Final Report – X-Hab 2014

Vertical Habitability Layout Studies
Neutral Buoyancy/Parabolic Flight Habitat Studies

Final Report for National Space Grant Foundation
Contracts XHab201406 and XHab201407

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I. Introduction

In the Summer of 2013, the University of Maryland was selected for two projects under the NASA X-Hab 2014 program, administered by the National Space Grant Foundation: Vertical Habitability Layout Studies (XHab201406) and Neutral Buoyancy/Parabolic Flight Habitat Studies (XHab201407). This document, at the direction of the NASA Technical Monitor, comprises the final report for both of these contracts.

Recognizing from the outset the mismatch between the desired scope of research activities under the contracts and the severely limited funding and duration, the University of Maryland leveraged the X-Hab support by integrating the programs into a number of academic classes throughout the 2013-2014 academic year. By far the most significant interaction was with the Department of Aerospace Engineering Senior capstone experience in spacecraft design sequence, ENAE 483/484. Throughout the academic year, 42 students in this sequence worked on both projects in conjunction with their senior project to design an artificial gravity research station in a distant lunar retrograde orbit. As part of this research project, the students worked with previously created 1-G habitats and underwater simulations to better understand habitat design from microgravity to full Earth gravity, as well as at lunar and Mars gravity levels between those two endpoints.

II. Background

Space habitat design and testing is perhaps one of the most difficult areas in which to sustain a vital, ongoing research program. After forty years in low Earth orbit with U.S. operations in Skylab, Mir, and the International Space Station (ISS), a "standard" design practice for the layout of microgravity habitats in pressurized cylinders has been well codified in the ISS practice of horizontal orientations and rack-based systems modularity. Habitats for the Moon and Mars are clearly not going to be needed for (most likely) decades, reducing the priority for near-term research and development in a funding environment which is already inimical to advanced science and technology studies for in-space systems. Opportunities for funded academic research in this area are rare, and generally of a short-term nature.

In 2009-2010, the SSL was awarded a contract by the NASA Exploration Systems Mission Directorate for the design of a minimum functional habitat element (MFHE) for early lunar exploration. In response to this program, the SSL performed parametric optimization showing the desirability of a vertical cylindrical habitat configuration; the project culminated in the construction and testing of a full-scale two-level habitat. As shown externally in Figure 1 and internally in Figures 2 and 3, the UMd ECLIPSE habitat is 3.6 meters in diameter with two floors, designed with mission operations elements on the lower floor and habitation elements on the upper floor.[1]

In 2011, UMd participated in the first NASA/National Space Grant Foundation X-Hab Academic Challenge, and

Figure 1. Exterior of ECLIPSE habitat in the UMd Moonyard Planetary Surface Simulation Facility

Figure 2. Interior of ECLIPSE habitat upper level

Figure 3. Interior of ECLIPSE habitat lower level

was one of the schools selected to construct an inflatable habitat for the NASA Habitat Demonstration Unit. While this program was successfully completed,[2] the inflatable habitat does not lend itself to extensive internal reconfiguration and habitability testing, and will not be used for the 2014 program. However, as part of the 2012 X-Hab program, the SSL developed HAVEN, a single-level 5-meter diameter habitat (Figures 4 and 5), which has a number of features which greatly facilitate habitat reconfiguration and testing, including modular replaceable wall segments.[3] ECLIPSE and HAVEN, both located in the UMd Planetary Surface Simulation Center or Moonyard (Figure 1), provide three separate habitat spaces which can be used independently or together for habitat simulations and habitability assessments.[4]

In late 2013, the National Space Grant Foundation announced the awardees for the 2014 X-hab Academic Challenge; the University of Maryland received two grants, one for 1-G habitability studies of vertically-oriented habitats, and the other for habitat-related studies at various gravity levels using the University of Maryland Neutral Buoyancy Research Facility (NBRF, Figure 6). Built around a 50 ft. diameter, 25 ft. deep water tank, the SSL has used this facility for both microgravity simulations (true neutral buoyancy) and ballasted simulations of various gravity levels including lunar, Mars, and Earth gravities underwater. To the extent possible within the short duration and extremely limited funding of the X-Hab grants, the University of Maryland team chose to undertake a variety of examinations of habitat design and assessment, aiming at adding some quantitative data to long-standing issues such as the optimum habitat volume/area based on crew size and mission duration, and the real differences in habitat design based on operational gravity levels.

