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Model and Full-Scale Testing of Outfitting Approaches for Inflatable Habitats

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Inflatable habitats feature prominently in many future space program concepts, but generally there is little focus on how the system transitions from its newly inflated configuration to a fully operational system. The nearest flight analogue was the Skylab "wet workshop" concept in the early 1970's, which was rejected due to the length of time required to outfit an empty volume into a functional habitat. Under support from the NASA Moon to Mars Exploration Systems and Habitats program, the University of Maryland has initiated an experimental study of outfitting inflatable habitats to an operational configuration. To keep the study manageable, the team adopted the basic TransHab configuration developed at NASA Johnson Space Center. The pressure envelope would launch packaged around a central 3m diameter core, which takes all launch loads and contains all necessary systems and components. The envelope would inflate to an 8m diameter, and then be outfitted by moving selected components into the newly inflated volume. Potential agents include both human crew and robotic systems. While the systems were initially modeled in CAD, it was decided that the large number of potential operations and movement trajectories would be prohibitively difficult to evaluate using only computer graphics. For that reason, an approach was developed which used CAD, a 1/12 scale physical model, and full-scale segments of the habitat for evaluation purposes. The CAD model was used to derive the basic configuration of the central core, and to define major components such as crew compartments, movable and fixed equipment, and utilities including air handling, power, and data. Initial testing was done at 1/12 scale, including human and robotic figures, to consider strategies and test cases. Final testing was planned to incorporate both humans and robots in the laboratory, and underwater to provide both microgravity and lunar simulated environments. Results to date are presented, along with future plans.

Nomenclature

CAD	Computer-Aided Design
CTB	Cargo Transfer Bag
EVA	Extravehicular Activity
NBRF	Neutral Buoyancy Research Facility
SSL	Space Systems Laboratory
TLX	[NASA] Task Load Index
UMD	University of Maryland

I. Introduction

In the early stages of the Apollo Applications Project, there was a plan to launch a "wet workshop" space station: the third stage of the Saturn V would, after orbit insertion, be purged of residual propellants and the Apollo spacecraft would dock to the top of the S-IVB liquid hydrogen tank. The crew would ingress the tank and turn the large volume into a functioning space station. Realizing the magnitude of the task of creating a fully capable habitat on-orbit, the

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decision was made to go with a “dry workshop”, fitting out the S-IVB stage on the ground and launching it using the first two stages of the Saturn V to create the first U.S. space station, which came to be called Skylab.

Any random photograph of the interior of a space habitat, such as the view of International Space Station (ISS) shown in Figure 1, will show a bewildering assortment of installed and portable equipment, wires, logistics storage, exercise equipment, and myriad other items necessary for long-term habitation in space. One of the incentives for inflatable habitats is to increase the available habitable volume for larger crews and longer-duration missions, such as lunar bases or Mars transit habitats. However, the interior of an inflatable habitat, such as the Bigelow Expandable Activity Module (BEAM) on ISS shown in Figure 2, is by necessity initially empty, and will require extensive outfitting to be a functional habitat.

Figure 1. Interior of U.S. laboratory module on International Space Station

Figure 2. Interior of BEAM inflatable module on ISS

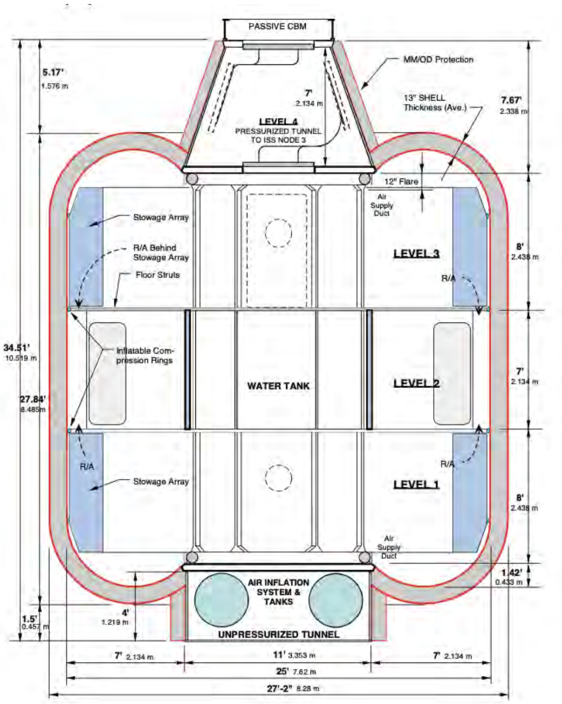

Figure 3. Section view of baseline TransHab interior layout [1]

As part of the 2022 Moon to Mars Exploration Systems and Habitats (M2M X-Hab) Academic Challenge program, NASA included a proposed theme to experimentally investigate the outfitting of orbital habitats in an academic environment. The University of Maryland (UMD) Department of Aerospace Engineering and Space Systems Laboratory (SSL) were selected for a supported research effort during the 2021-2022 academic year in that area. While the central focus of the M2M X-Hab program is to support capstone design activities, the University of Maryland has always strived to incorporate students at all levels in this type of student-focused research. To that end, the UMD approach to this project was to create two teams working in parallel. A team from the first-year ENAE 100 Introduction to Aerospace Engineering course that worked in the Fall 2021 term on a scale model to visualize the issues with inflatable habitat outfitting. A larger team from the ENAE 483/484 Space Systems Design sequence began design activities and test planning in the fall, but spent the Spring 2022 term on full-scale simulation and testing of approaches to inflatable outfitting.

To simplify the design space and ensure that both teams were working on the same concept, an initial decision was made to adopt the NASA “TransHab” design as the project baseline [2]. This design pioneered many of the common design aspects of later inflatable concepts, most significantly the use of a rigid core module to support launch loads for the envelope. Critical systems permanently located within the core could be pre-installed and verified prior to launch [3]. While launch vehicles under development would allow larger concepts, the TransHab design is compatible with any launch vehicle with a nominal 5m diameter payload fairing. The decision was also made to retain the TransHab vertical layout, which prior SSL studies [4] had shown to maximize available interior volume across a wide range of envelope configurations.

As shown in section view in Figure 3, the TransHab baseline design was a three-deck vertically-oriented cylinder. The center core was 3m in diameter, allowing sufficient toroidal volume in which to pack the deflated envelope and still fit within a 5m payload fairing. After inflation, the pressure envelope was 8m in diameter. While development units of inflatable habitats on Earth have featured penetrations to the inflatable envelope for external airlocks, the TransHab developers assumed that docking ports or other inter-module connections would be made on the axial ends of the core structure.

While TransHab was envisioned as a transit habitat in microgravity for travelling to and from Mars, the UMD X-Hab teams were focused on both microgravity and lunar/Mars surface applications of the habitat. The vertical orientation of the structure was maintained for both applications, but the process of manipulating structural elements had to be compatible with both types of environments. As will be demonstrated later, some modifications to the TransHab architecture were accepted, such as an extension of the core structure to allow the inclusion of an airlock with walking headroom under the inflated envelope for planetary surface applications.

II. Habitat Scale Model

As part of the ENAE 100 Introduction to Aerospace Engineering course for first-year students, a five-person team was created to work on a scale model for X-Hab outfitting visualization. The process started with considering various scales for the model, ranging from 1/35 scale and up. There was a desire to choose a scale in which human figures were commercially available, for use in visualizing volume and access. Larger scales were favored to obtain greater detail on tasks such as structural deployment of floor panels. The largest feasible scale was fixed by physical room to house the model, as well as being able to fabricate it in a reasonable time with available fused deposition method (FDM) printers.

