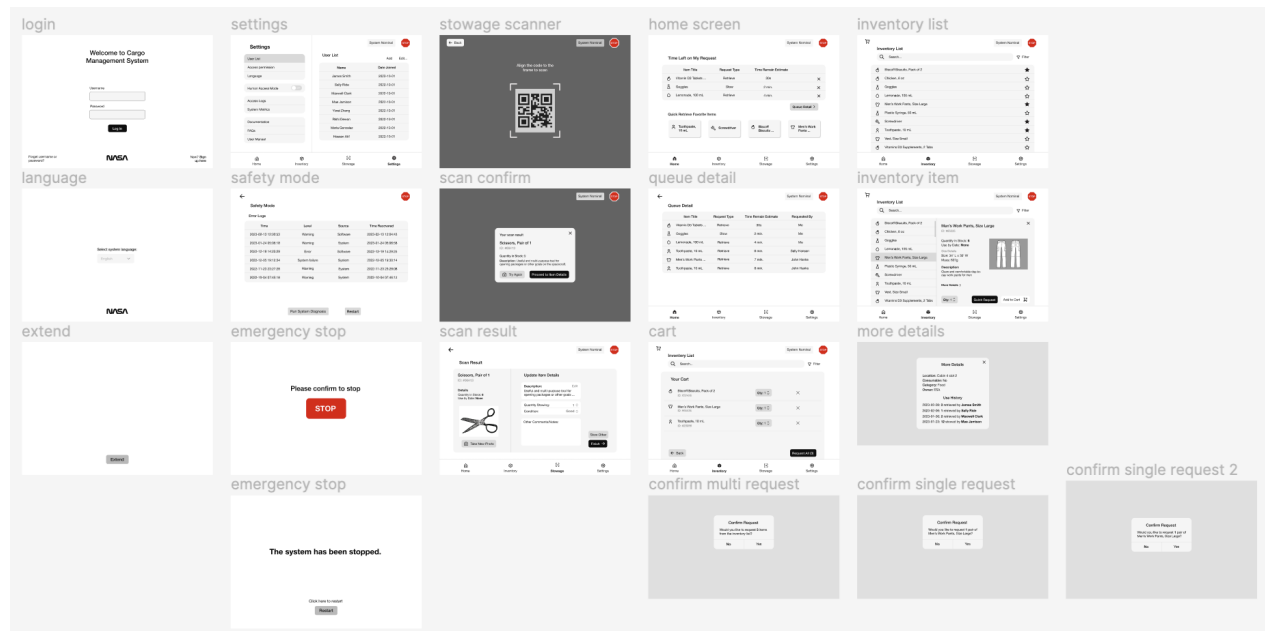


Figure 6: Screenshots of the user interface screens.

Robotics

Overview

The Robotics subteam oversaw all design of actuating systems, including the sizing and procurement of motors for each conveyor belt, and the motor for the elevation system. They were also responsible for designing the cargo-conveyor belt interfaces, the conveyor belt design, and any miscellanea required to support successful integration and operation of these systems.

Trade Studies

The Robotics subteam conducted numerous trade studies over the lifecycle of this project, the most important of which will be outlined below.

Robotics-Capsule Interface

The first trade study completed by the Robotics subteam focused on how the mobility system would interface with the capsule. The winning solution was a polygonal roll-cage that would be designed to reach from a central column outwards towards the edges of the capsule for however many conveyor belt sections were necessary. This solution was chosen for its potential for simple assembly and ability to cover a large volume of the capsule.

Table 12: Robotics capsule interface trade study results.

Option	Polygonal Roll-Cage	Radial Roll-Cage	Independent Legs	Rail Guide
Score	30.8	26.1	29.4	28.5

Robotic Actuator

The next trade study was to determine what type of actuator would control the conveyor belts. The final design solution was electric motors because of their high force output, reliability, and lack of dependence on liquid or gas (which introduces an extra failure mode).

Table 13: Robotics actuator trade study results.

Option	Electric Motor	Hydraulic Actuator	Pneumatic Actuator	Piezoelectric Motor
Score	35.9	23.9	23.5	26.2

Cargo Latch Mechanism

Another trade study was conducted to determine the design of the latch, and a mechanical latch was chosen. It is worth noting that the mechanical latch was only the third best option, with suction cups not far behind. This is because all alternatives were evaluated based on certain criteria in addition to, but independently of, their ability to satisfy system requirements. Although velcro latches and suction cups were deemed to be about the same or better than mechanical latches, confidence was low with regards to their ability to withstand the force and vibrational requirements of launch. Similarly, electromagnets had a number of advantages over mechanical latches, but the large quantity would have required a very high power draw in excess of requirements.

Table 14: Robotics cargo linkage trade study results.

Option	Vacuum Latch	Electromagnet	Mechanical Latch	Velcro Latch	Suction Cups
Score	15.1	27.9	26.8	34	26.3

These trade studies encapsulate the higher level design decisions that were made. For the sake of brevity, the component-level trade studies will not be detailed. It is worth mentioning that there was further exploration of which type of mechanical latch to use and whether the latches should be actuated automatically or manually. The following other trade studies were performed and are listed according to the component/system with the winning design in parentheses:

- Cargo linkage power commitment (full passive, i.e. manual)
- Cargo linkage mechanical component (cam latch)
- Belt type (chain)
- Brake (electromagnetic)
- Chain tensioner (worm gear screw jack)
- Chain lubricant (tungsten disulfide)

Sensors & Software

Overview

The Sensors & Software subteam managed the sensors, actuators, and other peripheral electronics required for system operation. Control is accomplished through a microcontroller with WiFi capabilities for wireless communication with the user device. Uploaded to the controller is a custom Arduino script that utilizes low-level logic and memory management to efficiently and accurately carry out necessary system actions. RFID sensors are used to identify and track cargo containers, while QR codes serve to identify individual items. A mesh of infrared break-beam sensors, dubbed the “light curtain,” serves to detect object entry into the cargo module. Wired momentary push buttons are used to zero the position of the cargo belts upon system initialization. Figure 18 in APPENDIX [B] provides a block diagram of the power and data interfaces within the microcontroller, power system, and the peripheral sensors.

Trade Studies

The following section provides a summary of the key subsystem and component-level trade studies conducted by the Sensors & Software team.

Cargo Item Identifier

After consulting with industry experts, including a former astronaut, a system to track individual items was deemed necessary to avoid disorganization. A trade study was conducted in order to determine the best tracking method, with high emphasis on ease of use to minimize the impact on astronaut use time. While another RFID system was considered to be the frontrunner solution, potential interference with a cargo container RFID system and issues with universal adaptability reduced its final score. Additionally, a new requirement required that the solution utilized existing technology to avoid adding unnecessary complexity to the system, which removed the RFID and barcode options from contention. Ultimately, a deep-link QR code system that utilized the camera on the user device was selected.

Table 15: Cargo item identifier trade study results.

Option	QR Code	ID Number	RFID	Barcodes
Score	21.4	21.2	N/A	N/A

Cargo Container Identifier

A similar trade study was conducted to determine the best method of tracking each cargo container, with the resulting scores shown below in Table 16. The primary criteria were reliability and integrability, which led to two frontrunner solutions: RFID and barcode. In the end, an RFID sensing system solution was chosen, as it required fewer constraints on cargo container motion and orientation as opposed to a barcode solution.

Table 16: Cargo container ID trade study results.

Option	RFID	Barcode	QR Code	Manual Programming
Score	21.4	21.2	19.3	18.7

Error Monitor

All belt position tracking methods considered in this design track relative position from an arbitrary setpoint. As such, a method to “zero” the belt position is required to prevent error accumulation in position data, as well as for system initialization upon system start or in the event of a controller failure. The design solutions considered in this trade study rely on a sensor being triggered by the belt when the chain is in position “zero”. Key criteria included accuracy and fatigue endurance, and led to the selection of a small momentary push button as the sensor of choice.

Table 17: Error monitor trade study results.

Option	Push button (wired)	Toggle Switch	Push button (wireless)	Lever Arm Switch	Rocker Switch
Score	11	7.8	5	6.9	9.2

Light Curtain

Several optical and one ultrasonic sensor options were traded to determine the architecture of the obstruction sensing system, which prevents objects and people from entering (and potentially damaging themselves or the components of) the cargo mobility system during operation. As one of the most safety-critical component systems, high accuracy and low response time were strongly weighted. User and cargo interaction with the system was also heavily considered, as it couldn’t incorporate technology that could be damaging to the crew or interfere with system operation. Ultimately, the use of infrared transmitters and receivers to form break-beam sensor pairs was chosen due to its low profile, high speed, and minimal impact on system operation. Additionally, the low cost and modularity of the solution meant that there was great freedom in designing the number and alignment of sensor-pairs, which was beneficial in meeting the system requirements.

Table 18: Obstruction sensor trade study results.

Option	Infrared	Ultrasonic	LIDAR	RADAR
Score	29.3	27.1	24.9	24.6

Structures & Manufacturing

Overview

The Structures & Manufacturing subteam worked on various tasks related to all load bearing structural design, their interfaces with other subteams, and manufacturing the system prototypes.

Trade Studies

The following section provides a summary of the most recent key subsystem and component-level trade studies conducted by the Structures & Manufacturing team.

System Architecture

The main trade study for the structures subteam was to help determine the best overall architecture for the system. This was conducted as a full project team based on their areas of expertise. As such, the structures team provided all input on the estimated volume efficiency, structural complexity, and the overall scalability of the design to different launch capsules. The conveyor belt is a general architecture where cargo travels along one or more belts or chains in delivery and retrieval. The robot arm is an architecture where a robotic mechanism delivers and retrieves cargo from its respective storage location. The cheese wedge is an architecture where cargo is stored on axial layers in the capsule (shaped like wheels of cheese with one slice removed), and cargo is delivered and retrieved by vertical elevation through the missing slice. The sliding block architecture is similar to a sliding block puzzle where one moves pieces along certain routes on a surface to achieve a certain configuration to win; in this case, the 'playing surface' is the walls of the capsule and the 'winning configuration' is achieved when the desired cargo container reaches the capsule hatch. The conveyor belt scored very highly here for its efficient use of volume and relative low complexity. Its design requires low robotic degrees of freedom and does not constrict storage location. However, it did struggle in the scalability category, as most of its components would require replacement to fit different sized capsules. As volume efficiency was the greatest weight in this trade study, the conveyor belt was a clear winner. The resulting scores are shown in Table 19.

Table 19: Overall system architecture trade study results.

Option	Conveyor Belt	Robot Arm	Cheese Wedge	Sliding Block
Score	91	40	39	70

Conveyor Belt Architecture

There were several different architectural designs for the conveyor belt, which is the system that rotates the cargo containers about the axis of one of the arms to give access to the desired cargo container. The cheese belt is an architecture where cargo is stored in containers that are oriented in axial planes (rendering each plane to look like a wheel of cheese) and chains move in a vertical loop to deliver and retrieve the containers. The heating coil is an architecture where a single chain moves cargo around the container in a helical path to the delivery point, its shape is similar to that of an extruded stove top heating coil. The clothesline is an architecture where cargo is stored in containers that move about a single cable that moves in a vertically zigzagging path about the walls of the capsule. The rotary manifold is a system where cargo is stored in spherical containers, which traverse the capsule in the same fashion as the bearings in a ball screw. Volume, simplicity, adaptability, repairability, anticipated loads, and capsule integration were the criteria used to trade the solution space being assigned weights of 5, 3, 1.5, 1.5, 1.5, 2.5, and 2 respectively, with scores for each option ranging from 0 to 5. As volume efficiency was the greatest weight in this study, the cheese belt performed extremely well as it is the only design that yields a convex optimization problem to minimize wasted space. It did suffer a bit due to its complexity, as it requires many more conveyor belts than the other options, but this weakness came with the benefit of requiring lower torques and faster retrieval times. The resulting scores are shown in Table 20.

Table 20: Conveyor belt system trade study results.

Option	Cheese Belt	Heating Coil	Clothesline	Rotary Manifold
Score	135	86	73.5	89.5

Cargo Skeleton Material

A trade study was conducted in order to determine what kind of material would be best for the construction of the cargo container skeletons. In this case, the material was chosen based on the criteria of critical buckling load, cost, flexibility, and manufacturability. Each of these were weighted at 0.9, 0.6, 0.3, and 0.7, respectively, making critical buckling load the most important. Due to the great resistance to buckling and its overall compliance, Ti 10-2-3 was very successful in this trade study. It had the smallest required mass to achieve a stability safety factor of 1.5 subject to launch loads. However, it is one of the more expensive materials in the options. Additionally, it takes a skilled TIG welder to construct the containers with this material, likely raising the construction cost even further. Though there were these concerns with cost, this component is paramount to the success of the system. If any buckling occurs at launch, it could compromise the system entirely. As the allocated budget provided enough to support this sacrifice, Ti 10-2-3 was chosen as the clear winner. The resulting scores are shown in Table 21.

Table 21: Cargo skeleton trade study results.

Option	Titanium 10-2-3	Titanium 4-6-3	Stainless Steel 316	Stainless Steel 304
Score	5	2	1	.9

Truss Material

A trade study was conducted in order to determine what kind of material would be best for the construction of the central column and roll-cage truss system. In this case, the material was chosen based on the criteria of specific strength, flexibility, cost, and manufacturability. Each of these were weighted at 0.9, 0.6, 0.2, and 0.7, respectively, making specific strength the most important. Due to the great specific strength and compliance, Ti 4-6-3 was very successful in this trade study. It required the least mass to support a sufficient safety factor subject to chain tensioning and retrieval moments of inertia. However, it is one of the more costly of the material options. Though there were some concerns with cost, the reduced system mass in addition to a significant budget allocation provided more than enough motivation to deem Ti 4-6-3 the winner.. The resulting scores are shown in Table 22.

Table 22: Cargo truss material trade study results.

Option	Titanium 4-6-3	Stainless Steel 316	Stainless Steel 304	Aluminum 6061
Score	5	2	2	0

System Risk Analysis

Risk Identification and Management Structure

BLiSS: Cargo adopted a risk identification and management framework that involved identifying risks at an individual level and then escalating them to a group level analysis through notification of subteam, class, and/or project leads. Upon identifying a risk and bringing it to the group's attention, its Risk Priority Number (RPN) was evaluated based on its severity, likelihood of occurrence, and detectability using a standard ranking system provided in Figure 7. Based on the RPN, the risk was prioritized and either accepted, mitigated, or eliminated depending on the cost and complexity. BLiSS: Cargo's approach was to eliminate all identified risks unless analysis proved it to be impractical due to budget or schedule constraints, in which case the risk was mitigated as much as possible with available resources. Risks related to crew and capsule safety always took precedence over risks to the system itself. Once a risk solution was chosen, all changes were monitored and documented to catch and address new risks as they arose and continually improve the system to minimize risks.

Likelihood	Technical Estimated likelihood of not meeting performance requirements	Cost Estimated likelihood of not meeting cost commitment	Schedule Estimated likelihood of not meeting schedule commitment
5 - Very High	P>50%	P>75%	P>75%
4 - High	(25%, 50%]	(50%, 75%]	(50%, 75%]
3 - Moderate	(15%, 25%]	(25%, 50%]	(25%, 50%]
2 - Low	(2%, 15%]	(10%, 25%]	(10%, 25%]
1 - Very Low	(0.1%, 2%]	(2%, 10%]	(2%, 10%]

Risk	1 - Very Low	2 - Low	3 - Moderate	4 - High	5 - Very High
Technical	No impact to full mission success criteria	Minor impact to full mission success criteria	Moderate impact to full mission success criteria. Minimum mission success criteria are achievable with margin	Major impact to full mission success criteria. Minimum mission success criteria is achievable	Minimum mission success criteria are not achievable
Schedule	Negligible or no schedule impact	Minor impact to schedule milestones; accommodates within reserves; no impact on critical path	Impact to schedule milestones; accommodated within reserves; moderate impact to critical path	Major impact to schedule milestones; major impact to critical path	Cannot meet schedule and program milestones
Cost	<2% increase over allocated and negligible impact on reserve	Between 2% and 5% increase over allocated and can handle with reserve	Between 5% and 7% increase over allocated and cannot handle with reserve	Between 7% and 10% increase over allocated, and/or exceeds proper reserves	>10% increase over allocated, and/or can't handle with reserves

Figure 7: This ranking system was developed by Robin Dillon of Georgetown University in partnership with a team from Goddard Space Flight Center to improve upon NASA's standard risk ranking system. This system was chosen so as to meet NASA's expectations and requirements [1].

Using these risk identification strategies, BLISS: Cargo identified nine medium-risk items. These risks are as follows, listed in descending risk-score order:

Medium risk:

1. The cost of developing a cargo management software exceeds the project budget.
2. Software development runs significantly behind schedule.
3. Capsule dimensions prove insufficient for crew access during use.
4. The light curtain does not adequately halt system movement upon user intrusion.
5. Fires caused by static electricity or combustible cargo.
6. Failure to initiate safety mode if the crew device is down or loses connection.
7. Failure to exit safety mode if the crew device is down or loses connection.
8. Damage to cargo items caused by collisions within the cargo containers.
9. A delay in the ergonomic prototype model causing schedule delays in testing.

Mitigation plans for these risks are summarized as follows:

1. Simulation of all structures and testing of sensors, actuators, and software components to determine whether they meet requirements and can withstand 'Day-In-The-Life' cycle testing.
2. Accounting for unexpected costs in the cost margin per subteam.

- Accounting for risk severity and likelihood during system development trade studies and making necessary design modifications to reduce severity and likelihood of unexpected risks encountered in the project lifecycle.

A comparison of unmitigated- and mitigated-risk fever charts is shown in Figure 8.

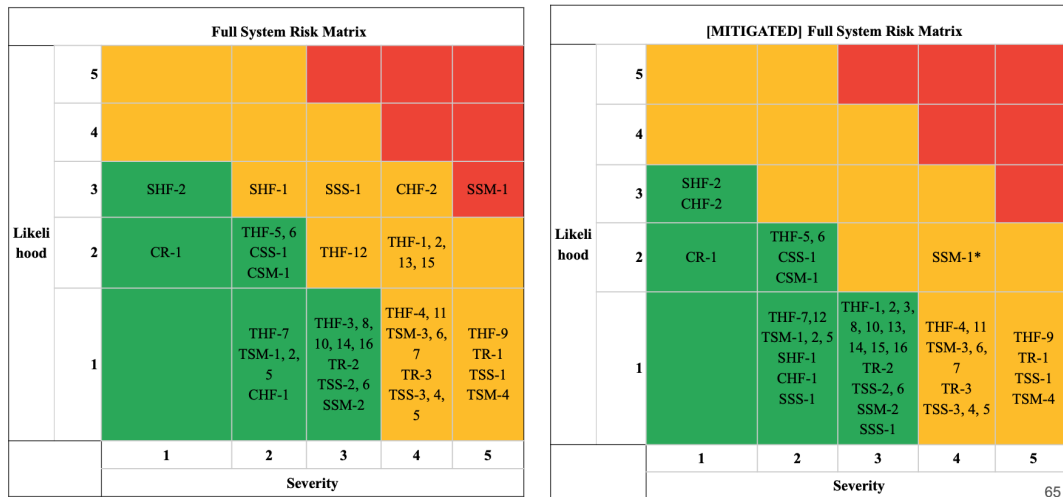


Figure 8: Fever chart comparison with unmitigated risks vs. mitigated risks.

Prototyping, Verification, and Validation

Prototypes

In order to complete as much in house verification of the system as possible, it was determined that it would be optimal to create two prototype systems. The first of these was the operational prototype, which would be used to test all actuator and brake operations, the elevation system, and their corresponding Sensors & software. The second prototype was the ergonomic prototype which would demonstrate the ability to remove cargo in multiple spatial orientations, as well as the operation of the light curtain subsystem.

Operational Prototype

Due to space constraints in the lab, it was decided that to test the internal operations of the system, a half-scale operational prototype would be created. The requirements that needed to be tested in full scale were those centered around human interaction, and were thus tested on the second, “ergonomic” prototype. The operational prototype contains one wedge of cargo two layers deep, for a total of four of each size of box. This allowed us to verify the accuracy and capabilities of the actuators, the software that controls them and the RFID and error monitoring subsystems.