As part of the X-Hab program, research activities were incorporated into a senior capstone design course. ENAE

Figure 4. Exterior of HAVEN habitat under construction

Figure 5. Interior of HAVEN habitat

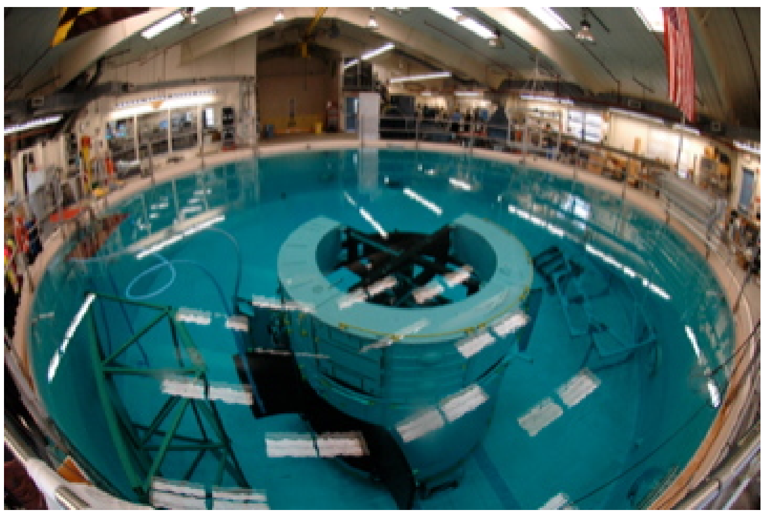

Figure 6. University of Maryland Neutral Buoyancy Research Facility with Hubble Space Telescope mockup

483/484 is the two-term capstone course in spacecraft design in the Aerospace Engineering department at the University of Maryland; the 42 students in the 2013/2014 sequence were engaged in habitat design and research activities throughout the academic year. While the focus of the X-Hab program (and, indeed, of this paper) was on the experimental research, the pedagogical needs of the capstone experience required the class to perform a full systems design of a human space program. To tie together the 1-G and variable gravity elements of the two X-Hab grants, the design focus of the class was on the detailed conceptual design of an affordable variable gravity space station in cislunar space (Figure 7). Such a station would provide a near-term justification for habitat design at a variety of gravitation levels, and would provide the real benefit of supplying data on human physiological adaptation and habitat design at lunar and Mars gravity levels, prior to a national commitment to active planetary exploration programs.

It should be noted, prior to the summaries of the research activities under each of the X-Hab awards, that each program required the development and approval of the use of humans as experimental test subjects, which was routed for approval through the University of Maryland Institutional Review Board. Due to the unusual nature of these experiments, particularly the ballasted simulation of partial gravity conditions underwater, the approval process took more time than originally anticipated, leading to a compression of the actual research studies and the use of a no-cost extension to allow the completion of these activities in the summer of 2014.