The final scale adopted was 1/12 scale, resulting in a model 80cm (32in) in diameter. This could be fabricated in an acceptable time frame with a reasonable number of components using the SSL's Creality CR10-S5 printer, with a bed size of 500x500mm. The final scale model habitat is shown in Figure 4. The inner core was represented by an octagonal structure, which provided linear surfaces for mounting hinge lines of deployable floor/ceiling panels, along with eight longitudinal elements for both structural support and routing electrical, data, and fluid lines in the pre-integrated core. Floors were represented by corrugated plastic sheets with holes to be placed over the longitudinal elements. Figure 4 shows the completed model in the deployed configuration, with all of the equipment inside the core for launch (left) and deployed into their operational positions (right). EVA suits were represented by 3D printed models, but at 1/12 scale a number of fully posable superhero figures are inexpensively available, and used to represent the shirtsleeve crew in the habitat. Equipment racks were modeled with appropriately-sized cardboard boxes, and cargo transfer bags by blocks of foam insulation. More complex hardware, such as crew exercise equipment, was modeled and 3D printed.

The exercise of populating the 1/12 scale model was valuable primarily in the ability to compare different layouts in an easier manner than would be available with a solid modeling package. The large corrugated plastic floor panels were easy to construct in quantity, and led to concepts in folding and deploying floor elements that were passed on to and expanded by the senior capstone class that followed in the Spring 2022 semester.

III. Full-Scale Design

Beginning at the midpoint of the Fall 2021 semester, a team of 20 seniors in the ENAE 483/484 Aerospace Engineering capstone sequence in spacecraft design began to work in parallel with the ENAE 100 first-year team. Using the resources supplied by the 2022 M2M X-Hab Program, this team was tasked with developing full-scale mockups of sections of an inflatable habitat for human factors testing. Critical elements of inflatable outfitting, including floor panel installation, transfer of installed equipment from the center core to the inflatable volume, and routing and connection of utilities including power, data, fluids, and air handling, would be performed in the laboratory environment, and in the water tank of the UMD Neutral Buoyancy Research Facility. This would allow evaluation of the outfitting activities in simulated microgravity, and through judicious ballasting of the test subjects and hardware, at lunar and/or Mars gravity levels.

To maximize the fidelity of the tests, the team first performed a detailed design of an inflatable habitat based on the TransHab configuration, as documented in this section. That design was then used to arrive at a concept of operations for the outfitting of the habitat after inflation, described in the following section. Finally, those details were used to selectively create mockup hardware and test procedures for experimental investigation of how the crew could perform outfitting activities, with the goal of quantifying the time and resource commitments required to create a fully

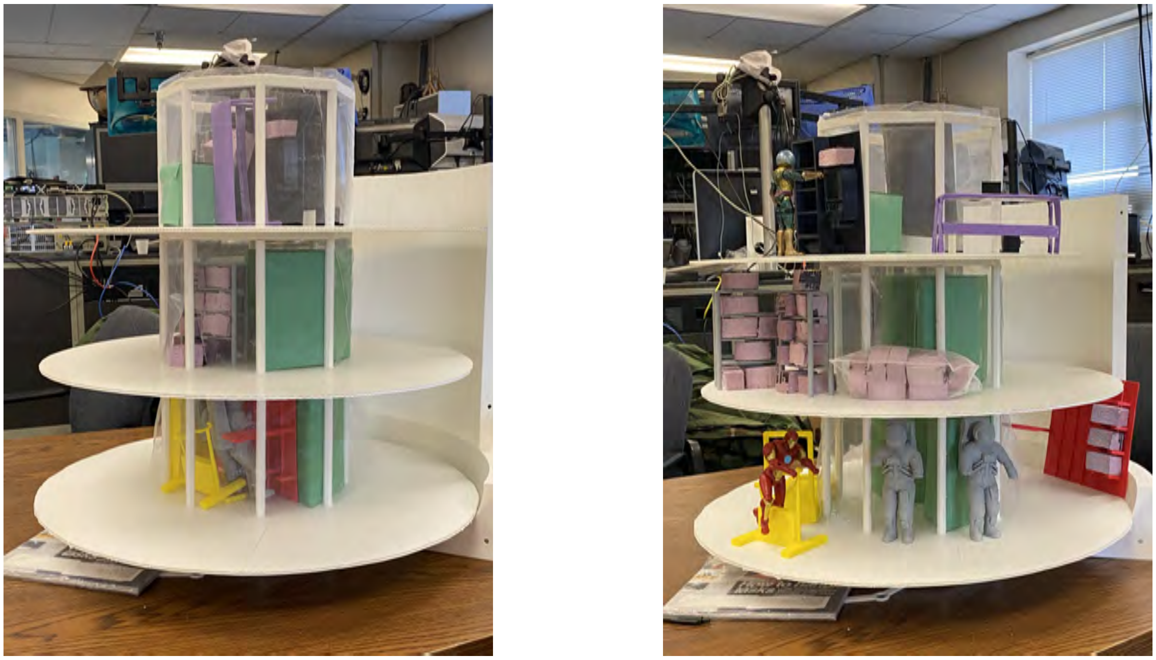

Figure 4. A scale model of the habitat interior with everything packaged into the center core (left) and the inflatable volume outfitted (right).

functional habitat.

A. Interior Layout

The design of the interior was conducted based on a ranked list from the most difficult designated areas to place to the areas that could effectively work anywhere. The layout is not designed with well-defined rooms, but rather functional areas. That is, the consideration to place an area was based on what the crew needed to do in the area and where a crew member might have to go after finishing their task. Top priority was given to the placement of the airlock, crew quarters, and life support systems, as they have significant constraints on where they can be placed. The mid-priority placements are defined as being constrained and dependent on the high priority placements. They are the laboratory, kitchen, and food storage areas. The lowest priority placement was the exercise area, as the equipment can be deployed to fit anywhere in the habitat. Figure 5 depicts the final layout of the habitat, color-coded based on priority placements.

The airlock was the first placement considered, as the TransHab architecture includes three main floors interior to the inflatable volume, and only the core structure protruding beyond the inflatable envelope along the central axis. For planetary surface applications, the core structure was extended at the lower end to allow the placement of the airlock there, as it allows direct access to the surface at that location. It is distinct from the rest of the habitat in this position, which provides an advantage in limiting surface regolith intrusion into the rest of the habitat. An airlock placement was investigated on the first inflated floor as well, but would require a more intensive exterior design to accommodate.

The crew quarters was the next priority item, as this area also has many constraints. In order to shield the crew from radiation, the crew quarters are placed in the core where they will have the maximum amount of material between them and the outside environment. The walls of the individual sleeping compartments for the crew will also include extra radiation shielding. Located on a planetary surface, most radiation will approach from the sides or top of the habitat. With this consideration, there were two options left for crew quarter placement: the first floor core or the second floor core. The first floor is very appealing from a radiation shielding standpoint, but there would be no way for the crew to enter/exit the airlock if the crew quarters were placed there. With this in mind, the final decision was to place the crew quarters in the second floor core, which is also the tallest floor, providing the most volume to fit the six crew members. The downside to this placement is the limited volume which cannot be rectified unless the crew quarters are moved outside of the core, increasing the potential for radiation damage. The crew quarters design section of this paper will further develop the considerations that went into designing the individual crew quarter cubicles.