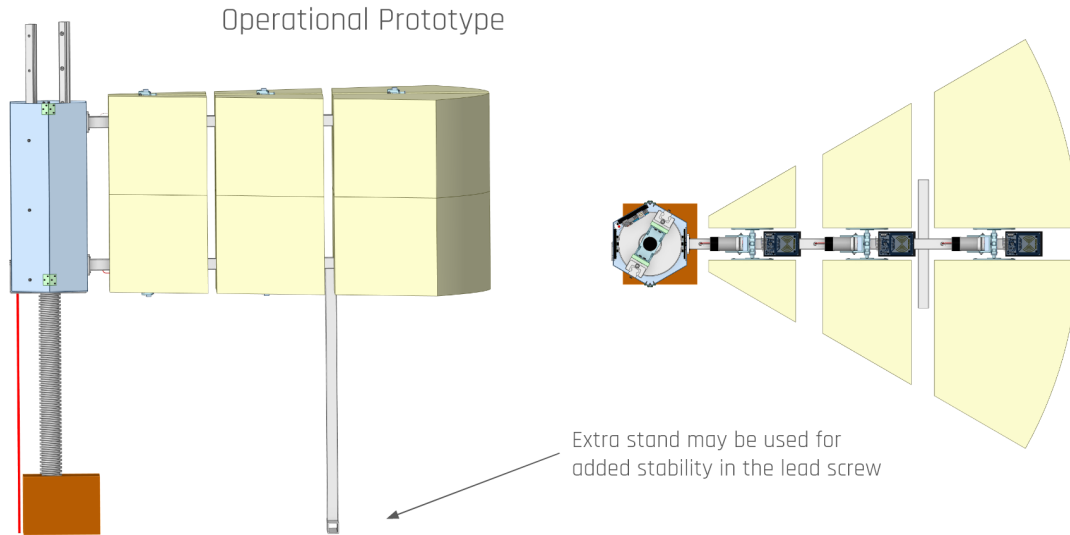


Figure 9: An overview of the operational prototype fully loaded with twelve cargo containers, displaying all motor interfaces, elevation system, and RFID placements. An extra stand was employed for stability as nothing could be permanently affixed to the floor of the workspace.

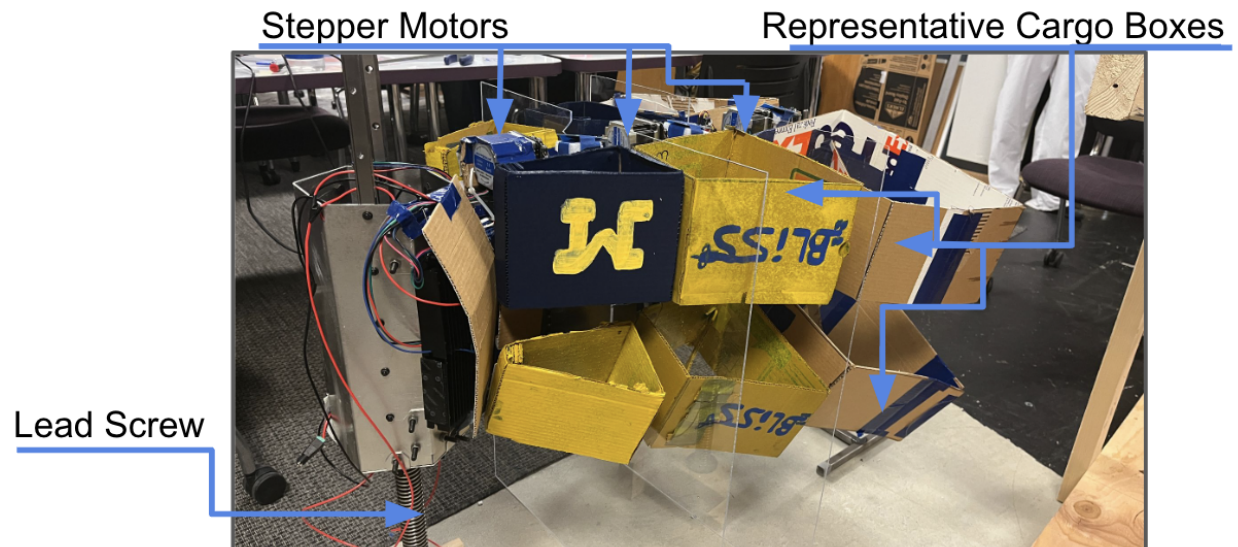


Figure 10: Operational prototype build.

This mockup covered verification of all requirements pertaining to operation of the system such as the actuator's ability to move cargo of the required mass, the software's ability to queue user inputs, and the elevation system's extension. Due to schedule constraints, requirement verification for lifetime testing, along with some accuracy and failure mode requirements were descoped. However, by extrapolating from the data obtained, the minimum viable product (MVP) requirements were still met.

Ergonomic Prototype

The ergonomic prototype is a mockup that models the accessibility and usability of the system pertaining to astronaut interaction. It consists of one cargo container of each size, their respective cam latches, and the light curtain. The ergonomic prototype is used to verify requirements pertaining to the kinematics of cargo retrieval and return, the minimum distance required for the system-to-cargo latching interface, and the light curtain detection capabilities and interface with the system.

For the cargo interaction verification, it was necessary to ensure that a crew member could access the cargo from various spatial orientations. The model verification method for this requirement was to demonstrate the removal of the cargo from the cam latch from 144 positions and return it. Verification of the system-cargo interface distance was by visual inspection to find the smallest straight-line distance between the male cam latch and the top face of the capsule that still allows the cargo to be removed and replaced within 1 meter of the hatch face. Finally, verification of the light curtain was done by placing a foreign object in the light curtain to confirm that it recognizes the interference and halts system operations.

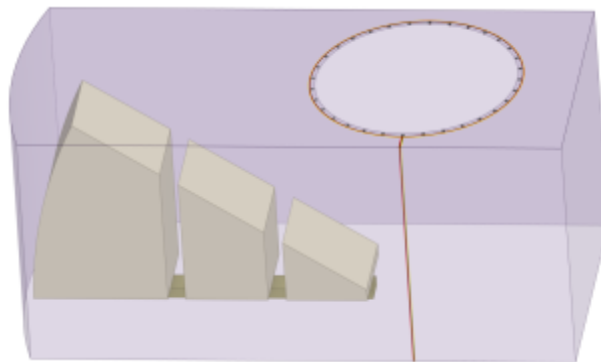


Figure 11: Ergonomic Prototype CAD.

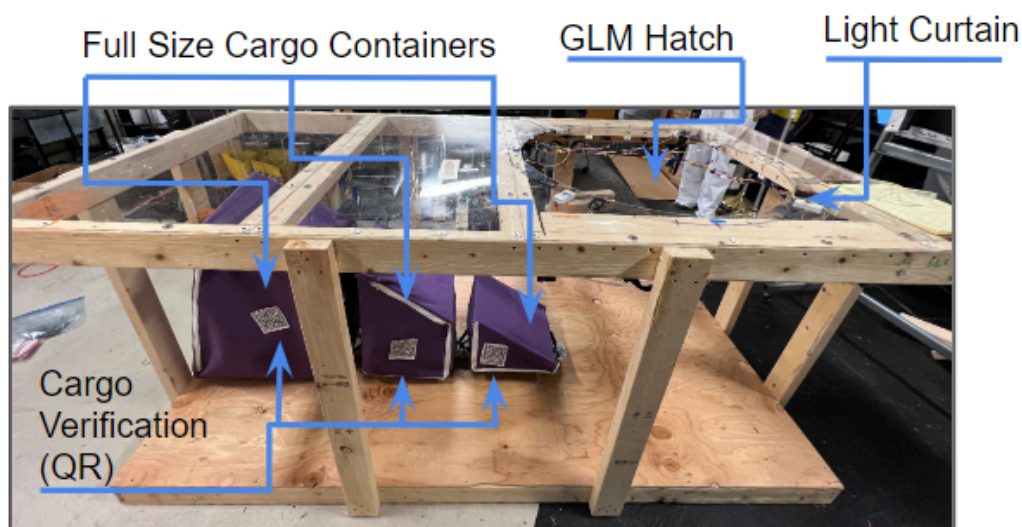


Figure 12: Ergonomic prototype build.

Requirements Verification

Verification of the system requirements was divided into system, subsystem, and component levels according to each subteam, as outlined in Figure 13 below. Every requirement was associated with a document. Within a document, the requirements were marked for whether they reasonably could be verified using resources at BLiSS: Cargo’s disposal and whether they pertained to the minimum viable product goal of “novel operation demonstration” as stated by the stakeholders. The documents also contain written-out test procedures for performing the tests marked as in-house verifiable and tables to record results. For BLiSS: Cargo’s purposes, the objectives and procedures for performing system-level verification paralleled those for system-level validation. Therefore, the system-level verification document does not have written out test procedures, as these can be found in system-level validation.

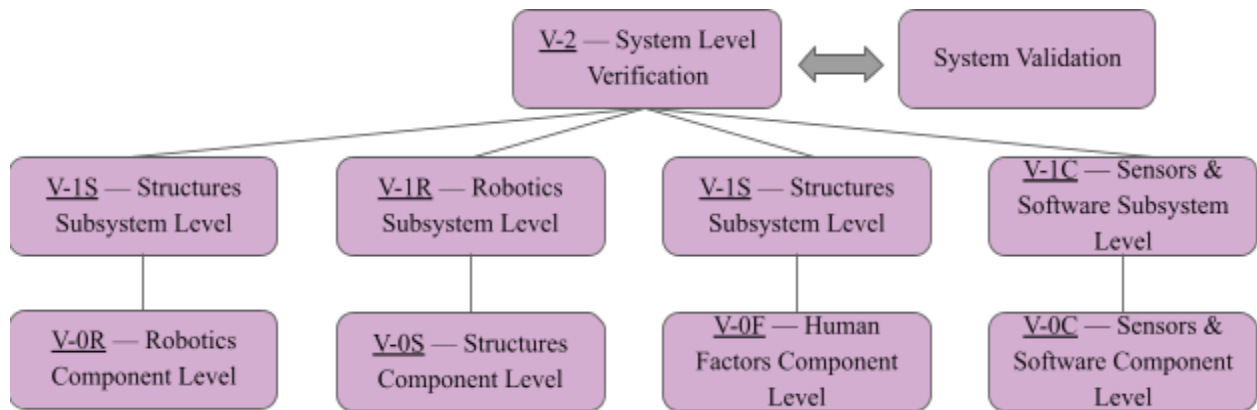


Figure 13: High level verification overlaps with system validation.

Due to time constraints, component differences between the full-system design and the mock-ups, and the overlap between system-level verification and validation, emphasis was placed on completing the system-level validation. Nevertheless, some verification tests were performed, especially those relating to structural performance under launch loads. These analyses were primarily completed using Ansys. To perform analyses of the system’s response to random vibrations, the team collaborated with Dr. Jonathan Van Noord at the University of Michigan’s Space Physics Research Lab to validate aspects of the simulation results. A full-scale, partial length segment of a steel chain was built to represent the segment freely suspended between adjacent cargo boxes. As the boxes were meant to be supported by each other during launch, it was assumed that their mutual friction would provide sufficient damping to approximate it as a fixed connection for the chain. The chain was then mounted to the table, and its tension was measured by a load cell. The acceleration of the chain was measured by an accelerometer and divided by the acceleration of the table to be able to identify the amplification of vibrations associated with a natural frequency. Figure 14 below shows these plots at different tensioning values overlaid with the natural frequencies obtained through simulations. For the most part, there was good agreement, which gave the team confidence in their simulation results.

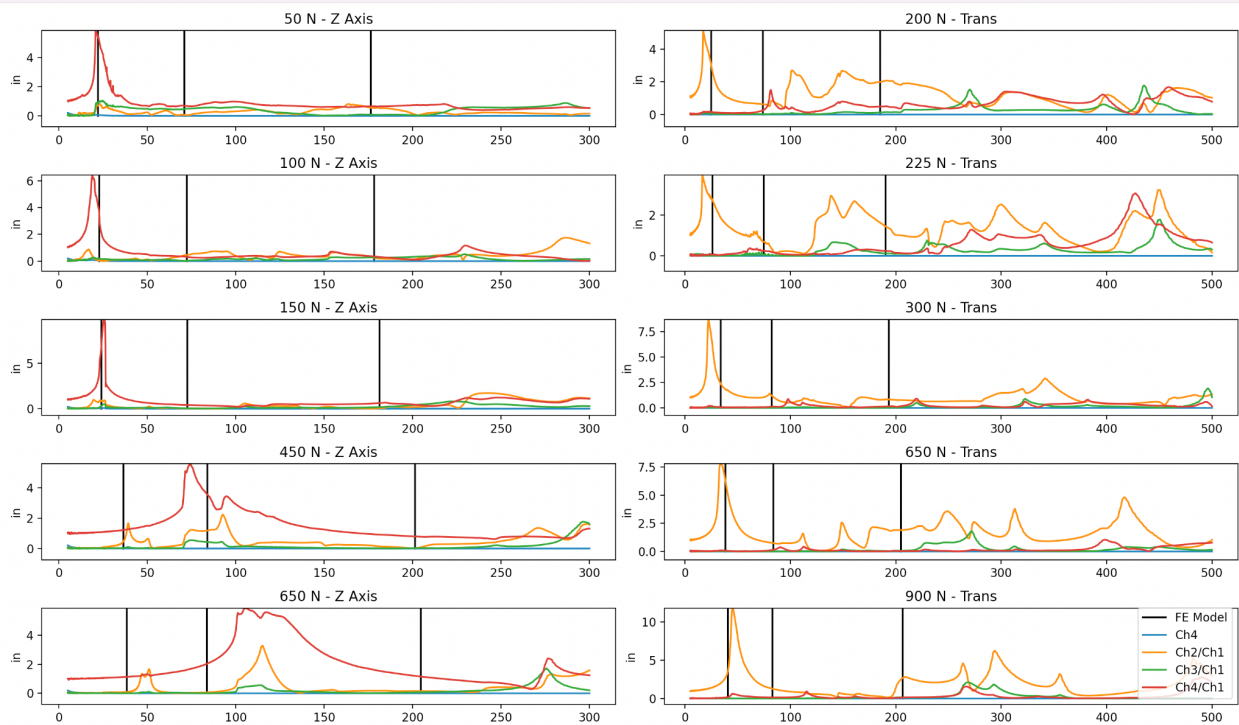


Figure 14: Plots showing results from the vibration table testing overlaid with results from finite element models.

System Validation

Validation was conducted on the system level as a Verification Closer Notice (VCN) utilizing stakeholder MVP objectives. These objectives were cascaded to system and lower level requirements in order to create a traceability between expectations and deliverables. MVP objectives that were validated are found in Table 23. To satisfy MVP objectives, the Operational Mock-Up and Ergonomic-Mock-Up stood as qualification test-rigs each with key test purposes with distinct procedures found in Appendix [F].

Operational Mock-Up Qual Purposes	Ergonomic Mock-Up Qual Purposes
• UI, Controls, Set-up • Cargo Retrieval and Return • Failure Mode Operation • Error Detection	• Safety Critical System • Module Containment • Cargo Container Attachment Demonstration

Table 23: Allocation of qualification purposes and their descriptions under the mock-ups.

Qual Purpose	Description
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UI, Controls, Set-up	- Perform UI Intuitiveness test on selected user - Present controls to user and observe learning process - Measure power consumption
Cargo Retrieval and Return	- Issue two cargo retrieval requests and observe details - Verify retrieved cargo and observe interaction of user - Cargo reorganization - Issue two cargo return requests and observe details - Verify returning cargo and observe interaction of user
Failure Mode Operation	- Cut power and observe user's cargo retrieval and return - Continue to verify cargo during failure mode
Error Detection	- Input "general errors" and observe system reaction - Measure emergency stop time
Safety Critical System	- Trigger "safety net" lasers with mock cargo items - Find blind-spot situations
Module Containment	- Measure dimensions of mock-up and containers - Compare sizes to GLM constraints and cargo sizes
Cargo Container Attachment Demonstration	- Randomly select users to attempt attachment and detachment - Manipulate, retrieve, and replace mock cargo in containers - Attempt various spatial orientations - Record ease of process

The selection of the mock-ups as test-rigs, rather than various levels of assemblies, was largely due to a combination of facility, cost, and schedule constraints. With the original goal of the mock-ups to stand as pieces of a prototype, the ability to validate MVP objectives was still a viable option, though not at a full assembly level.

Table 24: Minimum Viable Product derived Validation Objectives are listed along with the traced requirement, its method of verification, its parent ID, and on what mock-up.

Validation Objective	Requirement	Method	Validation ID	Mock-Up
Clarify a control system for the user to initiate the autonomous operations of the system and observe the cargo manifest	R1.1.2	Inspection	V-002	Operational
Show cargo in the domain of the system can be accessible without removing other cargo in nominal conditions	R2	Demonstration	V-003	Operational

Show the system has enough torque to transport cargo within its domain to a reception point within the 10 minute constraint	R2.3.1	Demonstration	V-003	Operational
Show the system has enough torque to transport cargo within its domain from a reception point to storage configuration within the 10 minute constraint	R3.4.1	Demonstration	V-003	Operational
Show novel operation that strays from the current method of cargo retrieval in the ISS	R4	Demonstration	V-002	Operational
Show that cargo requested by the user and known to be in a specific container is presented to the user for retrieval autonomously	R4.1	Demonstration	V-002	Operational
Show novel cargo retrieval operation that strays from the current method of cargo retrieval in the ISS	R4.2, R4.4, R4.4.1	Demonstration	V-002	Operational
Show that the cargo item selected by the user to be returned or retrieved by the system is done so as expected	R4.2.4	Demonstration	V-002	Operational
Show that multiple cargo requests can be handled with a consistent protocol that does not ruin other requests to the system	R4.5	Demonstration	V-002	Operational
Show that cargo is still accessible to crew in the event of a system failure	R7.8, R7.8.1, R7.8.2	Demonstration	V-006	Operational
Show that the system operates on available power outputs	R8.2, R8.2.1, R8.2.2, R8.2.3	Demonstration	V-004	Operational
Show the system allows for users to access cargo linkages and repair locations, unhindered by specific access points; cater to various user orientations due to microgravity environment	R1.1	Demonstration	V-001	Ergonomic
Show that no significant force is required to remove cargo containers from cargo linkage	R2.5.3	Demonstration	V-003	Ergonomic
Show that sensor data is handled internally in the system and does not require user interaction for operation	R4.6.3	Demonstration	V-002	Ergonomic
Show that user interaction is kept to a minimum with the system to prevent error and encourage usage	R4.8	Demonstration	V-002	Ergonomic
Show that the system follows flight and environment constraints	R8	Demonstration	V-004	Ergonomic

VCN evaluation criteria was segmented into three levels: green, yellow, and red. These corresponded to “Pass”, “Pass w/ plan to reduce error”, and “Do not pass,” respectively. In order for the VCN to “Pass,” all objectives are satisfied, and a “Do not pass” entails that one or more MVP objectives were not satisfied. “Pass w/ plan to reduce error” is set when all MVP objectives are satisfied, but not all listed objectives, or an objective has been refined/clarified in order to satisfy the requirement. For all qualification purposes, all MVP objectives were satisfied, and all additional objectives were either satisfied or waived.

Ergonomic Mock-Up Validation Results

Tables showing either the final or averaged values for objectives are found in this section. Results are briefly discussed, though a more cohesive set of takeaways can be found in the Conclusion section.

Module Containment Results

Table 25: Final measurements of Ergonomic Mock-Up compared to reference hardware.

Measurement	Experimental (cm)	Actual (cm)	Difference (%)
Hatch Diameter	80.4	80	0.499%
Capsule Radius	160.6	160	0.374%
Distance Between Cargo Attachment Points	40.9, 50	41, 50	0.244%, 0%
Depth to Cargo (from hatch)	79.3	80	0.879%

All measurements were within 1% of their true value, taken from reference hardware, indicating accurate portrayal of the full system and satisfying the objective corresponding to requirement R8.

Cargo Container Attachment Demonstration Results

The orientations in Table 26 were selected as representative orientations users could interact with the system from in the microgravity environment. Orientation-01 corresponds to a user interacting with the system while part of their body is outside of the hatch to the GLM. Orientation-02 corresponds to a user interacting with the system while fully entered inside of the GLM, facing forward (anterior, body-fixed), and fitted to the user-net. Orientation-03 corresponds to a user interacting with the system while fully entered inside of the GLM, facing backwards (posterior, body-fixed), and fitted into the user-net. An L_3 orthogonal array DOE approach was used to randomly test various combinations of the orientations, boxes, and net usage.

Table 26: L₃ orthogonal array of user orientations and cargo box sizes when demonstrating container attachment, with averaged results.