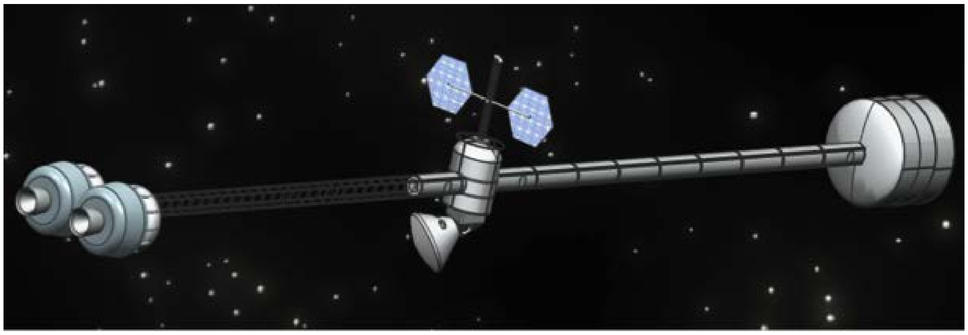

Figure 7. POLUS artificial gravity cislunar space habitat concept

III. Vertical Habitability Layout Studies

The original intention for this portion of the 2014 X-Hab research was to focus on the existing UMd habitats as the basis of extended human factors testing. However, as the year progressed, it became clear that there were serious shortcomings to focusing exclusively or primarily on full-scale habitat experiments. The design of the flight habitat focused on an eight-meter diameter habitat module, much larger than either the 3.6 or 5 meter habitats currently existing at the SSL. Some of the human factors aspects, such as the visual effects of a substantial rotation rate, could not be readily simulated in a static surface habitat. And, while some useful data could have been obtained by reconfiguring the existing habitat to represent portions of the flight design, the incredibly low funding level of this contract ($, with % overhead further reducing the effective buying power to approximately $) would not provide the funding needed for a meaningful set of internal layout tests.

As detailed below, the University of Maryland team responded to these challenges by leveraging other capabilities, most noticeably virtual reality. Habitat walkthroughs and window configurations could be more readily implemented in VR, and tested on a wider range of subjects. In the end, one series of full-scale habitat testing was conducted in the HAVEN module at UMd, but meaningful extensions of that research would require significantly more funding and time.

A. Virtual Reality Walk-throughs

During the UMd activities under the NASA ESMD Minimum Functional Habitat Element program, the SSL developed a number of conceptual designs for lunar habitats. Rather than entail the expense and time commitments of mocking up each design for evaluation purposes, the SSL team developed a virtual reality “walk-through” system using a set of low-cost stereo glasses. This system provided the user a sense of location and movement throughout the habitat models, although no head tracking was available, and motions were input via a X-Box-type hand controller. This system worked adequately for downselecting to the final design, but the limitations of the system were evident to all users.

Prior to the start of X-Hab 2014, the SSL had procured an Oculus Rift development unit. The salient differences between the Rift and the system used in 2009 include much higher scene resolution and frame rate, as well as reliable head tracking with slaved image motion. In order to utilize existing software, solid models of habitat interiors were imported into the Unreal Game Engine for display in the Oculus Rift. Test subjects navigated the interiors via hand controllers, while using the head tracking to enable realistic views while “looking around” (Figure 8). Subjective evaluations of the test subjects were used to refine interior designs, and to downselect to the final interior layouts of the variable gravity station study.

The students in the senior capstone design class developed a number of possible internal layouts for the vertical habitat element of the POLUS artificial gravity space station. Full, interactive immersion in each proposed habitat interior was achieved by first importing the CAD assembly for each floor into 3DS and creating an accurate collision model which completely surrounded all solid objects in the assembly. The CAD assemblies and associated collisions were then imported into Unreal Development Kit (UDK), where proposed models corresponding to the living quarters, work area, and the Mars SIM were stacked on top of one another to create a single “station simulator” for each possible permutation of the habitat. The three levels in each permutation were linked with an interactive ladder, allowing subjects to experience the transit between them in virtual reality. Data gathered through testing with these

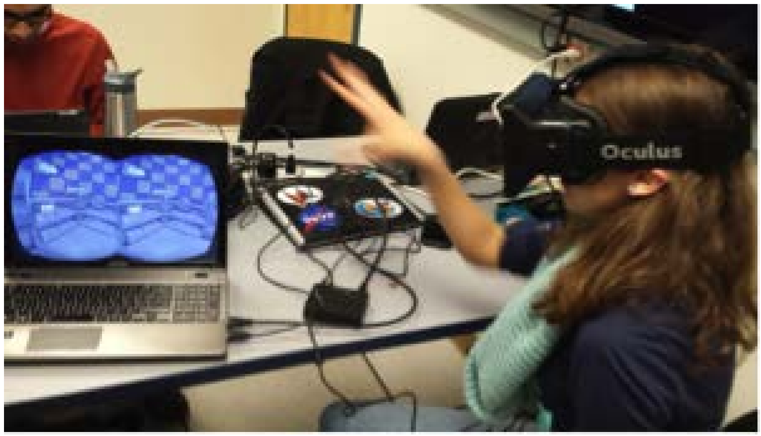

Figure 8. Early test setup with Oculus Rift for immersive simulation

simulators helped members of the Crew Systems team select a final interior layout from several competing proposals. The highest scoring floor plan utilized a "pod hotel" configuration (Figure 9) which allowed for the least-constricted crew movement out of the four options considered.