The life support systems have some of the tightest constraints for placement of any item in the habitat. These systems are highly interconnected in terms of power, data, fluids, thermal, and air handling, and therefore should be

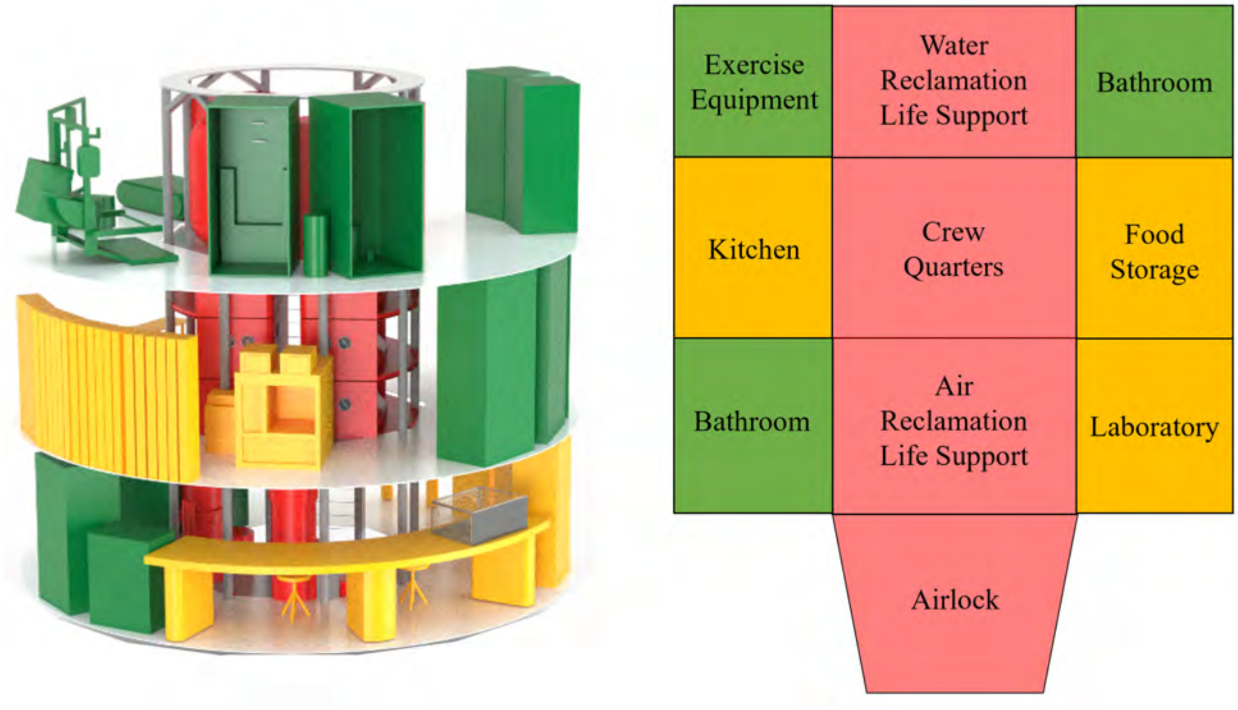

Figure 5. On the left: A colored render of the final layout with coinciding colors to the right image. All storage areas are green as well, as they have the lowest priority of all placements. On the right: Side view of final layout of TransHab displaying the areas of the habitat based on the priority of placement. Red = high priority, Yellow = mid priority, Green = low priority.

pre-installed in the core prior to launch and should also be operational before the crew enters the inflated habitat. That is, they will not be deployed from the core after inflation. Therefore, there are two potential places left for the life support systems: the first floor core and the third floor core. The water recovery system is placed on the third floor, along with the large water supply tank, to provide additional radiation shielding for the crew in the crew quarters. The oxygen recovery system, particulate scrubbing system, CO_2 scrubbing system, and all other atmospheric/air systems will be placed on the first floor core. The oxygen recovery system and CO_2 scrubbing and reduction systems are among the highest-mass components of the system, so placing them nearer to the bottom helps with distributing the structural loads. Additionally, placing all of the high-mass life support fixtures in the center of the habitat helps to maintain a favorable center of mass. There is a drawback of separating the life support systems, in that if maintenance is required for all of the components, crew members will have to ascend and descend the levels of the habitat to get to the systems.

The laboratory area was placed on the first floor in the deployed volume, as it is advantageous to be close to the surface. The crew will be taking extensive regolith and rock samples, and should be able to analyze the samples in a glovebox or other controlled environment within the habitat. Earth analogue habitats such as the NASA DSH/HERA facility have scientific airlocks accessible from the exterior that open directly into the internal glovebox. Since only the airlock is directly adjacent to the surface, it would require an extended staircase or ladder to have the same external science airlock to a laboratory, even if it is on the lowest level. The glovebox will be placed at least 3.5 m off the surface, as the crew requires extra headspace as they walk under TransHab's inflated bladder. Without a robotic or mechanical operating device, transferring samples into the glovebox externally becomes a significant issue. It is likely that a more convoluted system will evolve for in situ sample testing, such as sealing them into containers (as in Apollo), bringing the containers inside the habitat and transporting them to the laboratory, and sealing it to the glovebox before accessing the samples. In any case, it would be advantageous to locate the laboratory on the lowest level of the inflated volume, both for ease of access to the airlock, as well as minimizing any potential contamination from EVA operations. The laboratory will also be used for more extensive spacesuit maintenance, so again, proximity to the airlock is key. Experience from ISS shows that air regeneration systems are among the highest maintenance components in the habitat; adjacency to the laboratory will provide a more comfortable and productive environment for this category of maintenance activity as well. Ideally, a laboratory area would be placed as close to the lunar surface as possible so that the samples could enter from the surface directly into the glovebox without significant struggle. Placing the glovebox in this way in the given configuration is not possible, as the airlock inhabits most of the

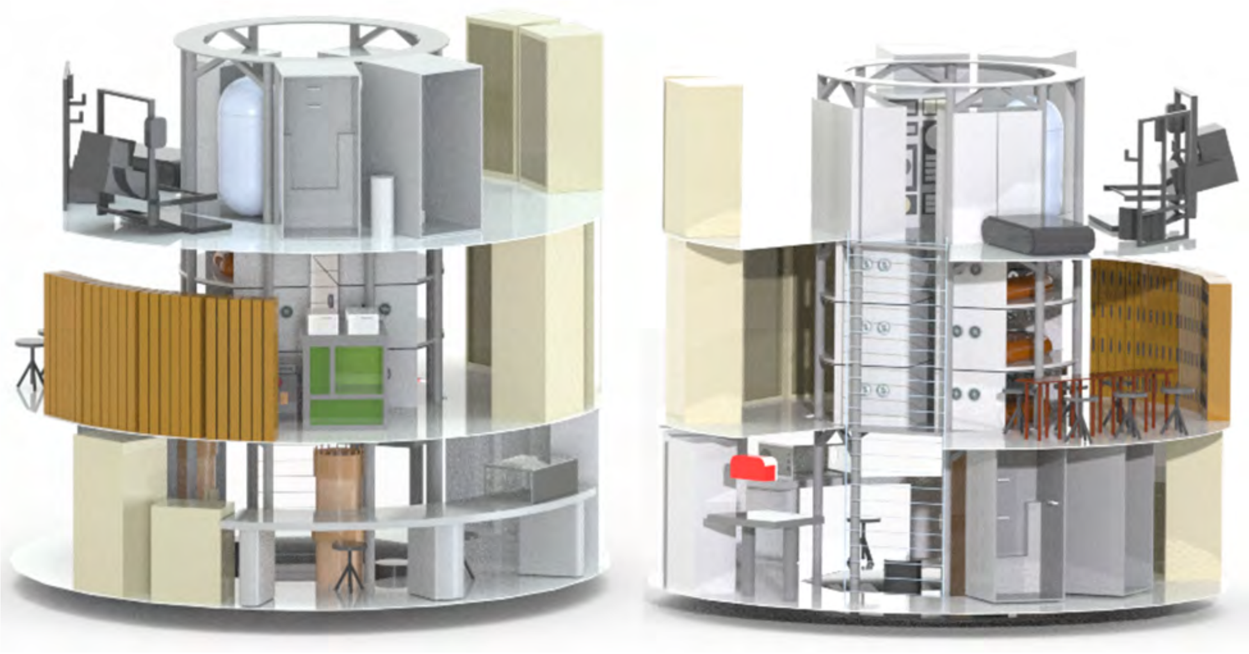

Figure 6. CAD diagram of the fully deployed and outfitted inflatable habitat configured for the lunar surface.

area on the lowest floor.