Orientation	Cargo Box	User Net	Mean Time (sec)	Ease (1-10)
O-01	Small	No	51.5	7
O-02	Small	No	48.0	8
O-03	Small	Yes	57.0	6
O-01	Medium	No	50.0	6
O-02	Medium	Yes	44.0	8
O-03	Medium	Yes	57.5	7
O-01	Large	No	N/A	Not Possible
O-02	Large	Yes	67.0	6
O-03	Large	Yes	64.0	7

For a 1-g test, this was a general success. All cargo containers are retrievable in a short time with below 50% effort expenditure, and the user net showed effective use especially with larger cargo containers. However, not all containers were shown to be retrieved from completely outside of the hatch, though all containers were retrievable in the representative top of the GLM. Along with these user observations, it was found that the cargo containers were flexible, requiring more force to achieve the necessary displacement when entering the cam latch. By using L-bracket frames rather than solid cylindrical rods, this flaw is assumed to be mitigated. Although, there is still difficulty when knowing if the cam latch is attached/detached. To combat this, it has been considered to use acoustic assistance, such as a “twang” of a metal tab on entering and exiting the cam female.

Safety Critical System

Table 27: Variety of objects of a type expected to exist in the Gateway are passed through the safety net in specific locations to record the system's response. Final values were taken.

Location	Center of hatch plane		Edge of hatch, in front of transmitter		Edge of hatch, in front of receiver		Edge of hatch, between sensors	
Object and character-istic length	<i>Detected?</i>		<i>Detected?</i>		<i>Detected?</i>		<i>Detected?</i>	
	User Head (20cm)	Yes	User Hand (17cm)	Inconsistent	User Foot (26.9cm)	Yes	User Wrist (4cm)	No
	Small Box (36.5cm)	Yes	Medium Box (37cm)	Yes	Large Box (71.5cm)	Yes	Small Box (36.5cm)	Yes
	Cargo Item (25cm)	Yes	Acrylic Pen (14.2cm)	Inconsistent	iPhone (15.2cm)	Yes	Foam Block (7cm)	Yes

The results indicate that blindspots of approximately 6 cm azimuthally at the very edge of the hatch prevent small objects from being detected. Additionally, blockage of a transmitter did not always trigger the safety response, indicating that the sensor arrangement and hardware characteristics allowed for receivers to capture unintentional IR signatures, not triggering a break of the beam. It is not expected for small objects to commonly enter the blindspots, however these risks can be mitigated by increasing the number of sensors and improving the alignment on flight hardware.

Operational Mock-Up Validation Results

Tables showing either the final or averaged values for objectives are found in this section. Results are briefly discussed, though a more cohesive set of takeaways can be found in the Conclusion section.

Power Analysis Testing Results

Table 28: The current, voltage, and power of the mock up was measured in each operational state to ensure power consumption never exceeded the proportional limit.

State	Voltage (V)	Current (I)	Power (W)
Idle	12	10	120
Nominal Operation	12	10	120
Error	12	10	120

Note that power draw during failure mode remains the same as nominal operation due to the removal of the braking system from the operational mockup. All values are controlled the same since the test rig was regulated and transformed from standard US outlet power.

Retrieval/Return Testing Results

Table 29: Throughout the demonstration process, two separate cargo containers are both retrieved and returned by and to the system respectively. The times for each are listed below.

Test Case (Nominal Operation)	Time
Cargo Retrieval Case 1 (min: sec)	00:28
Cargo Retrieval Case 2 (min: sec)	00:30
Cargo Return Case 1 (min: sec)	00:30
Cargo Return Case 2 (min: sec)	00:18
Test Case (Failure Mode)	Time
Cargo Retrieval Case 1 (min: sec)	00:25
Cargo Return Case 1 (min: sec)	00:50

With a linear dimension reduction of 1:7, the time for return and retrieval should be below 86 seconds of raw system operation time. It can be seen that each of the return/retrieval times, even with user interaction, is below the 86 second mark, satisfying the relevant requirements. User interface integration allows for faster retrieval and return times in the full system and would be a better indication of queued actions.

However, some additional observations were made. The chain was likely to slip off of the gears during operation due to boxes twisting or swaying with gravitational effects. This should not be a prominent issue during microgravity operation as long as large forces do not consistently disturb the GLM. Furthermore, during launch the boxes will be stationary and resist vibrations that may derail the chain.

Error Detection

A safe state mode is manually activated in the mock-up to represent that when triggered by a break in the light curtain. During a safestate, all signals from the motor controllers to the stepper motors are locked out, which instantly halts motion. Due to the low momentum of the cargo boxes, the braking speed was extremely low: far below the 1 second requirement, as well as below human reaction time of around 0.2 seconds. In all cases, this time was achieved and the safe state mode could be overridden in the computer commands, allowing the script to resume and the box to complete its actuation to the requested position.

Lessons Learned

During the project, the BLiSS: Cargo team took note of technical challenges that have been encapsulated in lessons learned documents and will be shared here. By recording these lessons, the BLiSS: Cargo team hopes to demonstrate the experience gained by student members of the team as well as ensure future projects of this type will avoid the same challenges.

During construction of the mock-ups, certain problems arose, typically as a result of the choice of materials and available manufacturing methods. Among these problems were derailment of the chain from the gear, loss of friction between the gear-inserts and the motors, poor adhesion between cam latches and chain, poor balancing of the cargo boxes, inadequate wire management, and lack of real-time sensitivity tuning for the light curtain. Many of these issues would not manifest in the full system due to design and material selections. For example, derailment of the chain was likely caused by the chain and gear parts having been made for a bike, whose chains are designed to move off of gears during shifting. Also, the lack of adhesion between the cam latches and chain was caused by the fact that 3D printed parts had to be attached to metal, which required careful application and a special type of epoxy. The full system is designed with a custom gear and chain with the cam latches to be made out of metal and welded to the chain, so these problems would similarly not have manifested.

However, the challenges faced while building and testing the mock-ups did reveal a few shortcomings of the full system design. Notably, it was discovered that the cam latches should be aligned with the center of mass of the cargo boxes to reduce additional forces and torques on the chain. There should be an audible signal to identify successful cam latch engagement. The chain tension should be incorporated into motor sizing requirements to ensure the belts can move easily. Chains should have a rail near the gear to further avoid derailment. The light curtain should be designed to avoid reliance on fine alignment and thus false positives. Many of these lessons reflect quality of life changes to improve assembly by ground crew and usability by astronauts, as the mock-ups were extremely beneficial in helping the BLiSS: Cargo team identify ways to improve the ergonomics of the design.

Conclusion

The system proposed in this document is a result of many rigorous and thorough trade studies at all levels. Preliminary testing and analysis has demonstrated it to be a viable method, for the purposes outlined in NASA's X-Hab Challenge solicitation, of autonomous cargo storage and retrieval, for use on the Lunar Gateway Module.

Because verification and validation testing and prototyping were limited by the resources available to the BLiSS: Cargo team, further work should include construction of a material- and size-accurate prototype, to be used for more extensive testing. This is necessary to ensure that the system truly meets all requirements and can fulfill all functional performance criteria.

The BLiSS: Cargo team, based on lessons learned throughout system prototyping and testing, has several recommendations for future improvements to system design, as noted in the Lessons Learned section. The cam latches should be aligned with the cargo container center of mass for improved functionality, and it would be useful for there to be a signal to indicate successful cam latch connection. Incorporation of chain tension into motor torque and gear requirements would improve system performance, as would added design against chain derailment. The light curtain could be improved by reducing blind spots and reliance on fine sensor alignment. Finally, it could be beneficial to explore potential interference between cargo-identifying RFID sensors.

Appendices

Appendix A: Requirement Traceability Matrix

Number	Requirement	Components	Operation
R1	The system shall function in microgravity		
R1.1	The crew shall interact with the system while they are in various spatial orientations	Canvas hatch net, cargo container handles	User can use net to link cargo containers to, provide footings, and reorient upon
R1.1.1	The cargo containers shall have a method of temporarily attaching to internal Gateway surfaces for crew access to contents	Canvas hatch net, cargo container handles	User can use net to link cargo containers to, provide footings, and reorient upon
R1.1.2	The system interface shall be contained in a movable device allowing for use by crew members	User Interface	User carries a tablet device that is used to operate the autonomous system at a distance and observe the logged-in and logged-out cargo
R1.2	The structures shall have a safety factor above 1.1 in microgravity	Axial support, radial struts, elevation system, capsule wall interface, chain links, cam latch, motor mount, tensioner, gear head, cargo container	Supporting the inertial mass of various parts of the system during idle and operation
R2	The system shall deliver desired cargo to the Gateway Logistics Module entry point		
R2.1	The system shall have a maximum of 6 degrees of freedom	Mobility system (subsystem)	Rotates cargo axially between two adjacent columns (1 DOF)
R2.2	The system shall deliver cargo with size bounded by a sphere of 0.8 m in diameter	Cargo containers, mobility system (subsystem)	Holds cargo within a volume less than that of a 0.8m diameter sphere to allow passage through the capsule hatch. Mobility system geometry allows uninterrupted motion of this cargo to user reception

Number	Requirement	Components	Operation
R2.2.1	The cargo interface shall link all cargo containers with an available interface surface of 40 x 15 mm	Cam latch, cargo containers	Cam latch female end is built into the cargo containers while cam latch male end is built into the chains of the mobility system. Interface between the cargo and the mobility system is made by cam latch action of keyholing the cam arm into the female hole and twisting 90° clockwise to create a friction hold
R2.3	The system shall deliver cargo with a maximum mass of 60 kg	Cargo containers, cam latch, mobility system (subsystem)	Cargo containers must hold the average density of cargo based on CRS missions while in microgravity. The cam latch must withstand the inertial mass of the cargo in a container during system operation. The mobility system must withstand the inertial mass of two full columns of cargo in the containers during operation.
R2.3.1	The actuator shall generate a torque of no less than 0.1 N-m	Mobility system motor	Generates a torque to accelerate the mobility system and reach a speed fast enough to deliver any cargo container to reception under ten minutes
R2.4	The system shall deliver cargo with its interface within 1 m of the hatch face of the capsule	Mobility system (subsystem), light curtain	Delivers selected cargo container to its apex closest to the hatch and halts motion until the user retrieves the container and leaves the hatch
R2.4.1	The system shall manipulate cargo position to within 5 cm of targeted location on 98.7% of all nominal attempts	Mobility system (subsystem)	Delivers selected cargo container to its apex closest to the hatch and halts motion until the user retrieves the container and leaves the hatch. "Apex" delivery location should be within this requirement
R2.5	The system shall interface with all cargo	Cam latch, cargo containers, chain	All cargo is stored in controlled container geometry that all have female cam latch ends to interface with the male cam latch arm on the mobility system
R2.5.1	The system shall provide telemetry of success at various stages in cargo delivery and retrieval	Microcontroller, rotary encoder, user interface, mobility system motor	Data from the rotary encoder is interpreted by the microcontroller that sends feedback commands to the motor to inform delivery apex. Delivery to apex confirmation will be transmitted from the microcontroller to the user interface
R2.5.2	The system shall successfully interface with cargo on 98.7% of attempts	Cam latch, cargo containers, chain	All cargo is stored in controlled container geometry that all have female cam latch ends to interface with the male cam latch arm on the mobility system by control of the user
R2.5.3	The cargo interface shall require no more than 2.1 N-m of torque to remove a cargo storage box from the system	Cam latch, cargo containers	Cam latch female end is built into the cargo containers while cam latch male end is built into the chains of the mobility system. Interface between the cargo and the mobility system is made by cam latch action of keyholing the cam arm into the female hole and twisting 90° clockwise to create a friction hold
R2.6	The system shall execute a queued request only after previous cargo is retrieved by user	User interface, microcontroller	Cargo requests can be queued in the user interface, but successive requests in the queue cannot be executed at the same time until the previous user has retrieved the first request (this is done for safety reasons so that the system is not operating while the user is inside the capsule)

Number	Requirement	Components	Operation
R2.7	The system shall recognize when cargo has been retrieved and replaced	User interface, microcontroller	After retrieving the cargo, the user must log the cargo unit by scanning its barcode with the user interface device. Once the cargo that was requested has been validated, the system will recognize that it is no longer in storage
R3	The system shall return various cargo containers from the entry point to a designated position		
R3.1	The system shall retrieve cargo interface from 1 m of the hatch face of the capsule	Mobility system (subsystem), light curtain	Retrieves selected cargo container in an empty cam latch at its apex closest to the hatch and halts motion until the user returns the container and leaves the hatch
R3.2	The system shall provide telemetry of success on cargo's return to designated position	Microcontroller, user interface	The user confirms on the user device that the cargo has been returned to its box by scanning its barcode, and the user confirms that the cargo container is in its location by verifying on the user interface. The microcontroller records the updated manifest
R3.3	The system shall return cargo with size bounded by a sphere of 0.8 m in diameter	Cargo containers, mobility system (subsystem)	Cargo retrieval process in reverse
R3.3.1	The cargo interface shall link all cargo containers with an interface surface of 40 x 15 mm	Cam latch, cargo containers	Cam latch female end is built into the cargo containers while cam latch male end is built into the chains of the mobility system. Interface between the cargo and the mobility system is made by cam latch action of keyholing the cam arm into the female hole and twisting 90° clockwise to create a friction hold
R3.4	The system shall retrieve cargo with a maximum mass of 60 kg	Cargo containers, cam latch, mobility system (subsystem)	Cargo containers must hold the average density of cargo based on CRS missions while in microgravity. The cam latch must withstand the inertial mass of the cargo in a container during system operation. The mobility system must withstand the inertial mass of two full columns of cargo in the containers during operation.
R3.4.1	The actuator shall generate a torque of no less than 0.1 N-m	Mobility system motor	Generates a torque to accelerate the mobility system and reach a speed fast enough to deliver any cargo container to reception under ten minutes
R4	The system shall fulfill requests autonomously upon user input		
R4.1	The system shall locate specific cargo within the capsule	Microcontroller, rotary encoder, user interface	The user interface is used to visually keep track of what cargo is logged-in and logged-out for the user. Due to logging protocol, the cargo will be in expected containers in expected locations in the system so that the rotary encoder information can directly relate to linear position of the cargo in a single chain

Number	Requirement	Components	Operation
R4.1.1	The cargo containers shall have a transmittable identifier	RFID chips	Each cargo container has an RFID with simple identification data that can be scanned by an RFID scanner, uploaded to the microcontroller, and transmitted to the user device. The user device can log-in/out individual cargo from this ID
R4.1.2	The system shall associate a unique identifier with each cargo item	Microcontroller, user interface, barcode	Each piece of cargo or cargo container shall have a barcode associated with it to identify the object. The barcode will be scanned by the user interface to validate log-in and log-out of cargo
R4.1.3	The system server shall store cargo organization data	Microcontroller, user interface	User protocol and cargo priming will create expected locations for cargo in containers along the mobility system. Due to the linear nature of the mobility system, the microcontroller will only have to store an ordered list of the containers. For the user interface, however, the locations of individual cargo units in which cargo containers will have to be stored
R4.1.3.1	The microcontroller shall store cargo layout	Microcontroller	Due to the linear nature of the mobility system, the microcontroller will only have to store an ordered list of the containers.
R4.1.4	The system server shall store logged cargo identification data	Microcontroller, user interface	Simple cargo container identification transmitted from its RFID will be stored on the microcontroller, as well as the user device to be used for organization of individual cargo into containers within the system server.
R4.1.5	The system server shall identify requested cargo for reception and return	Microcontroller, user interface	Due to the linear nature of the mobility system, the microcontroller will only have to store an ordered list of the containers with distinct identification between each value in a list, and between lists, to correspond to container ID. However verification of the correct cargo container in a location in the mobility system will be done at reception and return of cargo by the RFID and RFID scanner
R4.1.5.1	The microcontroller shall confirm cargo location with uploaded ID sensor data	Microcontroller, RFID scanner, cargo RFID, rotary encoder	Verification of the requested/returned cargo: upon retrieval or return of cargo, its RFID will be scanned by an RFID scanner, and that ID will be compared to the expected cargo container based on rotary encoder information (internal list). If the container is not what is expected, then the user device will alert the user and give the ID of the cargo in hand vs the ID of the cargo desired
R4.1.5.2	The ID sensor shall upload "selected" cargo ID data to the microcontroller	Microcontroller, RFID scanner	Verification of the requested/returned cargo: upon retrieval or return of cargo, its RFID will be scanned by an RFID scanner, and that ID will be compared to the expected cargo container based on rotary encoder information (internal list). If the container is not what is expected, then the user device will alert the user and give the ID of the cargo in hand vs the ID of the cargo desired

Number	Requirement	Components	Operation
R4.1.6	The microcontroller shall use stored cargo configuration data to locate cargo (belt + distance)	Microcontroller, rotary encoder	Distance between cargo in the linear order is controlled, so communication between the rotary encoder and microcontroller will be used to determine the number of rotations needed to bring a cargo item in the list to the apex. The spatial information of the cargo order will be stored and updated in the list within the microcontroller. A list will also exist to hold which cargo containers are in which belts to inform which mobility system to activate (done by the microcontroller after user input)
R4.2	The system shall retrieve cargo on command of the autonomous system action	Microcontroller, mobility system	The user will only input their requests or validations on the user device, while all cargo retrieval, return, and logging action will be done autonomously by the microcontroller and its interfaced mobility system
R4.2.1	The mobility system actuators shall be commanded with a voltage input less than or equal to 24V	Power management system, mobility system motor	Power from the capsule will be routed to the power management system that will allow up to 24V to the motors of the mobility system during operation
R4.2.2	All sensors and controllers shall be commanded by an input voltage less than or equal to 24 V	Light curtain, microcontroller, rotary encoder, RFID scanner, error sensor	Power is transmitted at 24V from the Gateway logistics module to voltage dividers that supply voltages to sensors within operation ranges
R4.2.3	The system shall measure linear motion of mobility system	Rotary encoder	A rotary encoder is embedded in the gearbox of the mobility system motor and will measure the rotations of the drive shaft and transmit that to a microcontroller
R4.2.4	The microcontroller shall output series of commands to bring cargo to pick-up location (hatch)	Microcontroller	Prebuilt command lines will be executed to rotate motors, receive rotary encoder data, and communicate with the user interface
R4.3	The microcontroller shall solely send commands to actuators in response to input from user interface	Microcontroller, mobility system	The user will only input their requests or validations on the user device, while all cargo retrieval, return, and logging action will be done autonomously by the microcontroller and its interfaced mobility system
R4.3.1	The microcontroller shall begin motion only upon detection and verification of correct cargo	Microcontroller	Prebuilt command lines will be executed to rotate motors, receive rotary encoder data, and communicate with the user interface
R4.4	The system shall deliver or return requested cargo within 10 minutes from request	Microcontroller, mobility system motor	After receiving the request from the user interface, the microcontroller will execute its commands to deliver/return cargo by signaling the motors to rotate with an acceleration and max speed to allow delivery or return within 10 minutes
R4.4.1	The microcontroller's processing time shall be less than 10 minutes	Microcontroller	All processing of inputs to the microcontroller must take less than 10 minutes to turn into output

Number	Requirement	Components	Operation
R4.5	The system shall queue requests when dealing with multiple inputs	User interface	The user interface will take multiple requests, but will not transmit request commands to the microcontroller until confirmation of return or delivery of the previous request
R4.5.1	The system shall order requests in the queue based on order of input	User interface	Priority of requests and so order of queue will be made on order of input
R4.5.2	The system shall provide a visual representation of the input queue	User interface	The queue of requests and history of all previous requests up to a certain time will be available on the user interface
R4.6	The system sensor suite shall gather and upload telemetry data	Rotary encoder, light curtain, microcontroller	Rotation data from the encoder and light continuity confirmation from the curtain will be consistently updated and transmitted to the user interface for viewing
R4.6.1	The system sensor suite's collected data shall be within 1% of real value	Rotary encoder	Rotation data from the encoder will be accurate to 1% of the length of the chain
R4.6.1.1	The rotary encoder distance data shall be within 1% of the true value	Rotary encoder	Rotation data from the encoder will be accurate to 1% of the length of the chain
R4.6.2	The rotary encoder shall upload data to the microcontroller	Rotary encoder	Rotation data from the encoder will be transmitted via electric wires to the microcontroller
R4.6.3	The safety sensor shall upload data to the microcontroller	Light curtain	If the light curtain is broken, confirmation of its breaking will be sent to the microcontroller via electric wires
R4.6.4	The microcontroller shall configure telemetry in a format consumable by user device	Microcontroller	All telemetry data will be converted to consumable format for the user in the microcontroller before being transmitted to the user device
R4.7	The system shall correct for accumulated error	Error monitor	A single link on every chain will have an attached foot that will press a button on the error monitor to send a signal verifying the position of the chain at that time in operation
R4.7.1	The monitor shall allow error to accumulate for no more than one full rotation	Error monitor	A single link on every chain will have an attached foot that will press a button on the error monitor to send a signal verifying the position of the chain at that time in operation
R4.7.2	The monitor shall allow bi-directional chain movement	Error monitor	A single link on every chain will have an attached foot that will press a button on the error monitor to send a signal verifying the position of the chain at that time in operation
R4.7.3	The monitor shall have a small enough profile to avoid intrusion on other parts	Error monitor	The error monitor will be interfaced to a radial truss and not break the profile of the mobility system chain