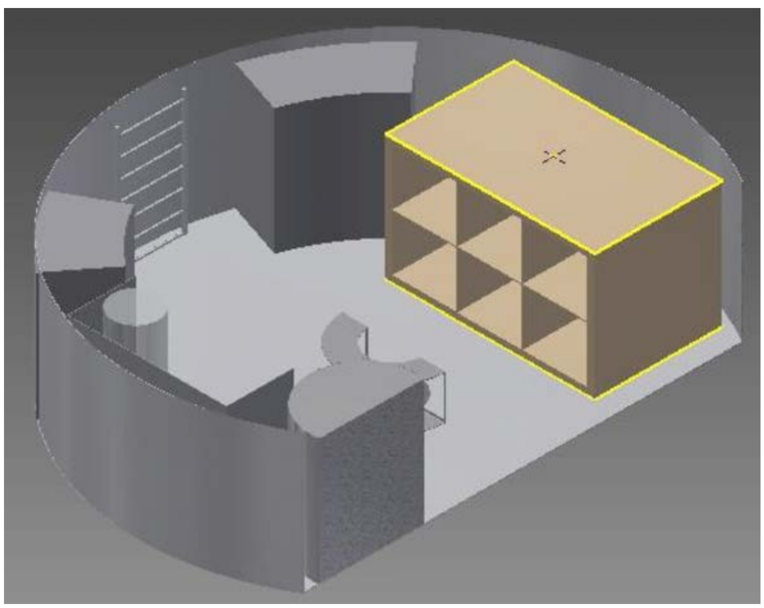

Figure 9. Final interior layout of living quarters level chosen with virtual reality walkthroughs

B. Virtual Reality Window Study

One application to which virtual reality is ideally suited is simulating the visual effect of rotation which will be perceived by POLUS crewmembers during periods of artificial gravity. It was important to understand whether or not this effect has a tendency to induce motion sickness, and, if it did, whether or not the location of windows relative to the plane of rotation correlates to the degree of motion sickness experienced.

To accurately reproduce this situation, a habitat simulation of an empty room with windows on all sides was furnished in UDK (for porting to the Oculus Rift) and surrounded by a rotating sphere onto which a virtual star-field was superimposed. The sphere was made to rotate at 23.76^{o}/sec about the local horizontal axis and centered at the habitat section. For an observer inside the habitat section, this created a visual effect indistinguishable from what would be experienced if the habitat was rotating at 4 revolutions per minute and the subject was observing stationary stars with respect to the inertial frame.

Four subjects participated in two different tests. The first one had a high density, high intensity star field, and simulated one level of the rotating habitat with three different window positions relative to the rotational plane of the space station: in- plane of rotation, off-plane of rotation and diagonal. Since the virtual star field used in the first test was not representative of what would actually be seen from a space station in cislunar space, another test with diminished star brightness (0, 0.002 and 0.005) and adding the Sun, Moon and Earth was conducted. To evaluate the tests, the Motion Sickness Assessment Questionnaire (developed by the Department of Psychology, Pennsylvania State University) was used.

The study shows that the diagonal windows (at 45^o to the direction of rotation) caused the lowest degree of motion sickness. When dealing with a lower star field density and brightness, the motion sickness decreases, as shown in Figure 10. Although not captured in the data collection protocols, one of the most striking visual aspects of this study was the effect of the bright Earth, Moon, and Sun through the windows of the rotating habitat. Beams of light from the direct sources of the three illuminating bodies passed through the windows and illuminated a similar-shaped section of the interior surface, and the "light beams" rotated around the interior of the habitat approximately four times per minute. This effect tended to dwarf the visual impact of everything else in the virtual reality presentation, and led to speculation that windows may not be desirable in rotating space stations, at least in living or working volumes.