The kitchen and dining area is located on the inflated second floor, and the rest of that floor will be dedicated to food storage, general storage, and crew recreation. This floor is coupled with the crew quarters, which conveniently creates a floor strictly dedicated to more relaxed time. One waste management compartment will be placed on each of the first and third floors, with a wash station next to each one. Including more than one bathroom is extremely important for crew accessibility. It is important to place the bathrooms away from the crew quarters, as they will be potentially loud and odorous areas. However, placing them away from the crew quarters also means that it is difficult to get to one when the crew needs to use one during their sleeping hours. Each bathroom is coupled with a wash station. Having a wash station (likely a sponge bath) next to the bathroom on the first floor is helpful, as it might become one of the areas that the crew goes to remove any regolith contamination from suit maintenance. The exercise equipment was the second-lowest priority item, which will sit on the top floor. This is also close to a bathroom and wash station so the crew can clean up after they exercise. The rest of the habitable volume will be dedicated to storage. The second floor storage will be personal crew items, as it is near their sleeping quarters. The first floor will be laboratory equipment storage. The first and floor also have volume to store other random supplies.

B. Crew Accommodation

1. Crew Quarters Design

The crew quarters needed to be placed in an area of significant radiation shielding, as previously discussed. The design of the crew quarters was particularly challenging, as it is important to maximize the utilization of the available volume throughout the core. This particular section of the core has a 1.7 m (5ft 6in) radius and 2.4 m (8ft) height, and needs to accommodate six crew members with the highest attainable level of comfort. Dividing the total volume of the core (21.5 m^3) by six, the maximum personal volume of a single crew quarter was 3.6 m^3, a more than comfortable volume for an individual crew compartment. However, this number represents the absolute maximum limit that the crew quarter volume can be. There are many additional items required for crew quarter safety and habitability including but not limited to: access corridors, air flow mechanisms, lighting, tablets and/or a personal communication device, radiation shielding walls, and noise mitigation material.

The final design for the crew quarters includes all of the previously mentioned components, and also an ability to control them based on the crew member's specific desire. A tablet is placed above their bed so that they can control the brightness of the lights and speed of airflow inside their personal space. The tablet, not included in Figure 7, will be attachable to multiple surfaces inside their personal volume. The volume itself was designed such that wires and air tubes can fit in the middle of the crew quarter volume. This decreases the total volume for the crew quarters, but is a vital consideration for habitability. The final crew quarters volume ended up being 2.6 m^3 per crew member. The

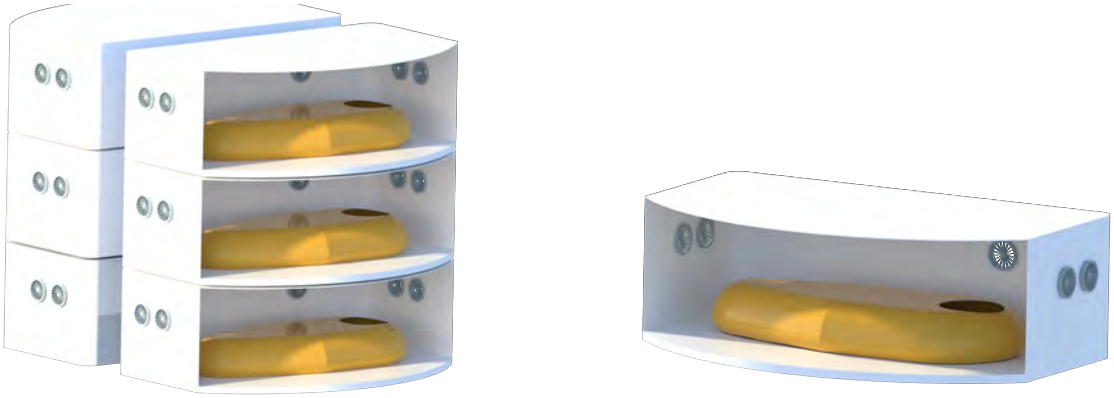

Figure 7. CAD model of the six crew quarters in the second level of the core with doors removed for visibility (left) and single crew quarter cubicle zoomed in with door removed (right). The sleeping pods simply display a representative size rather than a final design specification.

dimensions of a personal space is a 0.8 m height, 2.4 m length, and width that ranges from 1 m to 1.5 m as the area curves. Fans and lights are placed on the walls of each crew volume and can be turned on and off individually based on personal comfort. The bed will be outfitted with straps for the microgravity configuration that can be removed for lunar/Mars configurations. The height of the crew quarters is a significant constraint that limits the activities a crew member can pursue in their personal space. Though they have ample room to lay on their side to read or use their tablets, they will not likely be able to comfortably sit up in their beds.

2. Vertical Mobility

When considering options for vertical mobility within the habitat, the primary choices were a standard ladder or a steep staircase. Concepts for how staircase angles and step distances change with gravity level have been studied at the SSL in the past, and with more data an ideal system could be designed [5]. However, due to the limited distance between the outer edge of the core and the inflatable wall (2.1 m), the staircase angle may be close to 70°, at which point it is steep enough to be classified as a ship's ladder on Earth. For a ship's ladder with a width of 0.6 m (24 in) between the rails and a distance of 0.46 m (18 in) between the bottom of the ladder and the wall of the habitat, the angle would indeed be 70°. The ship's ladder would require an estimated 1.2 m^2 of surface area on the first floor and a volume of 5.5 m^3, including the space required directly above and below the ladder. With the thought of lowering the necessary staircase angle, the use of two separate staircases was also considered. Although using two separate staircases would decrease the angle of each to about 50°, this design would require twice as much floor space and occupy more of the overall habitable volume. Additionally, given the nature of TransHab, any staircase exterior to the core would have to be manually installed by astronauts and it would occupy valuable real estate while packed in the core for transit.

As such, vertical ladders were favored for their lower volume and their ability to be permanently installed on the core by only occupying wall space. Another benefit of implementing a standard 90° ladder may also be the conservation of available floor space after core deployment. A ladder with a width of 0.46 m (18 in) between rails and the required 0.18 m (7 in) distance between the rungs and the wall would require 0.6 m^2 of floor area, including the size of the ladder and the 0.76 m (30 in) of space necessary for the user [6]. Although one notable benefit to using a staircase over a ladder is that the astronauts would have at least one of their hands free to carry items between floors, compared to climbing a ladder which requires the use of all four limbs, this can be mitigated through the use of alternative methods of transporting objects within the habitat. Small and lightweight items such as food packages and clothing could easily be carried in a small bag or a pocket while an astronaut ascends the ladder. Furthermore, a hoist system could allow the frequent lifting of CTBs and heavier objects within the same ladder volume that is necessary for human use. Even with the additional complexity of a manual or mechanized hoist, the benefits of a vertical ladder's low volume and lack of installation led to its selection over a steep staircase.

3. Lab Space

The term "laboratory" is used as a shorthand designation for a general operations area, including (as mentioned above) bench space for working on habitat and EVA systems in need of maintenance or repair. For planetary applications, though, it will almost certainly have dedicated facilities for geological and exobiology investigations. A glove box is the most important part of this lab, which can minimize contamination of samples by providing a vacuum or, more likely, nitrogen atmosphere around the samples. A geological work station would include microscopic imagers, various spectrometers, and sample preparation equipment, with crew access via isolated gloves and arms. As such, the laboratory will require extensive data links for relaying experimental results to Earth, as well as more mundane tools and equipment for general-purpose repair and operations.

IV. Habitat Operations

A. Deployment of Core

Several systems including the lab, kitchen, bathrooms, and exercise equipment will need to be moved from the packed core, assembled, and installed on their respective floors in the inflated volume outside of the core. Since the space in the core is limited to critical systems such as life support and crew quarters, the larger inflatable volume outside of the core will be used to house these mid-to-low priority systems. Each system will require a thorough procedure of unpacking from the core, moving to its respective position in the inflated structure, and then being properly secured to the structure. Many systems will require additional interfacing as fluid, power and/or network lines will need to be fed from the core and attached to the subsystem. All habitable regions in the inflated volume will require air handling to ensure continual air flow and eliminate stagnant regions, particularly for microgravity habitats.