Number	Requirement	Components	Operation
R4.7.4	The monitor shall be robust enough to endure 12 months of operation	Error monitor	Repeated stimulation of the error monitor will not damage the button under nominal conditions
R4.8	The identifier will require no more than one additional simple action from the user during operation	User interface, barcode	Each piece of cargo or cargo container shall have a barcode associated with it to identify the object. The barcode will be scanned by the user interface to validate log-in and log-out of cargo
R4.8.1	The identifier will allow for new or updated cargo	User interface, barcode, microcontroller	For kitting and rearrangement purposes the user can move cargo between containers and update the system log to hold efficient return and retrieval operations
R4.8.2	The identifier will take advantage of current systems to minimize complexity impact	User interface	The user interface built-in camera will be used to scan the barcodes of the individual cargo items for identification and verification
R5	The system shall be controlled by a user interface(s) accessible from anywhere within the Lunar Gateway		
R5.1	The user interface shall require a maximum of 10 min of specific training in order to use in nominal operations	User interface	A tutorial will be available for the user interface that takes less than 10 minutes to complete
R5.2	The system cargo inventory data shall be remotely accessible to ground controllers	User interface	All user interface output data (not including commands) will be not be made unavailable to ground controllers (transmission is allowed)
R5.2.1	The user interface shall accept cargo requests exclusively from within the Lunar Gateway	User interface	All cargo requests are only available to the users who have the user interfaces within the Lunar Gateway (only available on the app paired to the system with short-range communication such as bluetooth)
R5.3	The system server shall provide feedback telemetry to user	User interface	All telemetry from the microcontroller shall be transmitted to the user interface and made visually available
R5.3.1	The system shall provide notifications of cargo deliveries via the UI	User interface, microcontroller	Once requested cargo has been delivered to its apex, telemetry of success from the microcontroller will be transmitted to the user interface which will immediately show a notification of the cargo delivery

Number	Requirement	Components	Operation
R5.3.2	The system shall provide notifications of cargo delivery and retrieval errors to the crew via the UI	User interface, microcontroller	Once requested cargo has been delivered to its apex, telemetry of success from the microcontroller will be transmitted to the user interface which will immediately show a notification of the cargo delivery. Additionally, any errors detected by the microcontroller will have alerts transmitted to the UI before system shutdown
R5.3.3	The system shall provide estimated time until cargo delivery to crew via the UI	Microcontroller, user interface	List information stored on the microcontroller about cargo container location will be used to make a quick calculation with controlled mobility system speed to determine the estimated time of delivery. This will be transmitted via short range wireless communication to the user interface and displayed immediately
R5.3.4	The system shall provide notifications of changes in system mode (nominal, failure, safe, etc.) via the UI	Microcontroller, user interface	Errors in control operations, sensor information, or breakage of the light curtain will be withheld by the microcontroller and immediately transmitted to the user interface and displayed
R5.3.5	The system shall provide a log of all requests and completed deliveries via the UI	User interface	All requests and their required telemetry will be logged and stored in the user interface app
R5.3.6	The system shall provide metadata on cargo in containers via the UI upon request	User interface	The full cargo manifest as well as logged-in and logged-out cargo will be visually available on the user interface and influence what is requestable
R6	The combined mass of the system and cargo shall be below 5.5 Tons		
R6.1	All non-cargo mass shall be at most 500 kg	Full system (including cargo containers)	N/A
R6.1.1	The mobility system mass shall be at most 200 kg	Mobility system (subsystem)	N/A
R6.1.1.2	The total mass of all actuators shall be no more than 60 kg	Mobility system motors and brakes	N/A
R6.1.1.3	The total mass of all cargo interface mechanisms will be no more than 50 kg	Cam latches	N/A
R6.1.2	The rigid structural mass shall be at most 255 kg	Axial supports, radial supports, extension device, wall interfaces	N/A
R6.1.3	The sensing/software suite shall be at most 15 kg	Microcontrollers, light curtain, rotary encoders	N/A

Number	Requirement	Components	Operation
R7	The system shall operate for the entire on-station lifetime of 12 months		
R7.1	Each component of the system shall have a lifecycle fatigue safety factor of 1	Full system	All operation fatigues (analyze closer)
R7.2	The system shall attach to cargo with 95% reliability at 90% confidence for the entire on-station lifetime of 12 months	Cam latches	Cam latch female end is built into the cargo containers while cam latch male end is built into the chains of the mobility system. Interface between the cargo and the mobility system is made by cam latch action of keyholing the cam arm into the female hole and twisting 90° clockwise to create a friction hold
R7.3	The system shall move cargo with 95% reliability at 90% confidence for the entire on-station lifetime of 12 months	Mobility system (subsystem)	All components of the mobility system will not fail operation after (a number) of uses
R7.4	The system server shall execute mobility commands with 99% reliability at 90% confidence for the entire on-station lifetime of 12 months	Microcontroller	The microcontroller will execute commands without error or full failure (a number) of times
R7.4.1	The rotary encoder shall have a reliability greater than 99%	Rotary encoder	The rotary encoder will transmit rotation data to the microcontroller without error or full failure (a number) of times
R7.5	The system server shall require no more than 80 hours of downtime over the course of the 12 month mission	Microcontroller, user interface	Counting updates, errors, and failure repair times
R7.5.1	The microcontroller shall be inoperable for no more than a combined 40 hours over 12 months	Microcontroller	Counting updates, errors, and failure repair times
R7.5.2	The app shall be inoperable no more than a combined 40 hours over 12 months	User interface	Counting updates, errors, and failure repair times
R7.6	The system shall accept updates to the system server and user interface through digital upload	Microcontroller, user interface	Software updates will be transmitted from mission control and accepted by the user interface device, including microcontroller updates that must be uploaded through wired connection between the user interface and system
R7.6.1	The microcontroller shall be able to accept software updates through its interface with the app	Microcontroller	Software updates will be transmitted from mission control and accepted by the user interface device, including microcontroller updates that must be uploaded through wired connection between the user interface and system

Number	Requirement	Components	Operation
R7.6.2	The app shall upload new software patches to the microcontroller	User interface	Software updates will be transmitted from mission control and accepted by the user interface device, including microcontroller updates that must be uploaded through wired connection between the user interface and system
R7.7	The system shall be installed in the Gateway Logistics Module manually before flight	Full system	The system must be able to be assembled while inside of the capsule on Earth
R7.7.1	The system shall be manually loaded with cargo before flight	Cargo containers	Cargo must be loaded into the cargo containers on Earth and be able to be attached to the system during assembly. This will be done with manual cargo attachment to the mobility system and manual actuation of chains with an external motor attached to the hand crank
R7.7.2	The system's cargo shall include critical spares indicated by the providers	Full system	Some components have more fallible parts or more crucial parts that must have extras to operate the system in the event of failures
R7.8	The system shall enable manual retrieval of cargo in event of failure	Mobility system, handcrank	In the event of a failure of motors, microcontroller, or user interface, the system can still be operated by means of a hand crank attachment to the uppermost gearhead on a mobility track that can used to manually rotate the chain
R7.8.1	The cargo interface shall enable manual retrieval of cargo in event of failure	Cam latches	In the event of a failure of the entire mobility system, cam latches can still be twisted, relieving the cargo, yet this must be done layer by layer
R7.8.2	Manual rotation of cargo attached to the system shall require no more than 100 N of force	Hand crank	The hand crank is an unattached tool that uses ratchet action to interface with the mobility system gear head and rotate the gear, and so the whole chain of cargo in the event of a failure
R7.9	The mobility system chain shall be lubricated	Chain lubricant	Lubricant applied before launch
R7.9.1	The mobility system chain lubricant shall be non-toxic	Chain lubricant	Lubricant does not harm crew
R7.9.2	The mobility system chain lubricant shall be non-flammable	Chain lubricant	Lubricant does not ignite
R7.10	The mobility system chain shall have adjustable tension	Tensioner	Tension of the chain can be adjusted manually by a worm-screw interfaced at the bow motor mount of the system
R7.10.1	The chain tensioning system shall be manually adjustable	Tensioner	Tension of the chain can be adjusted manually by a worm-screw interfaced at the bow motor mount of the system
R8	The system shall be contained within the Gateway Logistics Module		

Number	Requirement	Components	Operation
R8.1	The system shall leave the Gateway Logistics Module undamaged from installation or operation	Full system	Confirm installation operations (likely out of scope) ; cargo released by cam latch failure travels ballistically towards the capsule with a momentum of ____.
R8.1.1	The actuator shall leave the Gateway Logistics Module undamaged from installation or operation	Mobility system motor	The motor will not make any contact with the capsule
R8.1.2	The cargo interface shall leave the Gateway Logistics Module undamaged from installation or operation	Cam latches	The cam latches will not make any contact with the capsule
R8.2	The system shall operate with power provided by Gateway Logistics Module	Full system	Power is assumed to be provided from the walls of the capsule and will be routed to the power management system that powers the light curtain, motors, rotary encoders, microcontrollers, and elevation device
R8.2.1	The actuator shall operate on a power of no more than 230 W	Mobility system motors	Not all motors will be actuating at once; though, of the actuating motors, they shall not consume more than 230W from the capsule
R8.2.2	The cargo linkage shall operate on a power of no more than 10 W	Cam latches	No power necessary
R8.2.3	The microcontroller shall operate on a power of no more than 20W	Microcontroller	Power is assumed to be provided from the walls of the capsule and will be routed to the power management system that powers the light curtain, motors, rotary encoders, microcontrollers, and elevation device
R9	The system shall withstand launch conditions		
R9.1	The system shall withstand axial forces of 6.9g during launch	Axial support, cargo containers, elevation device	Due to the stacking of cargo at the bottom of the capsule, only these three components will bear axial forces (not counting random vibes)
R9.2	The system shall withstand lateral forces of 2.6g during launch	Radial supports, cargo containers, axial support, cam latches	Not counting random vibes
R9.3	Structural materials shall have a yield strength of at least 1.4 times that of maximum Von Mises Stress	Axial support, cargo containers, elevation device, capsule mounts, motor mounts, cam latches	Safety factor accounts for random vibes

Number	Requirement	Components	Operation
R9.4	Structural assemblies shall withstand vibrational loads during launch	Axial support, cargo containers, elevation device, capsule mounts, motor mounts, cam latches	Only accounting for random vibes
R10	The system shall have a one fault tolerance with regard to crew safety		
R10.1	The system shall cease motion within 1 seconds [TBR] of detection of an unintended object in its domain of motion	light curtain, microcontroller, brake	Breaking of the light curtain will signal the microcontroller to execute the breaking command to the mobility system breaks of all moving chains
R10.1.1	The system shall cease motion when object crosses light curtain installed over the hatch	light curtain, microcontroller, brake	Breaking of the light curtain will signal the microcontroller to execute the breaking command to the mobility system breaks of all moving chains
R10.1.2	The safety sensor shall upload data to the microcontroller with a speed that enables a total latency of less than 1 second	light curtain, microcontroller	To stop system motion within one second of breaking the light curtain, all latency of the light curtain sending a signal to the microcontroller must be less than one second
R10.1.3	The microcontroller shall, with the correct stimuli from the safety sensor, cease all motion within 1 second of detection	light curtain, microcontroller	To stop system motion within one second of breaking the light curtain, all latency of the braking command from the microcontroller must be less than one second
R10.2	The system shall have a safe state during which no inputs other than exiting the safe state are registered	microcontroller, user interface	During select errors, failures, or safety precautions, the microcontroller will not accept any commands other than to once again begin accepting commands (leave safe state). This will be visible on the user interface, where the only available command is to override the safestate with a passcode
R10.2.1	The system shall cease motion and assume a safe state within 1 seconds [TBR] of detection of software error	microcontroller, brake	Detection of error in software will signal the microcontroller to execute the breaking command to the mobility system breaks of all moving chains
R10.2.1.1	The microcontroller shall stop system motion if a software bug is detected	microcontroller	Detection or user alert of a bug in the software will signal the microcontroller to execute the breaking command to the mobility system breaks of all moving chains
R10.2.1.2	The app shall communicate any crashes/bugs to the microcontroller	user interface	Bugs detected by the user interface or by the user itself can be reportorted and an error signal will be sent to the microcontroller to react

Number	Requirement	Components	Operation
R10.2.2	The system shall cease motion and assume a safe state within 1 seconds [TBR] of detection of any sensor error	light curtain, rotary encoder, microcontroller, brake	Detection of error in sensor data will signal the microcontroller to execute the breaking command to the mobility system breaks of all moving chains
R10.2.2.1	The microcontroller shall stop system motion if any sensor's telemetry is 5% off of nominal range.	light curtain, rotary encoder, microcontroller, brake	Detection of error in sensor data will signal the microcontroller to execute the breaking command to the mobility system breaks of all moving chains
R10.2.3	The system shall cease motion and assume a safe state within 1 seconds [TBR] of request of local or remote user	user interface, microcontroller, brake	Bugs detected by the user can be reportorted and an error signal will be sent to the microcontroller to react
R10.2.3.1	The microcontroller shall stop system motion if an operator requests a safe state	user interface, microcontroller, brake	A safe state can be initiated by the user from the user interface at any time with a password. This request will be sent to the microcontroller
R10.2.4	The system shall resume operation within 5 seconds of request of local user after exiting the safe state	user interface, microcontroller, mobility system	Overriding of the safe state can be done by the user from the user interface with the entry of a password. All previous operations or requests will be resumed from where they left off, so there must be memory of the operation status held on the microcontroller
R10.2.4.1	The microcontroller shall exit the safe state within 5 seconds of a request from the app	microcontroller	All previous operations or requests will be resumed from where they left off, so there must be memory of the operation status held on the microcontroller
R10.2.4.2	The user shall be able to use the user device to communicate a request to return to nominal state to the microcontroller	user interface	Overriding of the safe state can be done by the user from the user interface with the entry of a password
R10.3	The braking system shall generate a deceleration torque of 50 N-m	brake	N/A
R10.3.1	The brakes and actuators shall only operate at different times	microcontroller, power management system	Control for the brake and mobility system motors will be done by the microcontrollers. Power to the actuators must be cut before power to the brake is supplied

Appendix B: Additional Resources

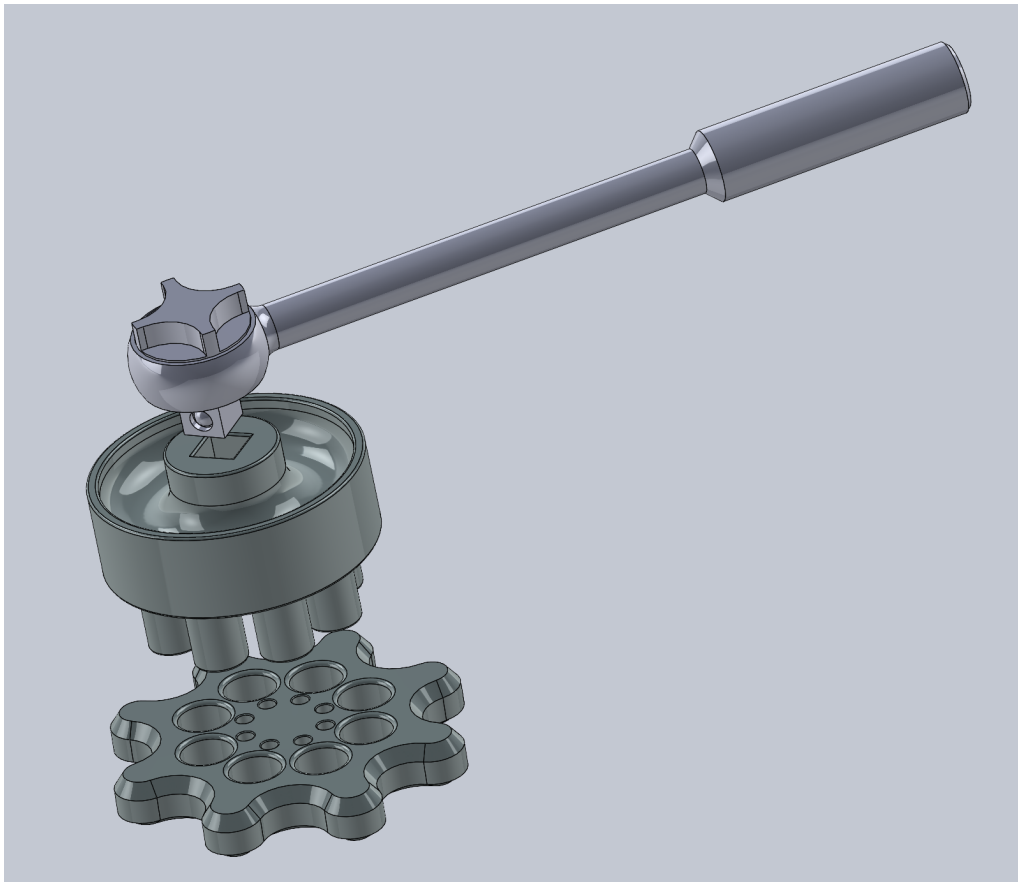


Figure 16: Manual crank attachment for the retrieval of cargo on conveyor belts with inoperable motors. The system is designed to interface directly with the gear and a COTS ratchet.

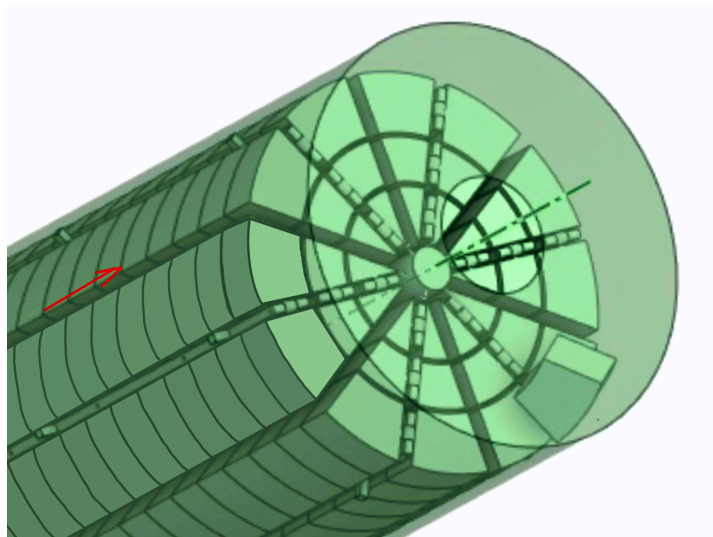


Figure 17: gif of how the cargo flips from one side of the pair to the other, with the high point showing off where a cargo container would be when being accessed.

Appendix C: Data Item Descriptions

<u>NASA Requirements and System Design Review</u>	<u>DID #: 1</u>
Schedule Date: 10/08/2022	
Purpose: System Design Review with NASA Sponsors to introduce an overview of the BLiSS Cargo design.	
Preparation Information: The requirements and System Design Review (SDR) shall be prepared by the BLiSS: Cargo team. The SDR will be conducted virtually utilizing slide show presentations delivered to NASA stakeholders. Information within the presentation shall include, but is not limited to: - Identify Team Members - Review Vision, Mission, Goal and Objectives of Project - Review System Architecture (includes system definition, concept and layout) - Review Level 1 Requirements - Review Traceability of requirements “flow down” - Review Work Breakdown Structure (WBS) - Review preferred system solution definition including major trades and options. CAD model of physical components of system if available. - Review preliminary functional baseline - Review draft concept of operations - Review preliminary system software functional requirements - Review risk assessment and mitigations approach - Review analysis tools to be used - Review Cost and schedule data - Review software test plan (approach) - Review hardware test plan (approach)	

<u>NASA Preliminary Design Review</u>	<u>DID #: 2</u>
Schedule Date: 11/29/2022	
Purpose: Preliminary Design Review with NASA Sponsors to outline a top-level requirements and preliminary design of the BLiSS: Cargo module.	
Preparation Information: The Preliminary Design Review shall be prepared by the BLiSS: Cargo team in a slide show format and presented to NASA stakeholders virtually. The report shall include, but is not limited to, the following information: - Review and updates of any documents developed and baselined since SDR - Review a matured ConOps - Review of any updates to any engineering specialty plans - Review risk management plan - Review cost and schedule data - Review top-level requirements and flowdown to the next level of requirements since SDR - Review any design-to specifications (hardware and software) and drawings, verification and validation plans, and interface documents at lower levels. A CAD model is required at PDR stage for all physical components of the system. - Review any trade studies that have been performed since SDR and their results - Review any performed design analyses and report results - Review any engineering development tests performed and report results - Review and discuss internal and external interface design solutions (and any interface control documents needed). This includes interface information provided by NASA since SDR - Review system operations - Review any potential safety issues (or data) - Select a baseline design solution A successful PDR shall demonstrate understanding of system requirements and show flow down to the preliminary design decisions. A general consistency between design, proposed operations, and design decisions shall be shown.	