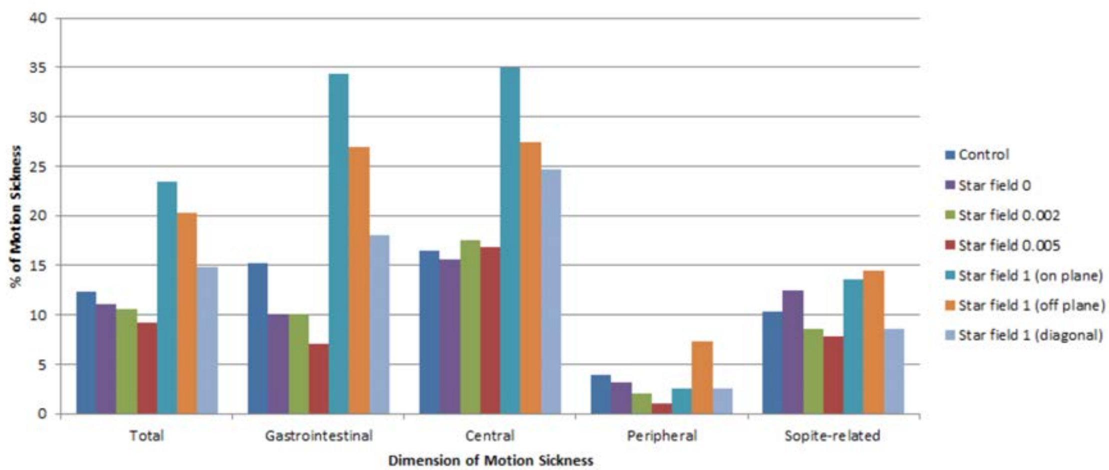

Figure 10. Motion awareness results from virtual reality simulation of windows in a rotating station

C. 1-G Habitat Mockup Development Activities

It was decided to focus 1-G habitat studies on HAVEN, the 5-meter diameter habitat mockup, due largely to its modular design features and larger diameter than ECLIPSE. HAVEN was originally designed as a two-level habitat, and still has the scarring for adding the upper level; an analysis showed that attempting to add the upper floor would not be practical as part of X-Hab 2014 study and still leave time and resources for testing, so the decision was made to limit testing to the existing level of the habitat. Outfitting of HAVEN was further complicated by the fact that it is located outside, and the 2014 winter was one of the snowiest on record in the mid-Atlantic region. Despite this, the habitat was refurbished and outfitted for analog testing, focusing on multi-person operations in restricted volumes/areas.

HAVEN had not been used actively since the completion of X-Hab 2012, and 20 months had passed before the 2014 X-Hab team was ready to begin restoring and using the facility. Its initial external condition is shown in Figure 11, with severe weathering to the exposed wooden walls despite the selection of outdoor-rated materials. A number of leaks from unsealed gaps in the modular removable wall segments, as well as in the roof which was weatherproofed only with a tarpaulin, caused severe interior degradation which necessitated some removal and replacement of interior components. The gaps around the modular wall segments were sealed with an expanding foam product, and the entire exterior was covered with two coats of paint. Doors for the three existing hatches were completed, and the hatchways were fabricated and installed along with the doors. The interior was cleaned up, and an additional work surface was built into the unit. The final stage of the HAVEN habitat is shown in Figure 12.

Figure 11. HAVEN habitat exterior before refurbishment

Figure 12. HAVEN habitat exterior after refurbishment

D. 1-G Habitability Assessments

After restoring the HAVEN habitat mockup to a functional status, the ENAE 484 senior capstone design class used the habitat to investigate the role of crowding and noise in habitability. Since HAVEN is currently limited to a single level, and the IRB research approval did not cover overnight study durations due to safety concerns, the focus was on the provision and use of common work and living areas, rather than sleeping quarters or other private volumes. To this end, the test operations were restricted to one side of the divider in the current interior, which was a half-circle of 2.5 m radius.

Test subject populations ranging from one to four were tested in the 10 m^2 floor area/20 m^3 volume of the public work side of the current HAVEN layout. Test duration for each case was set at one hour, and the subjects stayed until the end of the four-case sequence. Thus, the test subject who started the first hour as a solo occupant (Figure 13) would also participate in the cases of 2, 3, and 4 occupants (Figure 14). Habitat operations to be conducted included computer interactions with the remote monitoring personnel, simple science experiments, preparing and eating a light meal, and performing the assembly of new storage hardware (commercially available shelving units.)