After the equipment is moved to its respective location in the inflatable structure, it will either need to be secured to the bottom of a floor panel or to one of the ceilings from the floor above. Equipment will primarily be secured using simple machine screws, nuts and bolts, and power hand tools. Heavier equipment such as the treadmill may require special tools and support racks to withhold any additional force applied to the floor panels.

Once the equipment is secure, power and fluid lines and network cables will typically be attached to the ceiling or bottom side of the floor panel structure from floor above. These hoses and wires will primarily be secured with straps. These straps will be placed such that the load is evenly distributed and the wires are kept taut. The number of straps needed per each wire will be determined by the weight of the wire and the maximum load each strap can hold. Although the loads from these cables and fluid lines should be negligible compared to the load that the floor panel will endure from housing the actual systems, the total weight in surface environments such as lunar and martian gravity need to be considered in the stress analysis of the floor panels. The nature of the deployment process and the tools and effort required for deployment and installation of these systems will differ in microgravity versus planetary surface environments.

B. Concept of Daily Operations

Initially, the crew members will dedicate their time to set up the habitat from the configuration for launch and inflation. (It is a prime objective of this study to better understand how long this will take.) In this time, they will be transporting extra supplies in CTBs to the inflated habitat, and organizing the interior based on a planned procedure. Beyond the initial setup time, in order to keep the habitat up and running, life support and other habitat systems will need to be maintained with continuous servicing. Based on ISS experience, at least half of the crew members will likely spend their working hours each day servicing, repairing, and controlling these systems, depending on what is necessary. Maintenance must also be performed on the spacesuits before and after extra-vehicular activities (EVAs), as the suits will have to be reused almost daily. A planetary habitat could have EVAs nearly every day. Other crew members will support the science in the habitat by experimenting with the lunar samples delivered to the glove box.

Each morning after an eight hour rest, the crew will spend one hour preparing for the day with breakfast, washing, and some free time. At some point every day, each crew member will spend about two hours exercising to maintain muscle mass in lower-gravity environments. Much like it is on the ISS, the upkeep of the habitat itself will be of the highest priority - simply maintaining the onboard machines will take a significant portion of astronauts' time. EVAs and science will be a second priority, although on planetary surface environments, EVAs will likely be far more frequent. The expected work day of a crew member will average to 9 hours with ample time for three meals and some relaxation/personal time. If involved with an EVA, that particular work day may last longer, as each EVA will be scheduled to meet some objective. The nighttime routine will be similar to that in the morning, with approximately an hour allotted for washing and hygiene, and pre-sleep personal activities.

C. Extravehicular Activities

The EVAs will occur most frequently on the martian or lunar surface and, as previously discussed, will be for geological or astrobiological exploration and/or support the experiments run in the on-board laboratory. Sample collection and curation will be enhanced by the ability to do in situ analysis and down-select samples to be returned to Earth with the crew for further analysis. Seismometers and other instruments will need to be deployed, and some samples may need to be brought back for analysis as explained in the lab space section.

Whether for planetary surfaces or for in-space applications, EVAs will always be required for habitat maintenance, repair, and upgrades. An inflatable habitat could form the basis of an upgraded Gateway station in an extended Artemis program, and like ISS, be continually expanded and improved by the integration of new hardware externally.

V. Testing

A. Floor Panel Deployment

The largest structural outfitting task is the installation of the deck and ceiling structures for the various levels in the inflated volume. Results from the scale model design exercises showed that it should be possible to have the integrated floor/ceiling panels hinged to the decks of the central core, and folded up alongside the core underneath the pressure envelope for launch.

The overall concept for deck deployment is shown in Figure 8. Each deck (consisting ultimately of both a floor and the ceiling of the deck below) consists of eight rectangular panels hinged to the central core structure (left image). Triangular truss structures will rotate out from the central core to hold up the primary deck panels (center image). A triangular secondary deck panel will be hinged on each side of the primary panels, and will unfold and interconnect to form the contiguous floor/ceiling structure (right image). This deployment system took significant inspiration from the Constellation project configuration [7].

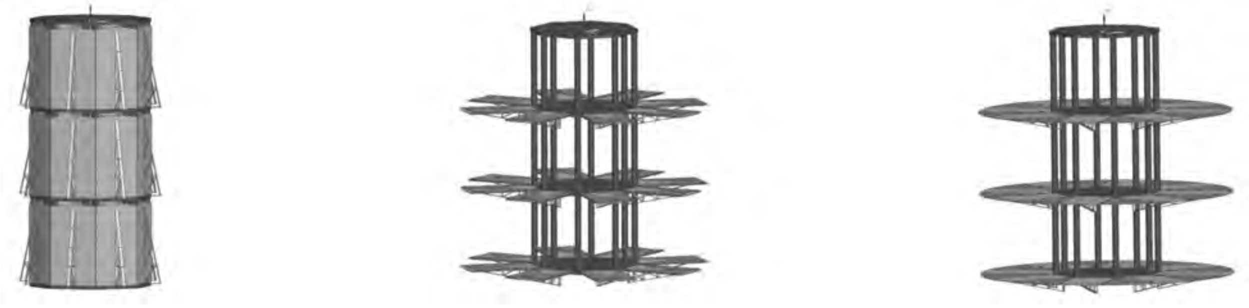

Figure 8. Design for the three steps necessary when deploying the floor panels. The leftmost image displays the pre-deployed configuration where the core will be packed. The center image displays the floors after being lowered from the packed configuration. The rightmost image displays the fully-deployed floor after the trusses are flipped and the panels flush to one another.

The deck deployment test set-up focused on one primary deck panel, along with one support truss along the center and hinged secondary panels. The central core structure was represented by an assembly of rectangular modular racks, developed in past X-Hab programs, to allow quick reconfiguration of habitats for testing of habitat size and shape[8]. The panels were hinged upward from the upper edge of the rack 2m above the local floor. For testing, the panel was made of 2cm thick PVC sheets because it is waterproof and close to neutrally buoyant for underwater testing. The set-up has a motorized deployment system that lowers the panel using a cable that could then be detached after it was in place. Before microgravity testing, the panel was assumed to be neutrally buoyant, and was planned to be used to investigate manual deployment using ISS-type hand rails mounted in various positions around the surface. The panels for lunar and potential Mars gravity cases were ballasted to reflect the local gravitational weight.

For lunar gravity configurations, the floor panel would be autonomously deployed using the motorized cable system. Then, a support truss would manually lock into place on the rack. In the completed microgravity test, it started similarly, however the panel was manually deployed using the previously mentioned hand rails. This manual deployment started with the center panel piece, followed by the right flap, then the left. The trusses were then locked into place in the same manner as the lunar tests. A prototype floor panel deployment test was conducted in order to gain qualitative data on the placement of structure and mechanisms. The test consisted of the floor panel being lowered into its deployed position and the securing of the support truss below the floor, shown in Figure 9.

The prototype floor panel for testing was actually buoyant in the tank even though the PVC sheet was chosen due

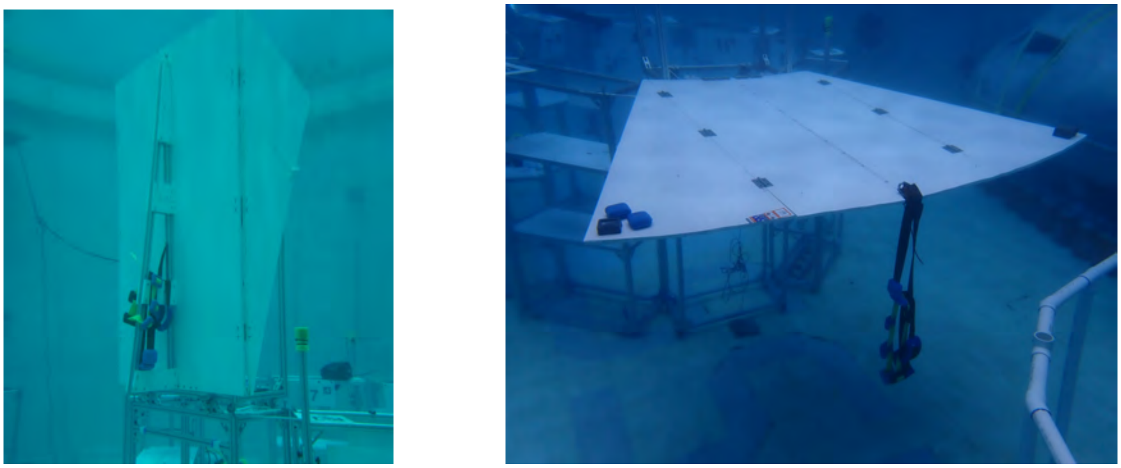

Figure 9. Images from the April 8 test of the floor panel deployment. The left image is the floor in its upright position and the right image is the deployed floor with the necessary weights on it.

to the material's neutrally buoyant properties, so the mechanical winch system could not be used. To combat this issue, the panel was lowered manually by the test subjects and weights were placed on top of it to keep it from returning to its upright position. The truss was then secured to a crossbeam attached to the bottom rack.