<u>NASA Critical Design Review</u>	<u>DID #: 3</u>
Schedule Date: 2/16/2023	
Purpose: Critical Design Review with NASA Sponsors to describe the top- and lower-level requirements of the project and explain the full design of the system.	
Preparation Information: The Critical Design Review shall be prepared in a slide show format by the BLiSS: Cargo team and presented to NASA Stakeholders virtually. The CDR shall show adequate completion of system design to begin construction of prototypes and software to begin testing and verification. The CDR shall include, but is not limited to, the following: - Review and updates of any documents developed and baselined since PDR - Review a finalized ConOps - Review of finalized engineering specialty plans - Review finalized risk management plan - Review finalized cost and schedule data - Review top-level requirements and flowdown to the next level of requirements since PDR - Review finalized design-to specifications (hardware and software) and drawings, verification and validation plans, and interface documents at lower levels. A CAD model is required at CDR stage for physical components of the system and showing the system in with the larger habitat model. - Review finalized design analyses and report results - Review finalized engineering development tests performed and report results - Review and discuss finalized internal and external interface design solutions (and any interface control documents needed). This includes interface information provided by NASA since PDR - Review finalized system operations - Present the finalized baseline design solution that will be built	

<u>Cargo System Prototypes</u>	<u>DID #: 4</u>
Schedule Date: 4/28/2023	
Purpose: The prototypes of the completed system will be assembled and demonstrated.	
Preparation Information: Cargo system prototypes shall consist of a scale functional prototype and full sized human factors mock up. Test plans and test reports for each system shall be created appropriately for each one by the BLiSS: Cargo team. The Test reports shall record the performance and deficiencies of the system as currently designed with known limitations of testing in the terrestrial environment. These reports may be delivered to NASA stakeholders but shall be used for design changes and remaining deliverables. Exact content of these reports is not formally specified.	

<u>Educational Outreach Report (Opt.)</u>	<u>DID #: 5</u>
Schedule Date: 5/--/2023	
Purpose: Educational Outreach Report	
Preparation Information: The BLiSS: Cargo team may elect to create an Educational Outreach Report to submit to technical conferences, other schools, and other publicity events. The exact content of this report is not formally described herein but is subject to requirements of applicable conferences, societies, etc to which the report may be sent.	

<u>NASA Final Presentation</u>	<u>DID #: 6</u>
Schedule Date: 5/04/2023	
Purpose: Final Presentation to NASA Sponsors at Kennedy Space Center describing the objectives, requirements, design, and testing of the BLiSS: Cargo module.	
Preparation Information: The BLiSS: Cargo team shall prepare the NASA Final Presentation in slide show format for an in person meeting with NASA Stakeholders. The content of which is not yet formalized but is expected to encompass all previous documents and relevant findings.	

<u>NASA Technical Final Report</u>	<u>DID #: 7</u>
Schedule Date: 6/2/2023	
Purpose: Final Technical Report to formalize project efforts and final design performance.	
Preparation Information: The BLiSS: Cargo team shall prepare the Technical Final Report in accordance with NASA and University publishing and export guidelines. The exact contents of the report are not formally delineated but is expected to encompass all previous documents with a focus on prototype performance and final system design incorporating any changes identified in testing.	

Bliss Cargo
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Cameron Sahagian-Crandall, Jacob Kaspriak, Kaisheng Li,
Maxwell Chappell, Monica Khalique, Jessica Fisher, Rohan

Sat, 10/1/2022

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Bliss Cargo
Miles Irmer, Drew Wright, Akashdeep Pawar,
Cameron Sahagian-Crandall, Jacob Kaspriak, Kaisheng Li,
Maxwell Chappell, Monica Khalique, Jessica Fisher, Rohan

Project Start:

Sat, 10/1/2022

Display Week:

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Maxwell Chappell, Monica Khaliq, Jessica Fisher, Rohan																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																															
Task ID	Task Title	Budget (Total \$)	% Complete	Duration	START	END	Milestone Observables	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S

SPACES83 Bliss Cargo

Bliss Cargo				Project Start:		Sat, 10/1/2022	
Miles Imer, Drew Wright, Akashdeep Pawar, Cameron Sahaglan-Crandall, Jacob Kasprlak, Kaisheng Li, Maxwell Chappell, Monica Khaliq, Jessica Fisher, Rohan				Display Week:		1	
Task ID	Task Title	Weight (Total PV)	% Complete	Duration	START	END	Milestone Deliverables
RS	Generate Power Budget	18	100%	43	10/17/22	11/29/22	
SS	Sensors and Software						
SS.1	Model system	42	100%	91	10/17/22	1/16/23	
SS.1.1	Set standards	8	100%	15	10/17/22	11/1/22	
SS.1.2	Build model	8	100%	15	11/14/22	11/29/22	
SS.1.3	Create test cases	6	100%	19	12/1/22	12/20/22	
SS.1.4	Validate model	10	100%	19	12/1/22	12/20/22	
SS.1.5	Leverage model	10	100%	26	12/21/22	1/16/23	
SS.2	Develop System Software	34	100%	73	1/17/23	3/31/23	
SS.2.1	Set standards	8	100%	15	1/17/23	2/1/23	
SS.2.2	Develop control algorithm	10	100%	41	2/1/23	3/14/23	
SS.2.3	Develop sensor data processing	16	100%	17	3/14/23	3/31/23	
SM	Structures + Materials						
SM.0	Preliminary Trades	10	100%	5	10/17/22	10/22/22	
SM.1	Model Geometry	102	100%	14	10/17/22	10/31/22	
SM.1.1	Model Sub-System Geometry	42	100%	14	10/17/22	10/31/22	
SM.1.2	Model System Assembly	60	100%	14	10/17/22	10/31/22	
SM.2	Hand Calculated Stress Analysis	75	100%	80	11/1/22	1/20/23	
SM.2.1	Define Boundary Conditions	30	100%	43	11/1/22	12/14/22	
SM.2.2	Hand Calculations	45	100%	37	12/14/22	1/20/23	
SM.3	Simulate Component Static Response	62	100%	75	11/6/22	1/20/23	
SM.3.1	Remodel Geometry for FEA	12	100%	38	11/6/22	12/14/22	
SM.3.2	Write Component Simulation	50	100%	32	12/14/22	1/15/23	
SM.3.3	Verify Simulation Output	2	100%	5	1/15/23	1/20/23	
SM.3.4	Design Optimization	9	100%	5	1/15/23	1/20/23	
SM.4	Simulate System Transient Response	55	100%	41	12/10/22	1/20/23	
SM.4.1	Remodel Geometry for FEA	15	100%	41	12/10/22	1/20/23	
SM.4.2	Write System Simulation	30	100%	41	12/10/22	1/20/23	
SM.4.3	Verify Simulation Output	10	100%	41	12/10/22	1/20/23	
P	Prototyping						
P.1	Design Ergonomic Prototype	25	100%	77	1/20/23	4/7/23	
P.1.1	Determine Prototype Dimensions	2	100%	14	1/20/23	2/3/23	
P.1.2	Assemble Ergonomic Prototype	90	80%	63	2/3/23	4/7/23	
P.2	Design Dynamic Prototype	25	100%	77	1/20/23	4/7/23	
P.2.1	Determine Prototype Dimensions	5	100%	14	1/20/23	2/3/23	
P.2.2	Assemble Dynamic Prototype	120	70%	63	2/3/23	4/7/23	

Appendix E: Verification Plans

Requirements verification matrix

Requirement ID	Level	Name	Shall Statement	Verification Success Criteria	Verification Method	Verification Plan
R1	1	Microgravity	The system shall function in microgravity	1. System is delivering/retrieving cargo in capsule 2. User inputs and system outputs are transmitted to system and user, respectively	Demonstration	To demonstrate that all functions of the system can have 100% performance under simulated microgravity conditions
R1.1	2	Interaction Orientation	The crew shall interact with the system while they are in various spatial orientations	1. Test subject can collect/replace sample cargo (0.8m spherical object) in mock-up	Demonstration	Demonstration by removing cargo from cam-latch in 144 positions (permutations of body-to-cargo angles and cargo-to-hatch-plane angles)
R1.1.1	3	Temporary Mounting	The cargo containers shall have a method of temporarily attaching to internal Gateway surfaces for crew access to contents	1. Cargo containers can temporarily attach to materials that will likely be used for the Gateway internal surfaces	Test	To test and show the cargo can be temporarily attached to gateway surface successfully
R1.1.2	3	System User Device	The system interface shall be contained in a movable device allowing for use by crew members	1. UI is contained within a portable device	Inspection	The app in mobile devices has full functionality and can be interfaced with system

R1.2	2	Structures Safety Factor	The structures shall have a safety factor above 1.1 in microgravity	1. FEA models on all components provide a 10 percent margin for structural yield given expected loads 2. Hand calcs confirm model accuracy	Analysis	Conduct an static structural simulation of the system CAD on Ansys Mechanical Workbench and validate the factor of safety to yield above 1.1
R2	1	Cargo Delivery	The system shall deliver desired cargo to the Gateway Logistics Module entry point	1. System delivers cargo to access hatch	Demonstration	This will be verified using demonstration of system operations with the success criteria being successful delivery of desired cargo to the access hatch in at least 49 out of 50 attempts.
R2.1	2	Degrees Of Freedom	The system shall have a maximum of 6 degrees of freedom	1. CAD model of system is seen to have 6 DOF 2. Mock-up of system is seen to have 6 DOF	Inspection	This will be verified through inspection of the system CAD models and end product to count the number of degrees of freedom.
R2.2	2	Cargo Container Dimensions	The system shall deliver cargo with size bounded by a sphere of 0.8 m in diameter	1.CAD model of system shows that cargo with size bounded by a sphere of 0.8m in diameter can fit on belts 2. CAD model of system shows that such cargo fits through modeled access hatch	Inspection	This will be verified through inspection of all cargo containers to measure external dimensions.

R2.2.1	3	Delivery Cargo Interface Surface	The cargo interface shall link all cargo containers with an available interface surface of 40 x 15 mm	1. CAD model shows cargo linkage is within required dimensions 2. Mockup shows cargo linkage is within required dimensions	Inspection	This will be verified through inspection of all cargo container linkages to measure external diameters.
R2.3	2	Maximum Deliverable Mass	The system shall deliver cargo with a maximum mass of 60 kg	1. Mock-up of conveyor belt system moves and does not malfunction subject to the load of a sample cargo 2. Mock-up conveyor belt system delivers sample cargo to mock-up delivery hatch	Demonstration	This will be verified through inspection of the masses of individual cargo containers and then demonstration of the fully loaded system moving cargo containers up to 60kg in mass.
R2.3.1	3	Minimum Actuator Torque	The actuator shall generate a torque of no less than 0.1 N-m	1. Unit test of actuator produces required torque	Test	This will be verified through unit testing of each actuator to determine minimum and maximum output torques at the item specified voltages.
R2.4	2	Cargo Delivery Distance	The system shall deliver cargo with its interface within 1 m of the hatch face of the capsule	1. Simulated system has displaced model of cargo 1 m beyond hatch plane 2. Handcalcs agree with simulation	Analysis/Inspection	This will be verified through inspection of the nearest straight-line distance between the male cam latch and the top hatch.
R2.4.1	3	Cargo Delivery Accuracy	The system shall manipulate cargo position to within 5 cm of targeted location on 98.7% of all nominal attempts	1. The system shall manipulate cargo position to within 5mm [TBR] of targeted location on 98.7% of all nominal attempts	Test	This will be verified through demonstration of the fully loaded system's capability to manipulate cargo to within 5 cm of the desired location on 98.7% of requests.

R2.5	2	Cargo Interface Ability	The system shall interface with all cargo	1. Sample cargo fits in mock-up of system 2. Sample cargo remains on conveyor belt of mock-up during movement of conveyor belt	Inspection	This will be verified through inspection of the ability of cargo containers to store all manifest cargo as defined in the respective ICD.
R2.5.1	3	Success Telemetry Delivery	The system shall provide telemetry of success at various stages in cargo delivery and retrieval	1. Notification of interface with cargo is observed via black box test	Test	This will be verified through test of the success notification as the system reaches the various defined stages of the delivery and retrieval process.
R2.5.2	3	Cargo Interface Accuracy	The system shall successfully interface with cargo on 98.7% of attempts	1. 98.7% of interfaces with cargo completed successfully over entirety of lifecycle testing	Demonstration	This will be verified through demonstration of the system's capability to interface with its intended cargo on 98.7% of all attempts.
R2.5.3	3	Cargo Removal Torque	The cargo interface shall require no more than 2.1 N-m of torque to remove and return a cargo storage box from the system	1. The cam latch design requires no more than 2.1N-m of torque required to remove a 60 kg cargo storage box.	Demonstration	This will be verified through demonstration of the torque required to actuate the cam latch mechanism.
R2.6	2	Cargo Request Queue	The system shall execute a queued request only after previous cargo is retrieved by user	1. Software is unable to act upon multiple requests simultaneously 2. Software will queue and execute multiple requests	Test	This shall be verified through testing the system's queue function to guarantee that the next queue item is only acted upon after the current queue item is completed.

R2.7	2	Cargo Absence Recognition	The system shall recognize when cargo has been retrieved and replaced	1. Upon inspection, there is a method of recognizing when cargo has been retrieved 2. Upon inspection, there is a method of recognizing when cargo has been retrieved	Demonstration	This will be verified through demonstration of the system's capability to recognize cargo retrieval and replacement.
R3	1	Cargo Return Requirement	The system shall return various cargo containers from the entry point to a designated position	1. Demonstration of a storage unit of cargo being received and remaining in its designated belt	Demonstration	Demonstration of the systems ability to return previously removed cargo from the entry point to the designated position.
R3.1	2	Cargo Interface Distance	The system cargo container interface shall be within 1 m of the hatch face of the capsule	1. Cargo replaced back into mock-up system is placed back within 1m of the hatch face, measured manually	Inspection	This will be verified by inspection of the closest straight-line distance between the male cam latch and the top face of the capsule.
R3.2	2	Cargo Return Success Telemetry	The system shall provide telemetry of success on cargo's return to designated position	1. Notification of cargo's return to designated position is observed via black box test	Test	This will be verified by testing the system's success telemetry transmission for successful cargo return achievements.
R3.3	2	Cargo Container Size	The system shall return cargo with size bounded by a sphere of 0.8 m in diameter	1. All cargo partitions have cross sectional distances less than 0.8m	Inspection	This will be verified by inspecting the dimensions of the system cargo containers.

R3.3.1	3	Return Cargo Interface Size	The cargo interface shall link all cargo containers with an interface surface of 40 x 15 mm	1. CAD model shows cargo linkage is within required dimensions 2. Mockup shows cargo linkage is within required dimensions	Inspection	This will be verified through inspecting the dimensions of the cargo interface surface.
R3.4	2	Maximum Cargo Retrieval Mass	The system shall retrieve cargo with a maximum mass of 60 kg	1. Mock-up of conveyor belt system moves and does not malfunction subject to the load of a sample cargo 2. Mock-up conveyor belt system retrieves sample cargo from mock-up delivery hatch	Demonstration	This will be verified through inspection of the masses of individual cargo containers and then demonstration of the fully loaded system moving cargo containers up to 60kg in mass.
R4	1	System Autonomy	The system shall fulfill requests autonomously upon user input	1. Logistics system delivers cargo upon astronaut input in system UI 2. Logistics system retrieves cargo upon astronaut input 3. System informs astronaut of inventory upon astronaut input	Demonstration	This will be verified through demonstration of the system's capability to autonomously deliver cargo, return cargo, and display cargo inventory based on user input.

R4.1	2	System Location Accuracy	The system shall locate specific cargo within the capsule	1. Mock-up of system configures into position ready for delivery/retrieval of specified cargo 2. User receives data on UI regarding availability of specified cargo	Demonstration	This will be completed by demonstrating the system's capability to locate specifically requested cargo within the capsule.
R4.1.1	3	Cargo Container Identifiers	The cargo containers shall have a transmittable identifier	1. All cargo containers are equipped with a transmittable identifier	Inspection	This will be verified through inspection of the cargo containers for a usable, and transmittable identifier
R4.1.2	3	Cargo Item Identifiers	The system shall associate a unique identifier with each cargo item	1. Each unique cargo item is defined by its own unique identifier within the server	Inspection	This will be verified through inspecting the cargo log for each item's unique identifier
R4.1.3	3	Cargo Organization Storage	The system server shall store cargo organization data	1. Script runs test cases with sample data that demonstrates that the stored data matches expectations	Test	This will be verified through testing the server's capability to store cargo organization data
R4.1.3.1	4	Cargo Layout Storage	The microcontroller shall store cargo layout	1. Script runs test cases with sample data that demonstrates that the stored data matches expectations	Test	This will be verified through testing the microcontroller's ability to store cargo layout.
R4.1.4	3	Cargo Log Storage	The system server shall store logged cargo identification data	1. Script runs test cases with sample data that demonstrates that the stored data matches expectations	Test	This will be verified through testing the server's ability to store cargo identification data.