Figure 13. Habitat operations with solo test subject

Figure 14. Habitat operations with four test subjects

The tests conducted by the students during X-Hab 2014 were pathfinders for more elaborate 1g habitat testing planned in the near future. The operations for the subjects were relatively contrived, and did not require substantial interaction between test subjects other than the pairs collaborating on constructing the shelving units. None of the tasks required time-critical responses, and there was no structure to the tasks related specifically to their presence in a simulated space habitat. Subjective evaluations of the test subjects tended to be maxed out at the positive end of the spectrum, which did not provide much insight into the habitat design or operational performance. A fixed wide-angle camera captured sequential images every half-second for reconstruction of subject motions and interactions in the limited volume, but its utility was limited due to the stark lighting from exterior windows along. The test also had to be interrupted to deal with a nest of hornets inside the habitat which made themselves known suddenly in the middle of the three-person test.

For future tests, greater attention will be paid to creating a logically consistent scenario for habitat operations. A simulation program is currently under development to model habitat operations, with provisions for introducing simulated system failures with time-critical implications. The habitat will be modified to increase the fidelity of the simulation, including additional hardware elements representing habitat systems to be monitored, operated, and repaired upon (simulated) need. Higher bandwidth connectivity between the HAVEN module and the NBRF control room will allow for both real-time monitoring and interactions between the “flight crew” and “mission control”, providing additional structure to the simulation.

Data collection will likewise be advanced beyond Likert-scale subjective questioning. The NASA Task Load Index (TLX) will be used to obtain individual assessments across the various workload indices, and tasks will be designed to allow quantification of performance. Simulation activities will be bounded in time, but no specific duration will be established, allowing the use of individual and aggregate completion times as a performance metric. In addition, the interior layout of the habitat will be varied to investigate the impact of architecture on crew performance.

E. Habitat Interior Robotics

The University of Maryland Space Systems Laboratory has decades of experience in developing and operating dexterous manipulators and free-flying vehicles for space, most of which were designed to function in the underwater simulation environment. Given multiple existing robotic systems, it was logical to incorporate some aspects of human/robotic collaboration into the X-Hab 2014 habitat studies. Under the MERIT scholarship program, a group of four first-year women engineering students were mentored by SSL personnel on a project to develop a ceiling-mounted dexterous manipulator to perform autonomous robotic tasks, and to support human crews in collaborative tasks. This system is designed around a linear ceiling-mounted track running from the center of the habitat to the periphery, and capable of being rotated through 360^o to reach any internal segment of the habitat floor in which it is mounted. The arm itself is driven in translation along the radial ceiling track to allow positioning anywhere in the ceiling area; linear actuators drive successive pitch joints on the arm itself, and rotary actuators allow wrist pitch and roll. Along with the ceiling track rotation and linear traverse of the arm mount, the overall system provides a full 6 degree-of-freedom (6DOF) control of the end effector state throughout the entire volume of that level of the habitat. This system, shown in Figure 15, is being prototyped in the lower level of ECLIPSE, due to reduced system requirements of that habitat’s smaller diameter, and also due to lower usage of ECLIPSE since all of the other X-Hab 2014 1-G activities are focused on the HAVEN module. The ceiling-based robot was not completed during the X-Hab 2014 active period, but the development will continue without external support until completed.