Based on the test, the team plans on using two trusses for each panel with one at each folding edge to allow more head space. Attachment panels will also be added to the connection points of the floor panel to allow for more support and decrease deflection, and the hinge bolts will be more staggered in placement so the panel can fold more completely. These changes would allow for a smoother process for future testing.

B. Deployment of Key Subsystems

The capabilities of the Space Systems Laboratory at the University of Maryland allow for testing in various gravity conditions through the use of body segment parametric ballasting in the UMD Neutral Buoyancy Research Facility. By ballasting divers with the appropriate amounts of weight on each of the major body segments, micro-, lunar, martian, or other gravity conditions can be simulated [9]. For microgravity, a small amount of weight is used proportional to diver weight for offsetting the natural flotation of the human body. The same is done for lunar gravity, but the weight is spread across the chest, thighs, and ankles to sum to what the diver's weight would be on the Moon. Tests to simulate the deployment of similarly ballasted subsystem simulators (shown in Figure 10) were conducted in both microgravity and lunar gravity. From the test, subjects were able to provide an assessment using the NASA Task Load Index (TLX) [10] on a scale of 1 to 10 for each of the tasks related to outfitting the inflatable volume of a habitat, with 1 being the most favorable response for the six TLX categories. The time it took the divers to complete each step of the deployment of key subsystems test was also recorded in order to estimate the time to deploy the rest of the habitat equipment.

Figure 10. Test equipment used for microgravity and lunar tests. The small, medium, and large PVC structures are displayed.

The testing followed a 2-step procedure, with timing and TLX data collected between each step: move the equipment to the designated location, and secure the equipment. The equipment used in the test consisted of three PVC structures, a small structure with a volume of 0.18 m^3 and a mass of 68 kg, a medium sized structure with a volume of 0.29 m^3 and a mass of 127 kg and a large structure with a volume of 1.29 m^3 and a mass of 169 kg. The small, medium and large PVC structures are an approximate representation of the waste management compartment, the advanced plant habitat, and a standard instrumentation rack, respectively. Additional to the moving and securing tasks, attachment of power, liquid, and air lines to a deployed payload was simulated by connecting small-, medium-, and large-diameter tubing.

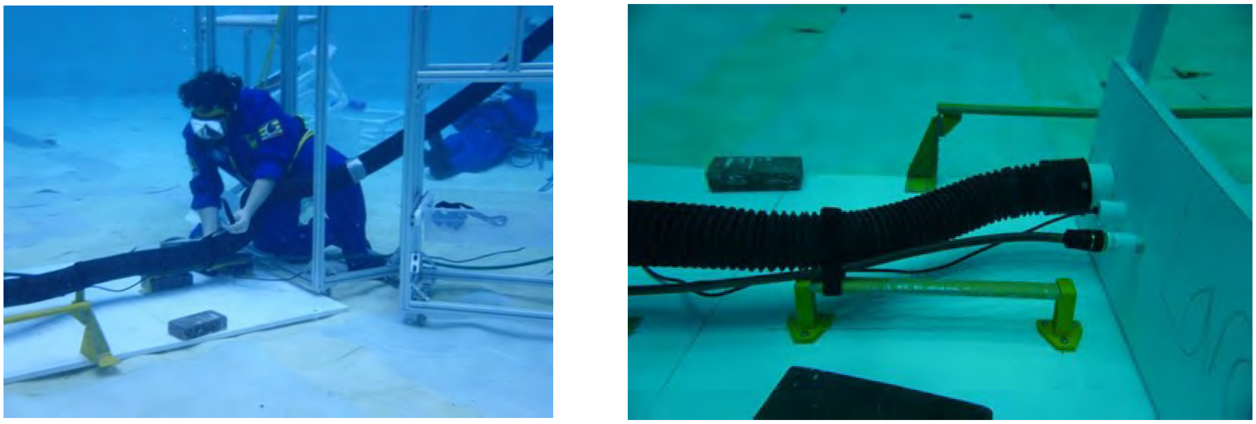

Figure 11. Images from the microgravity test. In the left image, the diver is attaching utility lines to the large equipment. In the right image, the utility connections are finished.

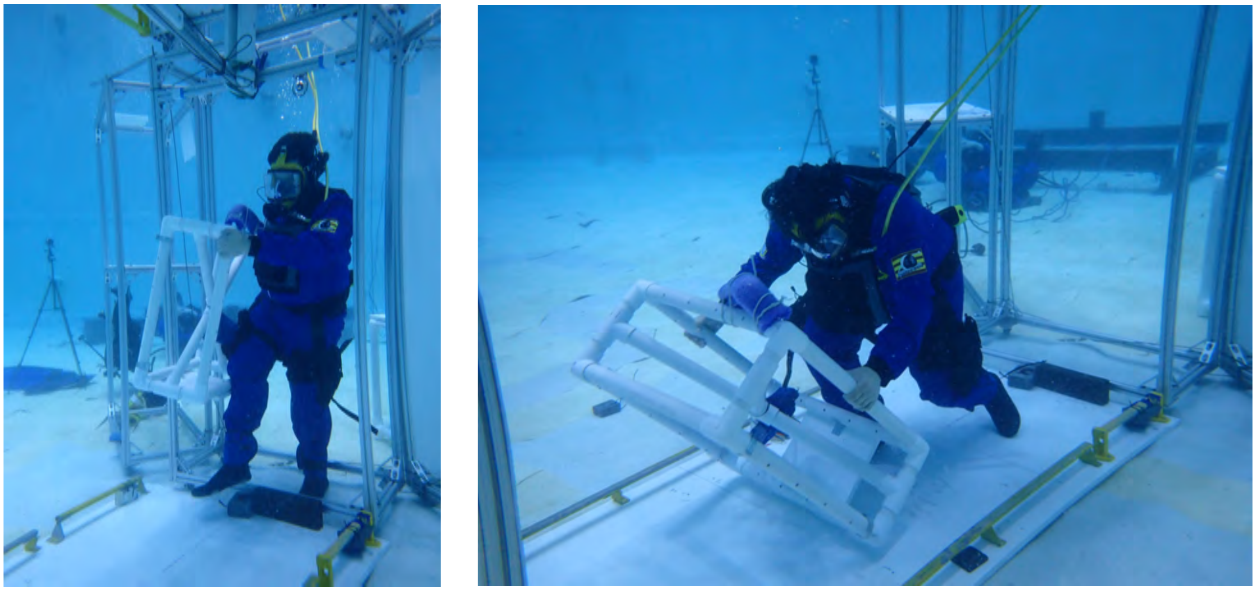

Figure 12. Images from the lunar test. Diver is moving the equipment, representing the first step in the testing procedure.