R4.1.5	3	Requested Cargo Identification	The system server shall identify requested cargo for reception and return	1. Script runs test cases with sample data that demonstrates that the requested cargo matches what the system server identifies	Test	This will be verified by testing the server's ability to identify requested cargo within the system.
R4.1.5.1	4	Cargo Location Confirmation	The microcontroller shall confirm cargo location with uploaded ID sensor data	1. Script runs test cases with sample data that demonstrates that the specific cargo matches the ID given, and that the location given matches the location of the cargo	Test	This will be verified by testing the microcontroller's ability to confirm cargo location using the uploaded ID sensor data
R4.1.5.2	4	ID sensor data upload	The ID sensor shall upload "selected" cargo ID data to the microcontroller	1. Data collected from microcontroller shows that the ID sensor correctly uploaded the selected cargo ID	Test	This will be verified through testing the ability of the ID sensors to upload the selected cargo ID data to the microcontroller
R4.1.6	3	Cargo Location Usage	The microcontroller shall use stored cargo configuration data to locate cargo (belt + distance)	1. Script runs test cases with sample data that demonstrates that the stored data matches the location of test cargo (belt + distance)	Test	This will be verified through testing the microcontroller's ability to use stored cargo configuration data to locate cargo within the system.
R4.2	2	Cargo Retrieval Command	The system shall retrieve cargo on command of the autonomous system action	1. Mock-up locates and displaces sample cargo upon user input into system UI (done 3 times for 3 different cargo/locations)	Test	This will be verified by testing the system's capability to retrieve cargo based

R4.2.1	3	Mobility System Actuator Input Voltage	The mobility system actuators shall be commanded with a voltage input less than or equal to 24V	1. Unit test of actuator produces required torque under voltage measured to be within the requirement	Inspection	This will be verified by inspecting the input voltage of the mobility system actuators
R4.2.2	3	Sensor And Controller Input Voltage	All sensors and controllers shall be commanded by an input voltage less than or equal to 24 V	1. Unit test of actuator produces required torque under voltage measured to be within the requirement 2. Unit test of linkage mechanism shows the linkage toggles under voltage measured to be within the requirement	Inspection	This will be verified through inspecting the input voltage of the system sensors and controllers.
R4.2.3	3	System Linear Motion Measurement	The system shall measure linear motion of mobility system	1. Series of tests that demonstrate the rotary encoder is able to show distance data as the cargo is in motion	Test	This will be verified through testing the system's ability to linearly track the motion of the mobility system
R4.2.4	3	Microcontroller Command Management	The microcontroller shall output a series of commands to bring cargo to pick-up location (hatch)	1. Test cases which output the correct commands to bring cargo to the hatch	Test	This will be verified through testing the microcontroller's ability to output the necessary commands to move cargo containers to the pick-up location
R4.3	2	Microcontroller Command Sending Criteria	The microcontroller shall solely send commands to actuators in response to input from user interface	1. Mock-up configures into cargo return configuration compatible with 3 different sample cargo upon user input into system UI	Test	This will be verified through testing the microcontroller algorithm to respond to user interface inputs

R4.3.1	3	Microcontroller Movement Criteria	The microcontroller shall begin motion only upon detection and verification of correct cargo	1. Mock-up will not continue through requests until the previously removed cargo container is replaced and the RFID scanned can verify that it is the correct cargo container	Demonstration	This will be verified through demonstration of the microcontroller's ability to begin cargo motion only after it has detected and verified the correct cargo
R4.4	2	System Cycle Speed	The system shall deliver or return requested cargo within 10 minutes from request	1. Delivery time of mock-up system is 10 minutes 2. It takes 10 minutes to return cargo to mock-up system	Demonstration	This will be verified through demonstrating the time it takes for the system to deliver and return requested cargo
R4.4.1	3	Microcontroller Processing Time	The microcontroller's processing time shall be less than 10 minutes	1. Timing microcontroller command execution duration	Test	This will be completed through testing the microcontroller's processing time
R4.5	2	System Request Queueing	The system shall queue requests when dealing with multiple inputs	1. Mock-up system completes requests one after the other in order of user input	Test	Queue loading Test, user will input a series of 3, 5, 7, and 10 requests into the system in rapid succession to create queues of different lengths.
R4.5.1	3	System Request Priority Order	The system shall order requests in the queue based on order of input	1. System queues order requests based on order received	Demonstration Inspection	Inspecting the results of the system's queue loading to demonstrate the system's accuracy of task order completion
R4.5.2	3	System Queue Visualization	The system shall provide a visual representation of the input queue	1. Once mock-up system has received user input, user sees position of their request in queue on UI	Demonstration Inspection	inspecting the UI after the queue loading test to demonstrate the systems logging accuracy of completed tasks

R4.6	2	Sensor Suite Data	The system sensor suite shall gather and upload telemetry data	1. Verified upon verification of R.4.6.2-5	Inspection	Inspecting the collected telemetry data for completion
R4.6.1	3	Sensor Suite Data Accuracy	The system sensor suite's collected data shall be within 1% of real value	1. Verified upon verification of R4.6.1.1-2	Test	Completing the suite of testing for each sub requirement for accuracy of components
R4.6.1.1	4	Rotary Encoder Data Accuracy	The rotary encoder distance data shall be within 1% of the true value	1. Series of tests to demonstrate with 95% confidence that encoder tracks data to within 99%	Test	Testing the rotary encoder by inputting requests and stopping the system at random intervals to measure the distance manually then referencing it with the encoder data to test accuracy
R4.6.2	3	Rotary Encoder Data Upload	The rotary encoder shall upload data to the microcontroller	1. Rotary encoder data is found on microcontroller	Inspection	Inspecting the microcontroller data after testing to see the rotary encoder data is there
R4.6.3	3	Sensor Data Upload	The safety sensor shall upload data to the microcontroller	1. Safety sensor data is found on microcontroller	Inspection	Inspecting the microcontroller data after testing to see the safety sensor data is there
R4.6.4	3	Microcontroller Telemetry Configuration	The microcontroller shall configure telemetry in a format consumable by user device	1. Test cases which verify that the data from the microcontroller is being stored in the correct format	Test	Testing the microcontroller by inputting requests for a predetermined list of cargo and then checking the telemetry data for accuracy

R4.7	2	System Accumulated Error Correction	The system shall correct for accumulated error	1. Testing of chain position data after 5 cycles to measure accumulated error	Test	Testing the position data accuracy by cycling the system 5 times and measuring the actual position and comparing it with the position data
R4.7.1	3	Monitor Error Accumulation Rate	The monitor shall allow error to accumulate for no more than one full rotation	1. Testing of chain position data after 1 full chain cycle to measure accumulated error	Test	Testing the functionality of the position resetting switch after 1 full rotation by running 5 rotations and checking the position data after each full rotation
R4.7.2	3	Monitor Chain Movement	The monitor shall allow bi-directional chain movement	1. Testing of chain position monitor for bi-directional movement	Test	Testing the monitor by manually moving the chain in both directions to determine if the monitor's position value is accurate
R4.7.3	3	Monitor Profile Size	The monitor shall have a small enough profile to avoid intrusion on other parts	1. Inspection of chain position monitor for points of intrusion in system cycles	Inspection	Inspecting the monitor during use for possible interferences with other components
R4.7.4	3	Monitor Operation Length	The monitor shall be robust enough to endure 12 months of operation	1. Lifecycle testing of one prototype system to measure degradation of chain position monitor	Test	Testing the monitor's life by running 3,650 requests (10 /day for a year) consecutively and measure the chain position to compare with the monitors value
R4.8	2	Identifier Simple Action	The identifier shall require no more than one additional simple action from the user during operation	1. Testing of identification system to demonstrate the one action from the user	Demonstration	Demonstration of the single additional task required to identify the cargo

R4.8.1	3	Identifier Cargo Updates	The identifier shall allow for new or updated cargo	1. Identification data has new cargo identification information	Inspection Demonstration	Inspecting the identification data to demonstrate the input of the new cargo
R4.8.2	3	Identifier Use Of Current Systems	The identifier shall take advantage of current systems to minimize complexity impact	1. Testing of the identifier for inter-system communication.	Test	Testing the identifier with and without the other systems to determine the use of the other systems by the identifier
R5	1	User Interface Accessibility	The system shall be controlled by a user interface(s) accessible from anywhere within the Lunar Gateway	1. User device is present in the Lunar Gateway at the maximum distance from the GLM	Demonstration	Demonstration of different user cases that fully represents real scenarios of crew controls the system by a user interface(s) from anywhere within the LunarGateway-like test-site
R5.1	2	User Interface Training	The user interface shall require a maximum of 10 min of specific training in order to use in nominal operations	1. Training materials are presented within ten minutes	Test	Record the learning time from the representatives of astronauts and 95 % of the recorded data shall be less than 10 mins
R5.2	2	Cargo Inventory Data Accessibility	The system cargo inventory data shall be remotely accessible to ground controllers	1. Mock ground control accesses cargo inventory	Test	To test and show the communication system and ability to transpond inventory data via ground testing site
R5.2.1	3	Request Constraints	The user interface shall accept cargo requests exclusively from within the Lunar Gateway	1. Some test campaign of false requests result in no action by the system	Test	To test and show that no external interfaces can be allowed and accepted via penetration testing

R5.3	2	Feedback Telemetry	The system server shall provide feedback telemetry to user	1. Telemetry report contains required telemetry data 2. Verified through verification of R.5.3.1-8	Inspection Demonstration	To show that the App in mobile device can provide feedback telemetry
R5.3.1	3	Cargo Delivery Notification	The system shall provide notifications of cargo deliveries via the UI	1. Confirm that correct notifications are sent to user device during all appropriate states through test campaign	Test	To test and show that the App in mobile device can provide notifications of after the deliveries of the cargos
R5.3.2	3	Cargo Error Notifications	The system shall provide notifications of cargo delivery and retrieval errors to the crew via the UI	1. Notification of cargo's return to designated position is observed through series of tests	Black Box Test	To test and show that the App in mobile device can provide notifications of errors of different error types
R5.3.3	3	Estimated Time	The system shall provide estimated time until cargo delivery to crew via the UI	1. UI provides time until delivery to UI	Black Box Test	To test and show that the App in mobile can provide estimate waiting time and reflects the real waiting time with 90% confidence of multiple requests
R5.3.4	3	Change Notifications	The system shall provide notifications of changes in system mode (nominal, failure, safe, etc.) via the UI	1. UI provides notification of change in system mode to UI 2. UI provides notification with new system mode to UI	Black Box Test	To test and show that the App in mobile can provide notification of change in system mode to UI and provides notification with new system mode to UI with tests under different scenarios
R5.3.5	3	Requested And Completed Work Log	The system shall provide a log of all requests and completed deliveries via the UI	1. UI provides activity log to UI upon request	Black Box Test	To test and show that the App in mobile can provide history of all types of request and completed deliveries of all time

R5.3.6	3	Metadata	The system shall provide metadata on cargo in containers via the UI upon request	1. UI provides metadata of cargo to UI upon request	Black Box Test	To test and show that the App in mobile can provide detailed metadata of all required information of all cargo item listed in the system
R6	1	Wet Mass	The combined mass of the system and cargo shall be below 5.5 Tons	1. Sum of measured component masses does not exceed the requirement	Demonstration	Weigh the system and cargo on the ground and the total mass is less than 5 tons
R6.1	2	Dry Mass	All non-cargo mass shall be at most 500 kg	1. All projected items required to build logistics system does not exceed a mass of 500 kg upon calculation	Inspection	Weigh the non-cargo portion of the system on the ground and the mass shall be less than 500kg
R6.1.1	3	Mobility System Mass	The mobility system mass shall be at most 200 kg	1. Verified upon verification of R6.1.1.2 - 6.1.1.3 2. Summation of masses inspected from R6.1.1.2 - 6.1.1.3 does not exceed 330 kg	Inspection	Weigh the mobility system on the ground and the mass shall be less than 200 kg
R6.1.1.2	4	Actuator Mass	The total mass of all actuators shall be no more than 60 kg	1. Motor unit mass multiplied by the total number of motors in the design is within the required limit	Inspection	Weigh the total mass of all actuators on the ground and the mass shall be less than 60kg
R6.1.1.3	4	Interface Mass	The total mass of all cargo interface mechanisms will be no more than 50 kg	1. Unit linkage mass multiplied by the total number of linkages in the design is within the required limit	Inspection	Weigh all cargo interface mechanisms of the system on the ground and the mass shall be less than 50kg

R6.1.2	3	Structural Mass	The rigid structural mass shall be at most 255 kg	1. CAD analysis of conceptual system to determine the rigid structural mass is under 255 kg.	Analysis	CAD analysis of conceptual system to determine the rigid structural mass is under 255 kg.
R6.1.3	3	Sensor Mass	The sensing/software suite shall be at most 15 kg	1. Mass calculated upon sum of components mass shows that the mass of the support cage does not exceed 15 kg	Inspection	Weigh the sensing/ software suite on the ground and the mass shall be less than 15kg
R7	1	System Lifetime	The system shall operate for the entire on-station lifetime of 12 months	1. System delivers/retrieves cargo upon all user requests within 12-months on station	Demonstration	
R7.1	2	Fatigue Safety Factor	Each component of the system shall have a lifecycle fatigue safety factor of 1	1. Transient FEA shows that all components can withstand expected loads repeated nominally throughout mission lifecycle	Analysis - Ansys Transient Structural	Conduct an transient static structural simulation of the system CAD on Ansys Mechanical Workbench and determine the fatigue factor of safety (FSF)
R7.2	2	Cargo Attachment Reliability	The system shall attach to cargo with 95% reliability at 90% confidence for the entire on-station lifetime of 12 months	1. 95% of the time, the system mock-up interfaces with cargo for 10 cycles (~ about how many times system is used per day, assuming 4 astronauts who retrieve food/water/clothes at the same time) 2. Aged mock-up of system interfaces with cargo	Test	Repeatedly test the system interface with cargo modules via assembly in sets of 10 iterations and record failure rate to demonstrate 95% reliability is established with 90% confidence. Repeat the test after 12 month of operation

R7.3	2	Functional Reliability	The system shall move cargo with 95% reliability at 90% confidence for the entire on-station lifetime of 12 months	1. 95% of the time, the system mock-up moves with cargo for 10 cycles 2. Aged mock-up of system moves cargo	Test	Repeatedly move cargo modules with the system in sets of 10 cycles and record failure rate to demonstrate 95% reliability is established with 90% confidence. Repeat the test after 12 month of operation
R7.4	2	Server Reliability	The system server shall execute mobility commands with 99% reliability at 90% confidence for the entire on-station lifetime of 12 months	1. 99% of the time, the system server mock-up executes mobility commands for X cycles 2. Aged mock-up of system server components allows for execution of mobility commands	Test	Repeated cargo belt mobility command execution to record failure rate and extrapolate to full system lifetime to demonstrate 99% reliability is established with 90% confidence. Repeat the test after 12 month of operation
R7.4.1	3	Rotary Encoder Reliability	The rotary encoder shall have a reliability greater than 99%	Fatigue tests demonstrate that, extrapolated to a full system lifetime, the rotary encoder shall be 99% reliable (according to R4.6.1.1) with a 95% confidence interval	Test	Conduct fatigue test on rotary encoder by repeatedly moving cargo belt and evaluate R4.6.1.1. Monitor failure rate and extrapolate to full system lifetime to demonstrate 99% reliability is established with 95% confidence
R7.5	2	Server Downtime	The system server shall require no more than 80 hours of downtime over the course of the 12 month mission	1. Mock-up system does not exceed 1.65 hours of downtime over the course of 1 week of testing capabilities such as cargo delivery and return	Inspection	Measure and sum the total time the cargo system is inoperable over the span of one week of nominal usage. Extrapolate results to full system lifetime to estimate under 80 hours of inoperability

R7.5.1	3	Microcontroller Lifetime	The microcontroller shall be inoperable for no more than a combined 40 hours over 12 months	1. Demonstration of microcontroller operation, extrapolation of demonstration runtime over a 12-month period	Demonstration	Measure and sum the total time the microcontroller is inoperable over the span of one week. Extrapolate results to full system lifetime to estimate under 40 hours of inoperability
R7.5.2	3	App Lifetime	The app shall be inoperable no more than a combined 40 hours over 12 months	1. App for mock-up system does not exceed 0.81 hours of offline/crash time over the course of 1 week of testing capabilities such as cargo delivery and return	Inspection	Measure and sum the total time the user app is inoperable over the span of one week. Extrapolate results to full system lifetime to estimate under 40 hours of inoperability
R7.6	2	Server Updates	The system shall accept updates to the system server and user interface through digital upload	1. Verified upon verification of R7.7.1-2	Test	Send a sample update to system server and user interface upon finishing system installation and assembly outlined in R7.7
R7.6.1	3	Software Updates	The microcontroller shall be able to accept software updates through its interface with the app	1. Microcontroller receives sample software updates sent by app	Test	Monitor and confirm microcontroller reception of software updates from the user interface on the app
R7.6.2	3	Application Updates	The app shall upload new software patches to the microcontroller	1. Microcontroller receives sample software (output) patches sent by app (input)	Black Box Test	Send a sample software update to the microcontroller from the user interface on the app using production interface.

R7.7	2	Installation Procedure	The system shall be installed in the Gateway Logistics Module manually before flight	1. CAD model shows that system can be installed in the Gateway Logistics Module (system fits within module) 2. System is actually installed before flight	Inspection Demonstration	Inspect CAD model and confirm the system assembly's ability to fit in the Gateway Logistics Module (GLM) CAD. Then upon final system delivery, install the system into the GLM
R7.7.1	3	Loading Procedure	The system shall be manually loaded with cargo before flight	1. Inspection of construction constraints show feasibility of in-site setup	Demonstration	Load cargo onto the cargo mobility system before the mission flight to demonstrate feasibility of pre-flight loading
R7.7.2	3	Critical Spares	The system's cargo shall include critical spares indicated by the providers	1. There is room within the system for critical spares (CAD model of system does not interfere with or can contain these items). 2. Cargo manifest shows allocation for critical spares	Inspection	Inspect CAD model and tabulate space for critical spares of system components. Then, upon final system delivery, inspect the cargo manifest to confirm presence of critical spares

R7.8	2	System Manual Retrieval	The system shall enable manual retrieval of cargo in event of failure	1. Upon powering-down of mock-up system, test subjects can manually take out cargo of interest without inflicting harm to themselves or the system 2. CAD model shows that a human can fit through access hatch 3. Layer of cargo closest to access hatch contains at least 4 portions (for 4 astronauts) of necessary cargo for survival	Demonstration Inspection	Inspect CAD model of system to verify humans can fit through access hatch. With assembled system, power it down and retrieve cargo manually to demonstrate that capability. Upon final system delivery, inspect manifest to verify closest access hatches contain 4 portions of survival-critical cargo for 4 astronauts.
R7.8.1	3	Cargo Interface Manual Retrieval	The cargo interface shall enable manual retrieval of cargo in event of failure	1. A user successfully removes the cargo without power into the system	Demonstrate	Assess interface ability allow manual operation and conduct manual retrieval of cargo from the system without using power or mobility commands
R7.8.2	3	Manual Rotation Force	Manual rotation of cargo attached to the system shall require no more than 100 N of force	1. The acceleration of the mobility system chain times the mass of the chain, the cargo containers, and cargo does not exceed 100 N	Inspection	Inspect the cargo manifest to ensure system mass remains below the threshold of requiring 100 N of force such that <i>acceleration*system mass < 100 N</i>
R7.9	2	Mobility Chain Lubrication	The mobility system chain shall be lubricated	1. Inspection of mobility system chain exhibits lubrication of chain elements	Inspection	Inspect mobility system chain to detect proper lubrication of chain elements

R7.9.1	3	Mobility Non-Toxic Lubricant	The mobility system chain lubricant shall be non-toxic	1. Lubrication agent is not toxic and does not contain toxic byproducts	Inspection	Inspect lubrication agent and its ingredients to verify lack of toxicity chemicals
R7.9.2	3	Mobility Non-Flammable Lubricant	The mobility system chain lubricant shall be non-flammable	1. Lubrication agent does not have a manufacturer flammability warning	Inspection	Inspect lubrication agent and its ingredients to verify lack of a manufacturer-specified flammability warning
R7.10	2	Mobility Adjustable Tension	The mobility system chain shall have adjustable tension	1. Tension in the cargo mobility chain can be adjusted using a worm gear jack screw	Demonstration	Lift and lower the worm gear jack screw system to tension or slacken the line respectively
R7.10.1	3	Chain Tensioning System	The chain tensioning system shall be manually adjustable	1. Jack screw lift can be raised manually in addition to automatic actuation via a motor	Demonstration	Manually lift and lower the worm gear jack screw system to tension or slacken the line respectively
R8	1	System Integration With Gateway Module	The system shall be contained within the Gateway Logistics Module	1. System fits in GLM 2. Interface between system and GLM remains intact 3. GLM remains undamaged	Demonstration	The demonstration will show that the system will fit inside the GLM without harming the GLM or the system. This includes the interface of the two.
R8.1	2	Undamaged System	The system shall leave the Gateway Logistics Module undamaged from installation or operation	1. Mockup of GLM is undamaged after demonstration of installation of system mock-up and cargo delivery/return	Demonstration	Demonstrating the safety of the GLM and the system during and after operation

R8.1.1	3	Undamaged Actuator	The actuator shall leave the Gateway Logistics Module undamaged from installation or operation	1. Operation of system mock-up and actuators does not cause damage to mock-up of GLM 2. No damages seen on mock-up GLM after installation of actuators	Inspection	Inspection of the system mounting surfaces after testing for damage to either the system or the mounting surface
R8.1.2	3	Undamaged Cargo Interface	The cargo interface shall leave the Gateway Logistics Module undamaged from installation or operation	1. Operation of system mock-up and cargo interface does not cause damage to mock-up of GLM 2. No damages seen on mock-up GLM after installation of interface	Inspection	Inspection of the cargo interface after testing for damage to either the GLM or the cargo
R8.2	2	System Use Of Gateway Power	The system shall operate with power provided by Gateway Logistics Module	1. Verified upon verification of R.8.2.1-3 2. System operates when interfaced with GLM in space	Test Demonstration	Testing the system using a regulated power source to demonstrate the system operates as designed
R8.2.1	3	Actuator Power	The actuator shall operate on a power of no more than 230 W	1. Unit test of actuator results in required torque and rpm under required power	Test	Testing the actuator on a regulated power source limited to 230 w to ensure proper functionality
R8.2.2	3	Cargo Linkage Power	The cargo linkage shall operate on a power of no more than 10 W	1. Unit test of cargo linkage results in required torque and rpm under required power	Test	Testing the cargo linkage on a regulated power source limited to 10 w to ensure proper functionality