The goal of these tests was to understand and obtain data on the duration and difficulty of operations and subsystem installment. To accurately model the dynamic properties of the hardware in different environments, it was necessary to independently match both the inertia and the perceived weight of the item in the desired gravity field. Inertial mass is simulated for underwater testing by incorporating a closed volume in a neutrally buoyancy structure that encloses a mass of water equivalent to the desired inertia. This step is sufficient for microgravity simulations, assuming the rest of the mockup is neutrally buoyant. The same hardware can be used for planetary simulations by adding ballast equivalent to the calculated weight in the specific gravity field of interest.

For the movement testing, the divers moved the item from the core to a designated spot in the deployed floors and the time it took for this task was measured. Next, the time required to secure and screw each equipment was recorded. This represents the first part of the unpacking and installation process of outfitting the inflatable volume of a habitat. The last test collected the amount of time it took for the test subjects to properly attach any external wires or fluid lines to the equipment. Due to the nature of all the underwater tests and their extensive preparation, there was only time to conduct two trials for each equipment size; one trial per test subject. Future testing is required to corroborate the results detailed below.

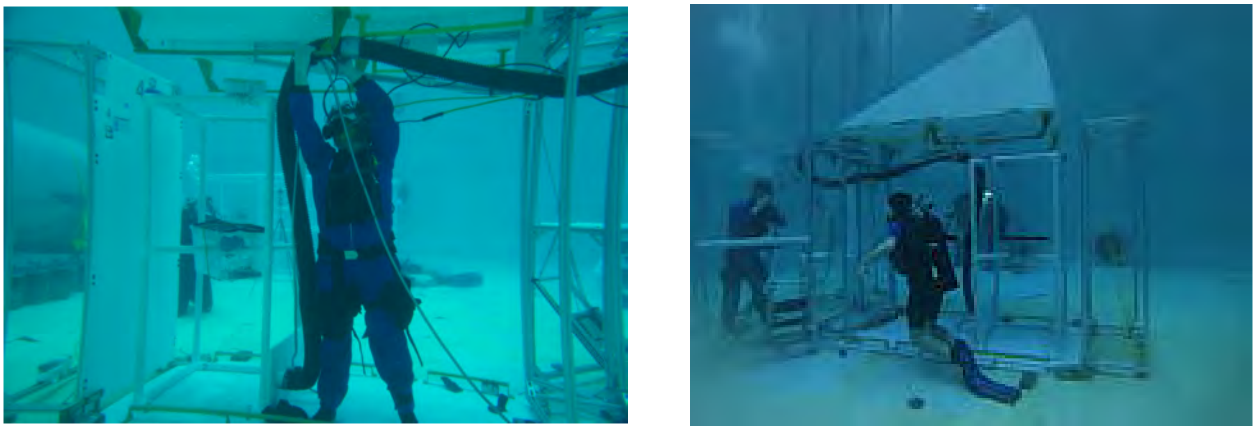

Figure 13. Images from the lunar test. Diver is attaching utility lines to the equipment, representing the third step in the testing procedure.

1. Microgravity Deployment Results

The time it took the divers to maneuver the small, medium and large PVC structures outside of the core, orient them correctly, and align them with the designated securing location were 47, 35 and 68 seconds, respectively. The designated location was the same for all three sized structures in order to keep the experiment controlled. A possible explanation for the larger time for moving the small equipment versus the medium sized is that the divers faced a learning curve as the small was tested first. Based on the results of the TLX, the large sized equipment was the most demanding across all categories. The time it took per bolt was averaged to 34 seconds across the three PVC structures. During the test, one diver was responsible for bolting down the equipment while the other diver held the equipment in place. Additionally, the medium and large equipment weren't perfectly neutrally buoyant, which created frustration for the divers.

Figure 14. Divers securing the small payload simulator during the microgravity test, representing the second step in the testing procedure.

The line securing test was only completed for the large equipment, as the attachment of lines to any deployed structure should be of effectively the same difficulty. The simulated lines were of different sizes and connector types. The time it took to attach each line was between 40 to 45 seconds. The TLX results indicate that the divers had the most difficult time during the line attachment testing.

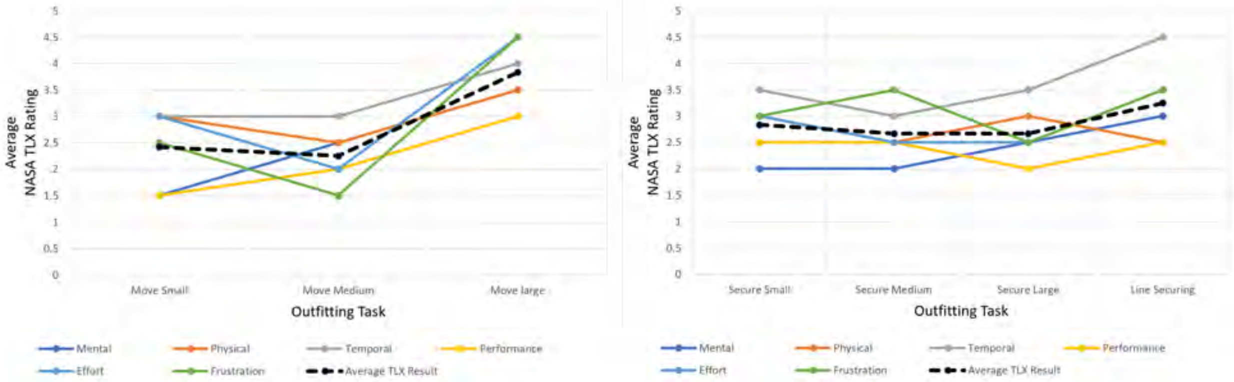

Figure 15. The TLX data for the microgravity testing. The left image is the TLX data for the moving of the components and the right image is the TLX data for the securing of components. Times for each test are shown in Table VI

2. *Lunar Gravity Deployment Results*

Testing was then conducted in lunar gravity to obtain results of similar fidelity and allow for fair comparison of results between the microgravity environment and the lunar environment. The subsystem simulators were weighted such that they effectively experienced the weight due to gravity in addition to the proper inertia given the system mass, which was controlled by capturing the appropriate volume of water. A significant change from the microgravity test was that the lunar test also featured a ceiling which was a part of the floor panel deployment described earlier. This allowed the divers to simulate attaching and running cables and wires along the ceiling rather than along the floor as the design initially intended. It is also important to note that in the actual habitat design, the ceiling would stand at approximately 8 feet high; however, due to the height limitations of the test racks, in the lunar test, the ceiling (floor panel) was 6.5 feet above the floor.

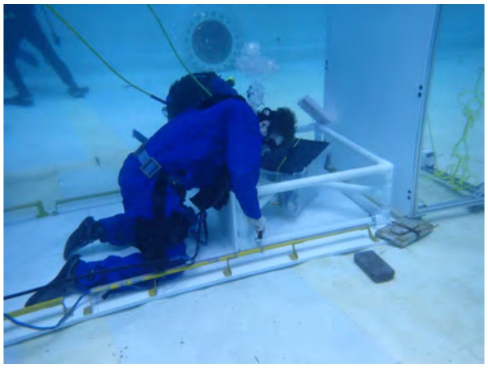

Figure 16. Images from the lunar test. Divers are securing down the equipment, representing the second step in the testing procedure.

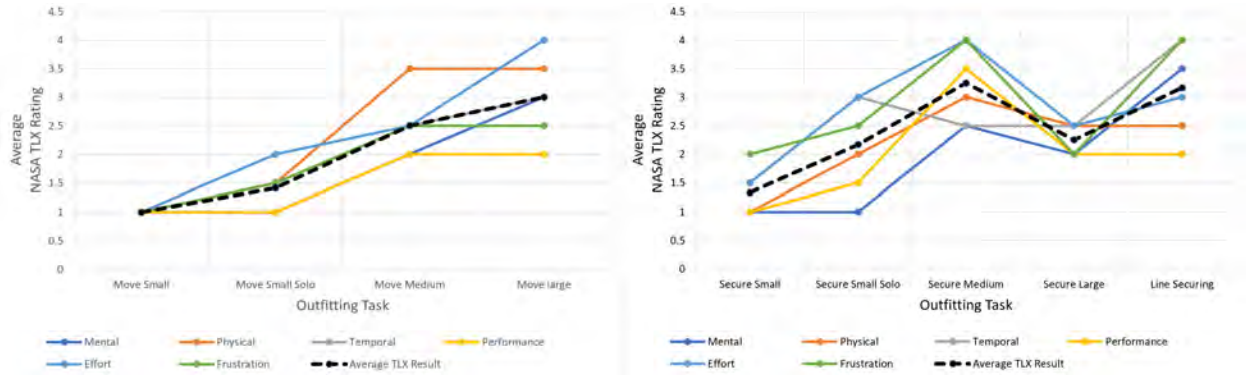

Figure 17. The TLX data for the lunar testing. The left image is the TLX data for the moving of the components and the right image is the TLX data for the securing of components. Times for each test are shown in Table VI

The time it took two divers to maneuver the small, medium and large PVC structures outside of the core, orient them correctly, and align them with the designated securing location were 19, 24 and 53 seconds, respectively. The time it took a single diver to move the small PVC structure was 20 seconds. That is, having two divers move the equipment versus one diver barely altered the time for the small-sized equipment. Similar to the microgravity test, the results of the TLX stated that the large sized equipment was the most demanding across all categories. Lastly, the time it took per bolt was on average 31 seconds across the three PVC structures when only one diver was responsible for bolting the equipment. Similar to the microgravity test, the line securing test was only completed for the large equipment.

VI. Conclusions

As shown in Figure 18, for the small and large payloads the TLX responses from microgravity testing eclipse that of the equivalent lunar simulation. The exception to this is for the medium payload movement test, where the lunar movement resulted in an average TLX score of 2.5 while the microgravity movement averaged only 2.3. The reason for this discrepancy could be the result of a rotationally non-neutral payload at microgravity, since the divers reported difficulty securing the same payload for those reasons. An interesting note is that even the single-person movements of the small payload conducted at lunar gravity resulted in more favorable responses than that of the two-person small payload movement in microgravity, despite the mass-handled per-person being greater in the single-person case. Even so, a single-person movement test will be conducted in the future for a direct comparison in microgravity.

Conclusions from the TLX data were corroborated by the divers' comments after the test: they both agreed that they found it easier to test in lunar gravity as compared to microgravity. Divers were only able to keep one hand on the payload in microgravity since the other had use handrails to react all forces. Once the payload was in its goal position and stationary, one diver preferred to couch the rails between their legs and feet to free up both hands for securing the payload while the other only secured with a single hand. Additionally for microgravity, the divers preferred moving around along the floor rails in the inflatable volume rather than using the rails on the ceiling, which may be due to the payloads being mounted to the floor.

Size of System	Microgravity Moving	Lunar Moving	Microgravity Securing	Lunar Securing
Small	47 s	19 s	91 s	67 s
Medium	35 s	23 s	179 s	102 s
Large	68 s	53 s	132 s	83 s

Table 1. The time to move and secure the different systems in microgravity and lunar gravity tests. All numbers are reported in seconds and are averaged values from all the timers for the various tasks.

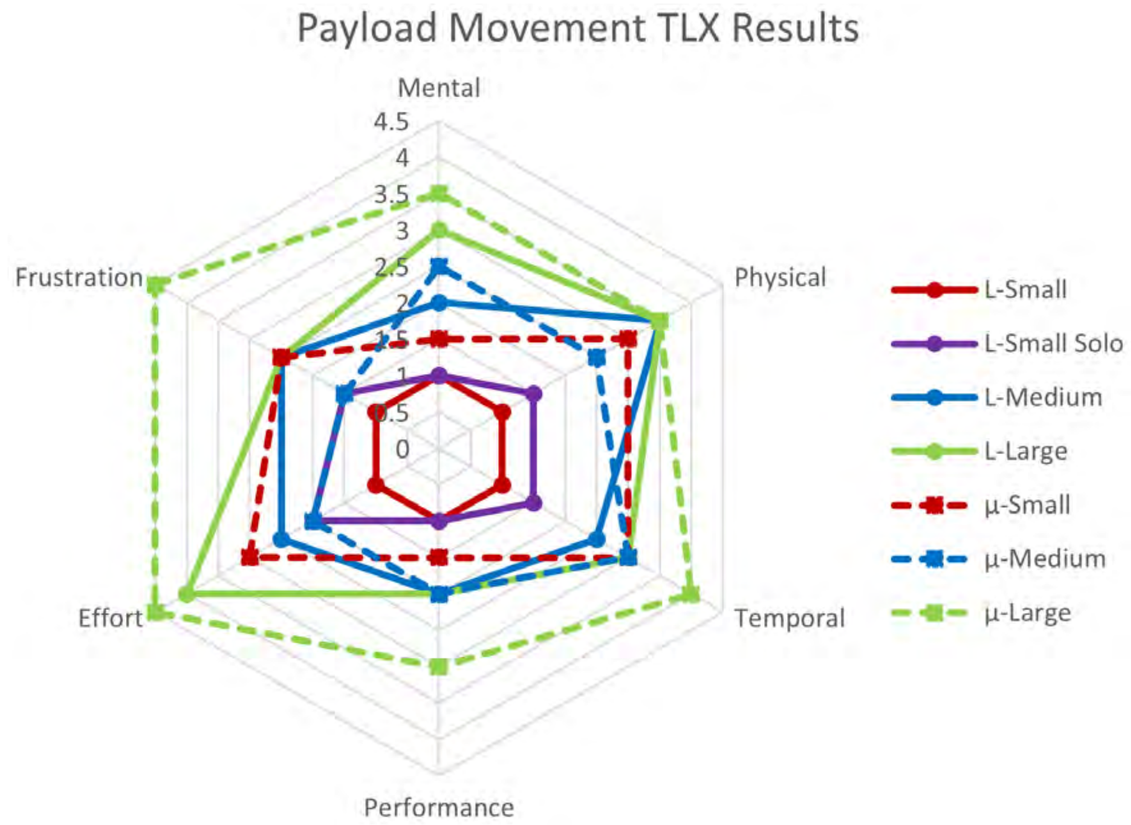

Figure 18. TLX responses for moving payloads in lunar gravity (solid lines) vs. microgravity (dashed lines). Matching colors represent equally-sized payloads. The single-person movement of the small payload at lunar gravity (purple) was unfortunately not replicated in microgravity.

The data gathered from the microgravity and lunar testing did not alter the macroscopic configuration of the habitat, but did influence the process of the deployment. The testing also reinforced the decision to place the life support systems in the core so that the life support systems could be active before the deployment takes place. As such, the astronauts conducting the deployment of subsystems into the inflatable volume could do so in shirtsleeves, without the dexterity and motion restrictions of a pressure suit.

VII. Future Work

The testing described here is that specifically in support of the 2022 M2M X-Hab project. Having performed some of the planned tests, the University of Maryland team is eager to continue and extend the tests to better understand the whole process of inflatable habitat outfitting. Although robotic deployment of internal structures and systems was an initial goal of this study, time and resource considerations along with unplanned maintenance required for the existing dexterous robotic systems of the SSL required us to descope to only human outfitting activities. The logical next step would be to perform robotic outfitting, as well as collaborative human/robotic outfitting activities. Extensive past SSL research has conclusively shown that teams of humans and dexterous robots working together in the course of satellite servicing are far more productive than either humans or robots working alone [11]; the close similarities of servicing and outfitting lead to a reasonable prediction that the same will be true in this case.

Beyond this step, a number of interesting research topics are evident, from a wider range of hardware to be installed at higher levels of fidelity to end-to-end simulations of complete habitat outfitting, both in Earth conditions as well as underwater simulation of micro-, lunar, and Martian gravity levels. Looking farther ahead, perhaps future habitats will be created a collection of easily repositionable modules, allowing long-duration crews on the Moon or Mars to evolve their own habitat design with experience.

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