R8.2.3	3	Microcontroller Power	The microcontroller shall operate on a power of no more than 20W	1. Unit test of microcontroller results in nominal and maximum operation under specified power	Test	Testing the microcontroller on a regulated power source limited to 20 w to ensure proper functionality
R9	1	Structural Launch Conditions	The system shall withstand launch conditions	1. System remains undamaged after launch 2. System operates on station	Demonstration	The demonstration will show that the system will have a successful launch meaning it will remain undamaged after launch and be fully operation once on station
R9.1	2	Structural Axial Forces	The system shall withstand axial forces of 6.9g during launch	1. Ansys simulation shows that the system remains intact subject to 6.9g of axial force	Analysis - Ansys Static Structural	The simulation will show that the system can withstand 6.9g of axial force and remains operational as planned
R9.2	2	Structural Lateral Forces	The system shall withstand lateral forces of 2.6g during launch	1. Ansys simulation shows that the system remains intact subject to 2.6g of lateral force	Analysis - Ansys Static Structural	The simulation will show that the system is structurally sound and can withstand 2.6g of lateral force and remains operational as planned
R9.3	2	Structure Yield Strength	Structural materials shall have a yield strength of at least 1.4 times that of maximum Von Mises Stress	1. Ansys simulation shows that the cargo packing device, capsule interface, and mounts withstand 1.4 time Von Mises Stress 2. System in launch configuration remains intact subject to vibration test 3. System delivers/returns cargo upon user command after vibration test	Analysis - Ansys Static Structural Vibration Test	The simulation will show that the system will remain intact subject to 1.4x of the maximum stress

R9.4	2	Structural Vibrational Loads	Structural assemblies shall withstand vibrational loads during launch	1. Ansys simulation shows that the structural assemblies can withstand vibrational loads during launch 2. System in launch configuration remains intact subject to vibration test 3. System delivers/returns cargo upon user command after vibration test	Analysis - Ansys Static Structural Vibration Test	The simulation will show that the structural assemblies can withstand vibrational loads during launch and remain fully operational
R10	1	System Fault Tolerance	The system shall have a one fault tolerance with regard to crew safety	1. No crew is harmed during operation of system for entire lifetime of mission	Demonstration	Demonstrations will show the system is safe for crew and is able to adapt to contingencies with crew safety as priority
R10.1	2	System Stoppage Time	The system shall cease motion within 1 seconds [TBR] of detection of an unintended object in its domain of motion	1. Mock-up system ceased cargo delivery upon test subject or foreign object entering its domain of motion within 1 second 2. Mock-up system ceased cargo return upon test subject or foreign object entering its domain of motion within 1 second	Inspection Test	Placing a foreign object within domain of motion and observing stoppage of system within 1 second of placement

R10.1.1	3	System Stoppage -- Light Curtain	The system shall cease motion when object crosses light curtain installed over the hatch	1. Mock-up system ceased cargo delivery upon test subject or foreign object crossing light curtain 2. Mock-up system ceased cargo return upon test subject or foreign object crossing light curtain	Test	Placing a foreign object along the light curtain and observing stoppage of system at time of placement
R10.1.2	3	Safety Sensor Relay Time	The safety sensor shall upload data to the microcontroller with a speed that enables a total latency of less than 1 second	1. Data from safety sensor is found on microcontroller within 1 second after breach of safety event on Mock-up	Inspection Test	Checking the microcontroller data and the time it took to retrieve data directly after a mock contingency
R10.1.3	3	Microcontroller Stoppage Time	The microcontroller shall, with the correct stimuli from the safety sensor, cease all motion within 1 second of detection	1. Microcontroller transmits data to rotary encoder upon retrieval of data from safety sensor 2. Mock-up system motion cease within 1 second of microcontroller transmitting data	Inspection Test	Creating a mock contingency and checking to see if the microcontroller transmits the correct data after retrieval from the safety sensor and stops the system within 1 second
R10.2	2	Mono-Input Safe State	The system shall have a safe state during which no inputs other than exiting the safe state are registered	1. Mock-up system is placed into safe state and does not register delivery/return requests	Test	Placing the system into safe state and attempting different inputs until incorrect input rejection is ensured

R10.2.1	3	System Stoppage -- Bug	The system shall cease motion and assume a safe state within 1 seconds [TBR] of detection of software error	1. Ansys simulation shows that the cargo packing device, capsule interface, and mounts have a safety factor of at least 1.1 2. System in launch configuration remains intact subject to vibration test 3. System delivers/returns cargo upon user command after vibration test	Inspection Test	Creating a mock contingency after structural tests and ensuring the system goes into a safe state 1 second after an error
R10.2.1.1	4	Microcontroller Stoppage -- Bug	The microcontroller shall stop system motion if a software bug is detected	1. Intentional bugs will be fed into system (software errors not in safety code, invalid data, etc.) and system will be tested to ensure a safe state is reached before program end	Test	Bugs will be entered into the software and system will be observed to ensure it has stopped motion
R10.2.1.2	4	App Error Communication	The app shall communicate any crashes/bugs to the microcontroller	1. Output of black box test is report of crash/bug	Black Box Test	Bugs will be entered into the software and a check will be done for an output of a black box test

R10.2.2	3	System Stoppage -- Sensor Error	The system shall cease motion and assume a safe state within 1 seconds [TBR] of detection of any sensor error	1. Mock-up system ceases operation of cargo delivery and assumes safe state within 1 second upon sensor damage/manually caused error or transmission of data that indicates sensor error 2. Mock-up system ceases operation of cargo return and assumes safe state within 1 second upon sensor damage/manually caused error or transmission of data that indicates sensor error	Inspection Test	A manual input of sensor error will be done, and the system will be observed to ensure motion has stopped after 1 second of input error
R10.2.2.1	4	Microcontrol ler Stoppage -- Sensor Error	The microcontroller shall stop system motion if any sensor's telemetry is 5% off of nominal range.	1. Microcontroller transmits data to rotary encoder upon retrieval of data from sensor that is out of nominal range 2. Mock-up system motion ceases	Demonstration Test	Off-nominal sensor data will be sent to microcontroller to ensure the microcontroller is sending this data to rotary encoder to cease all motion of system

R10.2.3	3	System Entering Safe State	The system shall cease motion and assume a safe state within 1 seconds [TBR] of request of local or remote user	1. Mock-up system ceases operation of cargo delivery and assumes safe state within 1 seconds of local test subject request 2. Mock-up system ceases operation of cargo return and assumes safe state within 1 seconds of local test subject request 3. Mock-up system ceases operation of cargo delivery and assumes safe state within 1 seconds of remote test subject request 4. Mock-up system ceases operation of cargo return and assumes safe state within 1 seconds of remote test subject request	Inspection Test	Both a local and remote user will send a safe state request to system and the system will be observed to ensure cease of motion within 1 second [TBR]
R10.2.3.1	4	Microcontroller Entering Safe State	The microcontroller shall stop system motion if an operator requests a safe state	1. Microcontroller transmits data to rotary encoder upon user input of request for safe state 2. Mock-up system motion ceases	Demonstration Test	An operator will send a safe state request to system and the system will be observed to ensure cease of motion

R10.2.4	3	System Resumption -- Local	The system shall resume operation within 5 seconds of request of local user after exiting the safe state	1. Mock-up system starts operation of test user input (delivery/return) within 5 seconds after safe state mode has ended	Inspection Test	An operator will end a safe state request to system and the system will be observed to ensure resume of motion after 5 seconds
R10.2.4.1	4	Microcontroller Safe State Exit	The microcontroller shall exit the safe state within 5 seconds of a request from the app	1. Microcontroller transmits data to rotary encoder upon retrieval of data from UI 2. Mock-up system resumes motion within 5 seconds of microcontroller transmitting data	Inspection Test	An operator will end a safe state request to the system and the microcontroller will be observed to ensure resume of motion after 5 seconds
R10.2.4.2	4	User Nominal Return To Microcontroller	The user shall be able to use the user device to communicate a request to return to nominal state to the microcontroller	1. A series of tests where the microcontroller is manually put into a safe state will be ran, and verification will be successful if a user can always reinitiate nominal operation from the user device	Demonstration/test	The system will be manually put into safe state, and the microcontroller will be observed to ensure the system can always recover from safe state and resume nominal operation after user can initiated exit
R10.3	2	Braking Deceleration	The braking system shall generate a deceleration torque of 50 N-m	1. Ansys simulation shows that the brakes do generate a deceleration torque of 50 N-m	Analysis - Ansys	Simulations will be ran to ensure brakes are operating and correct deceleration torques in which no harm is done to crew or system

R10.3.1	3	Brake Vs. Actuator Functionality	The brakes and actuators shall only operate at different times	1. Mock-up system does not have any interference from the brakes when the actuators are operating 2. Mock-up system does not have any interference from the actuators when the brakes are operating	Demonstration Test	A series of tests will be conducted where the actuators and brakes are repeatedly altered and observations will be made to ensure no crossover of operation
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Appendix F: Validation Plans

Note: Due to an unforeseen incident with the cleaning staff, the fully filled-in copies of the plans are unavailable.



Engineering Test Report

Bioastronautics and Life Support Systems

Test Name: <i>Operational Validation Testing Procedure</i>		
Test Number: V-O	Prepared by: Owen Faulkner Adam Jones	Date Created: 2/16/23 Date Last Edited: 5/1/23

Purpose:

This test serves to validate various objectives laid out in V-001, V-002, V-003, V-004, V-005, V-006, V-007, V-008, V-009 through the use of the partial-scale, representative mock-up. Within these objectives, the underlying minimum viable product (MVP) goal of “novel operation demonstration” stated by the stakeholders is prioritized. The actions of these validation tests serve to satisfy the MVP, as well as attempt to validate details of the full system design through a mock-up.

V-001: System Conformance to Operating Conditions
V-002: Stakeholder Expectations for Autonomous Use
V-003: Adequate Fulfillment of System Operation
V-004: Stakeholder Requirements on Cargo Specification
V-005: Stakeholder Expectations of User Interaction

Formal Objectives:** Minimal Viable Product*

Validation Objective	Requirement	Method	Validation ID
Clarify a control system for the user to initiate the autonomous operations of the system and observe the cargo manifest	R1.1.2	Inspection	V-002*
Show cargo in the domain of the system can be accessible without removing other cargo in nominal conditions	R2	Demonstration	V-003*
Clarify that complexity of the system motion is low	R2.1	Inspection	V-007
Show the system has enough torque to transport cargo within its domain to a reception point within the 10 minute constraint	R2.3.1	Demonstration	V-003*
Show the system has reliability in cargo retrieval and drop-off with repeated nominal operation	R2.4.1	Demonstration	V-003
Show that the user interface alerts the user that cargo is in motion to the reception location and has arrived at the reception location; user is made aware of system operation	R2.5.1	Demonstration	V-005
Search for high reliability of continuous cargo linkage during and not during operation	R2.5.2	Demonstration	V-003
Show that cargo requests will not be overwritten by new requests	R2.6	Demonstration	V-003

Show that cargo locations/presence is updated as cargo is removed and replaced during nominal operation	R2.7	Demonstration	V-002
Show that users can return cargo containers without having to search for their original location	R3	Demonstration	V-003
Show that the user interface alerts the user that cargo is in motion to a storage configuration and has arrived at the storage location; user is made aware of system operation	R3.2	Demonstration	V-005
Show the system has enough torque to transport cargo within its domain from a reception point to storage configuration within the 10 minute constraint	R3.4.1	Demonstration	V-003*
Show novel operation that strays from the current method of cargo retrieval in the ISS	R4	Demonstration	V-002*
Show that cargo requested by the user and known to be in a specific container is presented to the user for retrieval autonomously	R4.1	Demonstration	V-002*
Clarify that all cargo containers have means of identification and verification within the system server	R4.1.1	Inspection	V-002
Show that verification of any cargo container or item of cargo elicits a unique listing of the cargo item(s) bearing the identification	R4.1.2	Demonstration	V-002
Clarify that the user interface displays where	R4.1.3	Inspection	V-002

cargo items are stored in what containers at what times (providing a history log)			
Show that the user interfaces' cargo manifest information corresponds to how the system reacts to cargo requests; in order to transport the correct cargo container to the user, the layout must be stored in the controller	R4.1.3.1. R4.1.5	Demonstration	V-002
Clarify that the user interface displays what cargo has been checked in or out and in what orders, as well as what the identification labels for cargo/containers are	R4.1.4	Inspection	V-002
Show that the correct cargo to be retrieved or returned is done so and is verified by the system	R4.1.5.1, R4.1.5.2, R4.1.6, R4.2.3	Demonstration	V-002
Show novel cargo retrieval operation that strays from the current method of cargo retrieval in the ISS	R4.2, R4.4, R4.4.1	Demonstration	V-002*
Clarify that the system does not require a higher voltage than the Gateway Logistics Module can provide	R4.2.1, R4.2.2	Inspection	V-001
Show that the cargo item selected by the user to be returned or retrieved by the system is done so as expected	R4.2.4	Demonstration	V-002*
Show that the system works to mitigate human error in cargo retrieval and return	R4.3.1	Demonstration	V-002

Show that multiple cargo requests can be handled with a consistent protocol that does not ruin other requests to the system	R4.5	Demonstration	V-002*
Clarify that the request queue works as first in first out	R4.5.1	Inspection	V-002
Clarify that all users can be made aware of the current requests of the system	R4.5.2, R5.3.1, R5.3.2, R5.3.3, R5.3.4, R5.3.5, R5.3.6,	Inspection	V-005
Show that state-of-the-system telemetry is available to the user during operation	R4.6, R4.6.4, R5.3	Demonstration	V-002
Show that sensor data is handled internally in the system and does not require user interaction for operation	R4.6.2	Demonstration	V-002
Show that errors in sensor data are kept to a minimum	R4.7, R4.7.1, R4.7.2	Demonstration	V-007
Show that sensors do not hinder the execution of requests to the system	R4.7.3	Demonstration	V-007
Show that the system allows for reorganization of cargo and still operates nominally	R4.8.1	Demonstration	V-007
Show the system utilizes autonomous operation to retrieve/return cargo while the	R5	Demonstration	V-002

user is anyway within the Lunar Gateway			
Detail the reliability of cargo retrieval/return throughout the system's mission lifetime	R7.3	Analysis	V-009
Detail the reliability of system server commands throughout the system's mission lifetime	R7.4	Analysis	V-009
Detail the reliability of the primary cargo locator throughout the system's mission lifetime	R7.4.1	Analysis	V-009
Show that cargo is still accessible to crew in the event of a system failure	R7.8, R7.8.1, R7.8.2	Demonstration	V-006*
Show that the system operates on available power outputs	R8.2, R8.2.1, R8.2.2, R8.2.3	Demonstration	V-004*
Show that the safety critical system eliminates risks of harm to the users	R10, R10.1, R10.2, R10.2.1, R10.2.3, R10.2.3.1, R10.2.4	Demonstration	V-008
Show the system can detect and react to errors	R10.2.1.1, R10.2.1.2, R10.2.2, R10.2.2.1, R10.2.4.1,	Demonstration	V-008

	R10.2.4.2		
Show that the system eliminates risk of harm to itself	R10.3.1	Demonstration	V-008

Procedure

Demonstration set-up: This test requires that the representative mock-up is fully constructed, and that the control interface is functional.

UI, Controls, and Set-up

1. Select a system user and introduce them to the User Interface (UI) of the system using the UI Intuitiveness Test (see ____). Ensure to record the time it takes the user to complete the UI Intuitiveness Test. Additionally, brief the user with the User Manual.
2. Clarify to the user all of the system controls of the mock-up that correspond to those taught on the UI Intuitiveness Test.
3. Using a handheld multimeter, measure each node to adjacent node for voltage and current. This first time will be for idle draw. Repeat this process while the system is operating nominally. Additionally, repeat this process while measuring error detection modes (braking). See Table 1 for each node to test.

Node	Voltage (V)			Current (I)			Power (P)		
State	Idle	Nom.	Error	Idle	Nom.	Error	Idle	Nom.	Error
	12	12	12	10	10	10	120	120	120

Table 1: Node potentials, current, and power draw used to determine if power consumption exceeds what is allowable for the Gateway Logistics Module

Retrieval and Return Requests

1. Prepare the system user on the procedure before beginning. The system user shall use the mock-up control interface to find a randomly selected cargo item in the manifest and select that item to request retrieval. Begin recording time from the moment the system user opens the control system (time will stop being recorded once the user has scanned the cargo box QR code and confirmed the correct box after removing the cargo box).
 - a. Observe whether or not the control interface has a notification of the system in progress of a request
2. After the user requests a cargo item, they shall attempt to request another randomly chosen cargo item and observe whether or not the request is put in a queue.
 - a. Observe that the first request ONLY is being executed at this time. Record observations of the retrieval process.
 - b. Document any sensor, braking, or other failures to transport the cargo to the retrieval location
3. Once the cargo reaches the retrieval location, observe for a notification of the cargo's arrival. Also, observe whether or not the system has stopped motion (and in a position to physically retrieve the cargo from the chain).
4. To retrieve the cargo, the user shall place hands on the container handles, twist the container to the right 90 degrees, and remove from the chain. The user shall then scan the QR code on the container using a mobile device and observe the verification status. Stop recording time once the cargo has been verified.
 - a. Observe whether or not the correct cargo container bearing the selected cargo was retrieved from the system
 - b. Observe whether or not the retrieved cargo is removed from the virtual manifest
 - c. Document any failures or difficulties encountered by the user in removing the cargo from the chain
5. Once the cargo is verified, the system shall begin the next request in the queue. This will repeat steps 1-3 again. After repeating these steps, the user will now have two cargo containers in possession, and so it is time to request cargo returns.
6. The user shall use the mock-up control interface to rearrange individual cargo items within containers in the virtual manifest. The user shall rewrite the cargo item in the first box they retrieved into the manifest of the second container they retrieved. If this were to be done physically as well, the cargo item would have a QR code on it that would have to be scanned to verify the item and allow the virtual rewrite. However for this mock-up, simply observe that the reorganization was changed in the virtual manifest.

7. The user shall use the mock-up control interface to search through the manifest, select a removed cargo, and request a return for that cargo item. The system shall then begin to move the empty location on the chain that once held that cargo container to the previous retrieval location. While this is occurring, the user shall queue another return request for the remaining cargo container in possession.
 - a. Begin recording time from start of user entering the control interface
 - b. Observe whether or not the control interface has a notification of the system in progress of a request
 - c. Observe that the first request ONLY is being executed at this time. Record observations of the return process
 - d. Document any sensor, braking, or other failures to transport the cargo to the retrieval location
8. Once the empty attachment point reaches the previous retrieval location, observe for a notification of its arrival. Also, observe whether or not the system has stopped motion (and in a position to physically retrieve the cargo from the chain).
9. The user shall then scan the QR code on the container using a mobile device and observe the verification status that they are returning the correct box.
 - a. Observe whether or not the correct cargo container's location on the chain was presented by the system
10. To return the cargo, the user shall place hands on the container handles, guide the female cam to the male cam on the chain, and twist the container to the left 90 degrees once the male cam is inserted. Once attached, the user shall interface with the controls to verify successful return of the cargo container. Stop recording time at this point.
 - a. Observe whether or not the returned cargo is added back to the virtual manifest
 - b. Document any failures or difficulties encountered by the user in reattaching the cargo to the chain
11. Once the cargo return is verified, the system shall begin the next request in the queue. This will repeat steps 6-9 again. After repeating these steps, the user will now have zero cargo containers in possession.
12. Steps 10-11 can be repeated a larger number of times to better assess reliability of the system operation of time. Clear documentation of failures and difficulties will determine issues rooted in the mock-up's representative design versus the full system design.

Failure Mode Operation

1. Turn off all power to the mock-up. This will be treated as a failure mode where a critical component is offline and the nominal system controls are no longer available.

2. Brief a system user on the representative situation and command them to attempt a cargo retrieval on the failed system. The user shall attempt to use their hands (or whatever tool available) to induce motion in the unpowered chain in order to bring cargo containers to a removable position.
 - a. Document any failures or difficulties encountered by the user to manually move the cargo chain, as well as the method of motion used
 - b. Begin recording time once the use begins manual motion of the chain
3. The system user shall be able to use identification on the cargo containers (either QR code or sticky labels) to determine which cargo container they wish to retrieve. Once the desired cargo container is brought to a retrievable position, the user shall remove the container and verify the cargo. Stop recording time at this point.
 - a. Observe whether or not the cargo was removed from the virtual manifest
4. The user shall then reenter the cargo into the manifest and attempt a manual cargo return by fitting the container back onto its location on the chain.
 - a. Document any failures or difficulties encountered in this process
5. Steps 1-4 can be repeated a larger number of times to better assess reliability of the system's failure mode operation. Clear documentation of failures and difficulties will determine issues rooted in the mock-up's representative design versus the full system design.

Error Detection

1. Detection of errors can occur in a multitude of avenues on the full system, however all result in the same response of halting system motion swiftly and locking out operation until a user's override. For the operational mock-up, not all sensors and detection processes are present together, therefore only the system response will be tested.
2. Set up a camera facing the mock-up whereas the entire mock-up and control interface is in view. Begin recording video before any interaction with the system.
3. A system user shall use the control interface to request a random cargo item to begin system motion. While the system is in motion, the user shall interface the controls to incite a general error.
4. After the general error has been incited, observe for a notification of the error detection and a notification of the system entering a safe state. Also, observe if the system stops motion and document any difficulties or failures in this process.
5. Stop filming only after the system ceases motion, or if there is a failure that must be addressed. Assuming the system ceases motion, use the video recording to determine the time at which the general error is incited and the time at which the system ceases motion. Record the difference between these two timestamps.
6. After the system has ceased motion, observe that it has entered a safe state, whereas no cargo requests can be made without an override password to be entered into the control interface.
7. The system user shall enter the safe state override password into the control interface and observe that the safe state condition has been alleviated. The user shall now be able to make requests for cargo. A request can be made by the user if desired.
8. Steps 1-7 can be repeated a larger number of times to better assess reliability of the system's error protocol. Clear documentation of failures and difficulties will determine issues rooted in the mock-up's representative design versus the full system design.



Pre-Test Approval



Post-Test Approval

Deviations from Planned Procedure

Results

UI, Controls, and Set-up

UI Intuitiveness Test Time (min:sec)	
Notes:	

See Table 1 for results entry on power, voltage, and current

Retrieval and Return Requests

Cargo Retrieval Time 1	(min:sec)	00:28
Cargo Retrieval Time 2	(min:sec)	00:30
Cargo Return Time 1	(min:sec)	00:30
Cargo Return Time 2	(min:sec)	00:18

Table 2: Nominal operation times

Observation Objective	Satisfied	Observation Notes
Notification of first retrieval request in progress	Yes No	
Second cargo retrieval request is in queue	Yes No	
Only one retrieval request is being executed at a time	Yes No	
Notification of first cargo's arrival at retrieval point	Yes No	
System stopped motion with first desired cargo container in retrievable position	Yes No	
Positive verification of first cargo's retrieval	Yes No	
First cargo is removed from virtual manifest	Yes No	
Notification of second retrieval request in progress	Yes No	
Notification of second cargo's arrival at retrieval point	Yes No	
System stopped motion with second desired cargo container in	Yes No	

retrievable position		
Positive verification of second cargo's retrieval	Yes No	
Second cargo is removed from virtual manifest	Yes No	
Cargo item is shown to be rearranged in the virtual manifest	Yes No	
Notification of first return request in progress	Yes No	
Second cargo return request is in queue	Yes No	
Only one return request is being executed at a time	Yes No	
Notification of first cargo's empty attachment point at retrieval point	Yes No	
System stopped motion with first desired cargo container's empty attachment point in retrievable position	Yes No	
System present correct empty attachment point for first cargo	Yes No	
Positive verification of first cargo's return	Yes No	
First cargo is returned to the	Yes No	

virtual manifest		
Notification of second return request in progress	Yes No	
Notification of second cargo's empty attachment point at retrieval point	Yes No	
System stopped motion with second desired cargo container's empty attachment point in retrievable position	Yes No	
System present correct empty attachment point for first cargo	Yes No	
Positive verification of second cargo's return	Yes No	
Second cargo is returned to the virtual manifest	Yes No	

Table 3: Nominal mode observation confirmations

Documentation Objective	Documentation Notes
Sensor, braking, or other failures to transport cargo to retrieval location	
Difficulties or failures encountered by the	

user in removing the cargo from the chain	
Sensor, braking, or other failures to transport empty attachment locations to retrieval location	
Difficulties or failures encountered by the user in returning the cargo to the chain	
Unlisted abnormalities	

Table 4: Documentations of nominal operations

Failure Mode Operation

Manual Cargo Retrieval Time (min:sec)	
Manual Cargo Return Time (min:sec)	

Table 5: Failure mode operation times

Observation Objective	Satisfied	Observation Notes
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User was able to manually move the chain	Yes No	
Cargo was removed from virtual manifest	Yes No	
Cargo was re entered into the virtual manifest	Yes No	

Table 6: Failure mode observation confirmations

Documentation Objective	Documentation Notes
Failures or difficulties to manually move the chain	
Method of manual chain movement	
Difficulties or failures encountered by the user in retrieving the cargo from the chain	
Difficulties or failures encountered by the user in returning the cargo to the chain	
Unlisted abnormalities	

Table 7: Documentations of failure mode operations

Error Detection

Error 1 Stop Time (sec)	
Error 2 Stop Time (sec)	
Error 3 Stop Time (sec)	
Error 4 Stop Time (sec)	

Table 8: Error detection stopping times

Observation Objective	Satisfied	Observation Notes
Notification of error detection	Yes No	
Notification of safe state	Yes No	
System stops motion	Yes No	
System is in safe state: no requests can be made without an override password	Yes No	
Override password alleviates safe state of the system	Yes No	

Table 9: Error detection observation confirmations

Satisfaction of Validation Objectives

Validation Objective	Requirement	Satisfied	Valid. ID
Clarify a control system for the user to initiate the autonomous operations of the system and observe the cargo manifest	R1.1.2	Yes No	V-002*
Show cargo in the domain of the system can be accessible without removing other cargo in nominal conditions	R2	Yes No	V-003*
Clarify that complexity of the system motion is low	R2.1	Yes No	V-007
Show the system has enough torque to transport cargo within its domain to a reception point within the 10 minute constraint	R2.3.1	Yes No	V-003*
Show the system has reliability in cargo retrieval and drop-off with repeated nominal operation	R2.4.1	Yes No	V-003
Show that the user interface alerts the user that cargo is in motion to the reception location and has arrived at the reception location; user is made aware of system operation	R2.5.1	Yes No	V-005
Search for high reliability of continuous cargo linkage during and not during operation	R2.5.2	Yes No	V-003
Show that cargo requests will not be overwritten by new requests	R2.6	Yes No	V-003

Show that cargo locations/presence is updated as cargo is removed and replaced during nominal operation	R2.7	Yes No	V-002
Show that users can return cargo containers without having to search for their original location	R3	Yes No	V-003
Show that the user interface alerts the user that cargo is in motion to a storage configuration and has arrived at the storage location; user is made aware of system operation	R3.2	Yes No	V-005
Show the system has enough torque to transport cargo within its domain from a reception point to storage configuration within the 10 minute constraint	R3.4.1	Yes No	V-003*
Show novel operation that strays from the current method of cargo retrieval in the ISS	R4	Yes No	V-002*
Show that cargo requested by the user and known to be in a specific container is presented to the user for retrieval autonomously	R4.1	Yes No	V-002*
Clarify that all cargo containers have means of identification and verification within the system server	R4.1.1	Yes No	V-002
Show that verification of any cargo container or item of cargo elicits a unique listing of the cargo item(s) bearing the identification	R4.1.2	Yes No	V-002
Clarify that the user interface displays where cargo items are stored in what containers at what	R4.1.3	Yes No	V-002

times (providing a history log)			
Show that the user interfaces' cargo manifest information corresponds to how the system reacts to cargo requests; in order to transport the correct cargo container to the user, the layout must be stored in the controller	R4.1.3.1. R4.1.5	Yes No	V-002
Clarify that the user interface displays what cargo has been checked in or out and in what orders, as well as what the identification labels for cargo/containers are	R4.1.4	Yes No	V-002
Show that the correct cargo to be retrieved or returned is done so and is verified by the system	R4.1.5.1, R4.1.5.2, R4.1.6, R4.2.3	Yes No	V-002
Show novel cargo retrieval operation that strays from the current method of cargo retrieval in the ISS	R4.2, R4.4, R4.4.1	Yes No	V-002*
Clarify that the system does not require a higher voltage than the Gateway Logistics Module can provide	R4.2.1, R4.2.2	Yes No	V-001
Show that the cargo item selected by the user to be returned or retrieved by the system is done so as expected	R4.2.4	Yes No	V-002*
Show that the system works to mitigate human error in cargo retrieval and return	R4.3.1	Yes No	V-002
Show that multiple cargo requests can be handled	R4.5	Yes No	V-002*

with a consistent protocol that does not ruin other requests to the system			
Clarify that the request queue works as first in first out	R4.5.1	Yes No	V-002
Clarify that all users can be made aware of the current requests of the system	R4.5.2, R5.3.1, R5.3.2, R5.3.3, R5.3.4, R5.3.5, R5.3.6,	Yes No	V-005
Show that state-of-the-system telemetry is available to the user during operation	R4.6, R4.6.4, R5.3	Yes No	V-002
Show that sensor data is handled internally in the system and does not require user interaction for operation	R4.6.2	Yes No	V-002
Show that errors in sensor data are kept to a minimum	R4.7, R4.7.1, R4.7.2	Yes No	V-007
Show that sensors do not hinder the execution of requests to the system	R4.7.3	Yes No	V-007
Show that the system allows for reorganization of cargo and still operates nominally	R4.8.1	Yes No	V-007
Show the system utilizes autonomous operation to retrieve/return cargo while the user is anyway within the Lunar Gateway	R5	Yes No	V-002

Detail the reliability of cargo retrieval/return throughout the system's mission lifetime	R7.3	Yes No	V-009
Detail the reliability of system server commands throughout the system's mission lifetime	R7.4	Yes No	V-009
Detail the reliability of the primary cargo locator throughout the system's mission lifetime	R7.4.1	Yes No	V-009
Show that cargo is still accessible to crew in the event of a system failure	R7.8, R7.8.1, R7.8.2	Yes No	V-006*
Show that the system operates on available power outputs	R8.2, R8.2.1, R8.2.2, R8.2.3	Yes No	V-004*
Show that the safety critical system eliminates risks of harm to the users	R10, R10.1, R10.2, R10.2.1, R10.2.3, R10.2.3.1, R10.2.4	Yes No	V-008
Show the system can detect and react to errors	R10.2.1.1, R10.2.1.2, R10.2.2, R10.2.2.1, R10.2.4.1, R10.2.4.2	Yes No	V-008
Show that the system eliminates risk of harm to itself	R10.3.1	Yes No	V-008

Conclusions

Evaluation	Criteria
Pass	All objectives are satisfied
Pass w/ plan to reduce error	All MVP objectives are satisfied, but not all listed objectives, or the objective has been refined/clarified and now is satisfied by the requirement
Do not pass	One or more MVP objectives are not satisfied

Evaluation Score:

Reference Risk Matrix

Likelihood	Safety Estimated likelihood of safety event occurrence	Technical Estimated likelihood of not meeting performance requirements	Cost Estimated likelihood of not meeting cost commitment	Schedule Estimated likelihood of not meeting schedule commitment
5 - Very High	P>10e-1	P>50%	P>75%	P>75%
4 - High	(10e-2, 10e-1]	(25%, 50%]	(50%, 75%]	(50%, 75%]
3 - Moderate	(10e-3, 10e-2]	(15%, 25%]	(25%, 50%]	(25%, 50%]
2 - Low	(10e-5, 10e-3]	(2%, 15%]	(10%, 25%]	(10%, 25%]
1 - Very Low	(10e-6, 10e-5]	(0.1%, 2%]	(2%, 10%]	(2%, 10%]

Severity Categories					
Risk	1 - Very Low	2 - Low	3 - Moderate	4 - High	5 - Very High
Safety	Negligible or no impact	Could cause the need for only minor first aid treatment	May cause minor injury or occupational illness or minor property damage	May cause severe injury or occupational illness or major property damage	May cause death or permanently disabling injury or destruction of property
Technical	No impact to full mission success criteria	Minor impact to full mission success criteria	Moderate impact to full mission success criteria. Minimum mission success criteria are achievable with margin	Major impact to full mission success criteria. Minimum mission success criteria is achievable	Minimum mission success criteria are not achievable

Schedule	Negligible or no schedule impact	Minor impact to schedule milestones; accommodates within reserves; no impact on critical path	Impact to schedule milestones; accommodated within reserves; moderate impact to critical path	Major impact to schedule milestones; major impact to critical path	Cannot meet schedule and program milestones
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Detectability Categories					
Risk	1 - Very Low	2 - Low	3 - Moderate	4 - High	5 - Very High
Qualification	Highly likely to be detectable and addressable before production	Likely to be detected and addressed during any point in production	Can be detected and addressed only after significant production yet before operation	Unlikely to be detected before operation but near impossible to detect before production	Detectable only during or after onset of consequence

Risk Changes

Associated Risks	Previous RPN Score	New RPN Score	Justification for Change

Compliance Plan

Only necessary if the evaluation score is Yellow or Red.

IF YELLOW:

Plan to reduce error:

IF RED:

Plan to pass:



Engineering Test Report

Bioastronautics and Life Support Systems

Test Name: <i>Ergonomic Validation Testing Procedure</i>		
Test Number: V-E	Prepared by: Owen Faulkner Adam Jones	Date: 2/16/23 Date Last Edited: 5/1/23

Purpose:

This test serves to validate various objectives laid out in V-001, V-002, V-003, V-004, V-005, V-006, V-007, V-008, V-009 through the use of the full scale, ergonomic mock-up. Within these objectives, the underlying minimum viable product (MVP) goal of “novel operation demonstration” stated by the stakeholders is prioritized. The actions of these validation tests serve to satisfy the MVP, as well as attempt to validate details of the full system design through a mock-up.

V-001: System Conformance to Operating Conditions

V-002: Stakeholder Expectations for Autonomous Use

V-003: Adequate Fulfillment of System Operation
V-004: Stakeholder Requirements on Cargo Specification
V-005: Stakeholder Expectations of User Interaction

Formal Objectives:** Minimal Viable Product*

Validation Objective	Requirement	Method	Validation ID
Show the system allows for users to access cargo linkages and repair locations, unhindered by specific access points; cater to various user orientations due to microgravity environment	R1.1	Demonstration	V-001*
Show that cargo container attachment to internal surfaces aids user interaction with the system under microgravity	R1.1.1	Inspection	V-001
Show that no significant force is required to remove cargo containers from cargo linkage	R2.5.3	Demonstration	V-003 *
Show that all requested cargo containers are within reach to users from both inside and outside the Gateway Logistics Module	R3.1	Demonstration	V-003
Show that sensor data is handled internally in the system and does not require user interaction for operation	R4.6.3	Demonstration	V-002 *
Show that user interaction is kept to a minimum with the system to prevent error and encourage usage	R4.8	Demonstration	V-002 *
Show that the system follows flight and environment constraints	R8	Demonstration	V-004 *
Show that the safety critical system eliminates risks of harm to the users	R10.1.1, R10.1.2, R10.1.3	Demonstration	V-008

Procedure

Demonstration set-up: This test requires that the ergonomic mock-up is fully constructed. It additionally requires a representation of the safety net, user net, and attachable cargo containers.

Cargo Container Attachment Demonstration

1. Select a number of participants, of varying heights, weights, and genders, who will serve as representative users of the cargo delivery system. Instruct them to follow the following procedure:
 - a. Refer to Table 1, where a series of orientations and cargo container IDs are listed. You will perform two mock retrieval/return sequences per orientation/container pair. On the first trial, you will not attach the containers to the user net. On the second, you will use the user net to aid in retrieval/return.
 - b. Select the first orientation/container pair.
 - c. Under the listed orientation, retrieve the container fully from the mock-up. Scan the container to confirm retrieval. Retrieve an item from the container, replace it in the container, and return the container to its starting position.
 - d. Record time elapsed.
 - e. Record whether cargo was retrievable and returnable without fully entering the capsule. Repeat b-e for the second trial
 - f. Repeat b-f for every orientation/container pair
2. Analyze the difference in ease of interaction and time elapsed between the two versions of the retrieval/return trial. Record any significant trends ($p\text{-value} < 0.05$)
3. If average ease of interaction is significantly greater, or average time elapsed is significantly lower, then record R1.1.1 as satisfied. Otherwise, record it as unsatisfied.
4. If all ease of interaction values are below 50% of maximal effort, record R1.1, R4.8, R2.5.3, and R4.8 as satisfied. Otherwise, record them as unsatisfied.
5. If all cargo was retrievable and returnable without full entrance into the capsule, record R3.1 as satisfied. Otherwise, record it as unsatisfied.

Module Containment

1. Measure the maximum radial dimension of the ergonomic mock-up and of the hatch diameter, to a precision of 5 cm.

2. If these dimensions are lower than, and within 1% of, the listed dimensions of the Dragon XL specifications, record R8 as satisfied. Otherwise, record them as unsatisfied.

Safety Critical System

1. Refer to Table 2, where a series of entrance locations and objects are listed.
2. For each location/object pair, move the given object three times across the hatch plane in the given location at a speed of 1m/s. Record the system response.
3. If the system triggers a safe state for every given pair, record R10.1.1, R10.1.2, and R10.1.3 as satisfied. Otherwise, record them as unsatisfied

Table 1. Orientations (minimum options)

Orientation Number	Description	Location
O-01	User is outside of hatch and reaching in from waist up (chest facing cargo)	At hatch (various angles of approach)
O-03	User is completely inside capsule (chest facing cargo)	Inside capsule
O-04	User is completely inside capsule (back facing cargo)	Inside capsule

Pre-Test Approval

Post-Test Approval

Deviations from Planned Procedure

Results

Cargo Container Attachment Demonstration

Orientation Number	Cargo Box Size	User Net?	Time Elapsed (s)	Interaction Ease (1-10)
O-01	Small	No	51.5	7
O-02	Small	No	48.0	8
O-03	Small	Yes	57.0	6
O-01	Medium	No	50.0	6
O-02	Medium	Yes	44.0	8
O-03	Medium	Yes	57.5	7
O-01	Large	No	N/A	Not Possible
O-02	Large	Yes	67.0	6
O-03	Large	Yes	64.0	7

Module Containment

<i>Measurement</i>	<i>Experimental (cm)</i>	<i>Actual (cm)</i>	<i>Difference (%)</i>
Hatch Diameter	80.4	80	0.499%

Capsule Radius	<i>160.6</i>	<i>160</i>	<i>0.374%</i>
Distance Between Cargo Attachment Points	<i>40.9, 50</i>	<i>41, 50</i>	<i>0.244%, 0%</i>
Depth to Cargo (from hatch)	<i>79.3</i>	<i>80</i>	<i>0.879%</i>

Safety Critical System

Location	Object and Characteristic Length	Detected?
Center of hatch plane	User appendage - User Head (20cm)	Yes
	Cargo container - Small Box (36.5cm)	Yes
	Cargo item -Cargo Item (25cm)	Yes
Edge of hatch, in front of transmitter	User appendage - User Hand (17cm)	Inconsistent
	Cargo container - Medium Box (37cm)	Yes
	Cargo item - Acrylic Pen (14.2cm)	Inconsistent
Edge of hatch, in front of	User appendage - User Foot (26.9cm)	Yes

receiver	Cargo container - Large Box (71.5cm)	Yes
	Cargo item - iPhone (15.2cm)	Yes
Edge of hatch, between sensors	User appendage - User Wrist (4cm)	No
	Cargo container - Small Box (36.5cm)	Yes
	Cargo item -Foam Block (7cm)	Yes

Analysis and Observations

Satisfaction of Validation Objectives

Objective	Requirement	Satisfied	Valid. ID
Show that a demonstration of crew ability to interact with the system under various spatial orientations sufficiently explores the range of interaction modes users will engage in under microgravity	R1.1	Yes No	V-001*
Show that cargo container attachment to internal surfaces aids user interaction with the system under microgravity	R1.1.1	Yes No	V-001
Show that no significant force is required to remove cargo containers from cargo linkage	R2.5.3	Yes No	V-003 *

Show that all requested cargo containers are within reach to users from both inside or outside the Gateway Logistics Module	R3.1	Yes No	V-003
Show that sensor data is handled internally in the system and does not require user interaction for operation	R4.6.3	Yes No	V-002 *
Show that user interaction is kept to a minimum with the system to prevent error and encourage usage	R4.8	Yes No	V-002 *
Show that the system follows flight and environment constraints	R8	Yes No	V-004 *
Show that the safety critical system eliminates risks of harm to the users	R10.1.1, R10.1.2, R10.1.3	Yes No	V-008

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Risk Changes

Associated Risks	Previous RPN Score	New RPN Score	Justification for Change

Compliance Plan

Only necessary if the evaluation score is Yellow or Red.

IF YELLOW:

Plan to reduce error:

IF RED:

Plan to pass:

Works Cited

1: R. L. Dillon, G. A. Klein, E. W. Rogers and C. J. Scolese, "Improving the use of risk matrices at NASA," 2018 IEEE Aerospace Conference, Big Sky, MT, USA, 2018, pp. 1-11, doi: 10.1109/AERO.2018.8396382.