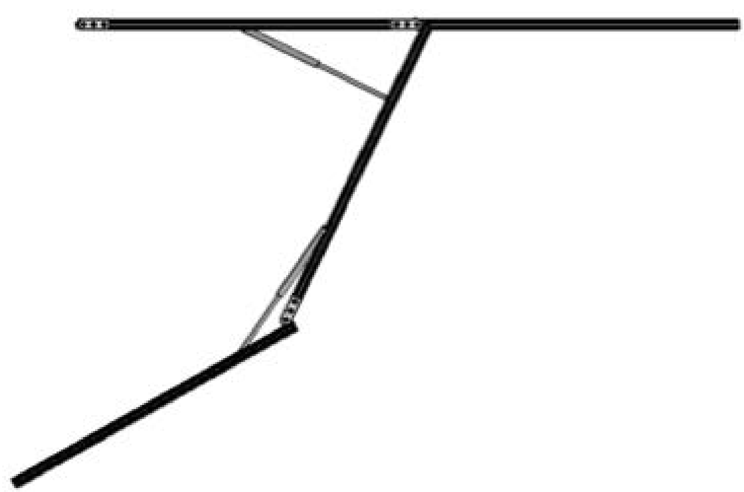

Figure 15. Side view of ceiling-mounted manipulator

IV. Neutral Buoyancy/Parabolic Flight Habitat Studies

A. Underwater Habitat Mockup

No prior mockups were available for underwater testing; habitat design in this environment is limited by the need to allow emergency egress to the surface from any location inside the habitat at any time. Rather than develop a full habitat structure, the decision was made to create a simple trusswork structure which defines the pressure hull of a habitat, without greatly limiting access to the surface. As shown in Figure 16, the habitat structure was developed based on commercially-available 1.5 inch PVC plumbing pipe and associated fixtures. This allowed the creation of an octagonal structure five meters in diameter and five meters high, including a representation of the conical end cap and common berthing mechanism pass-through-sized hatch of the International Space Station. In effect, the truss structure represents the mold line of one-half of an ISS laboratory module. As a way of expanding the opportunities for student involvement in this research, the design and construction of the underwater habitat truss was performed by a team of five first-year students in the UMd ENAE 100 "Introduction to Aerospace Engineering" course.

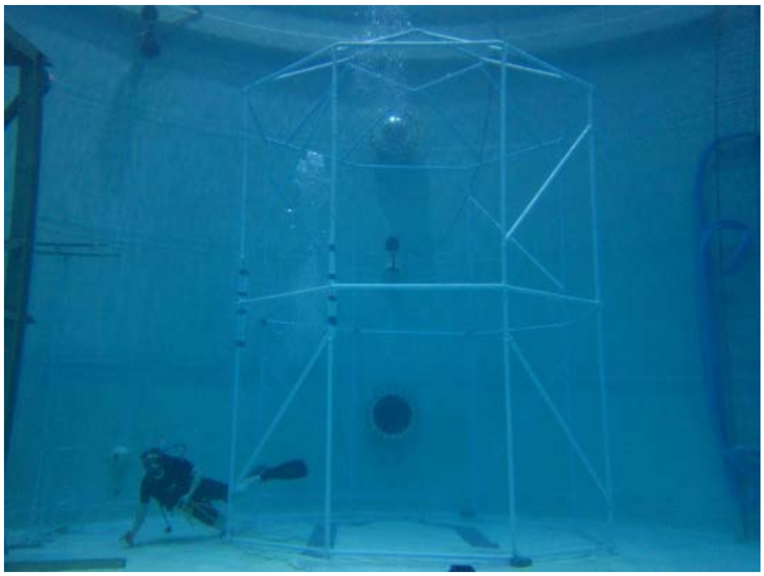

Figure 16. Underwater habitat pressure hull representation in NBRF tank

One of the major objectives for the underwater testing was to directly compare horizontal and vertical orientations of the cylindrical habitat shell in various gravity conditions. While the PVC structure can be oriented in either orientation underwater, it is too weak to support loads induced if it were to be used as the structural support for test hardware such as simulated racks or other flight systems. For this reason, a structural "deck" platform was designed to be built from fiberglass-extruded I-beam material and fiberglass panels. The resultant planar structure will not corrode in the underwater environment, but will support the weight of test subjects loaded to varying gravity conditions, as well as all needed test hardware. The three-meter tall deck structure fits inside the habitat truss structure in the vertical orientation to form an upper deck, with the lower deck area formed by the bottom of the tank (Figure 17). The deck structure also forms the basic floor area for the habitat in a horizontal configuration; in this case, the external hab truss structure is raised to place the deck at the appropriate level interior to the structure based in ISS interior layouts (Figure 18).

While the material for the deck platform was scavenged from older mockup hardware to save money, it became clear that the allotted time for this research program would require either building hardware or performing experiments. Favoring the development of useful data, the construction of the deck platform was put in abeyance pending the completion of the first round of underwater human factors experiments, which would inform the specific design of the final structure to ultimately be built.

B. Variable Gravity Simulations

Of all future environments for human space exploration, planetary surfaces such as the Moon and Mars are the least understood. With a total human history of less than two weeks on the Moon, accumulated no more than three days at

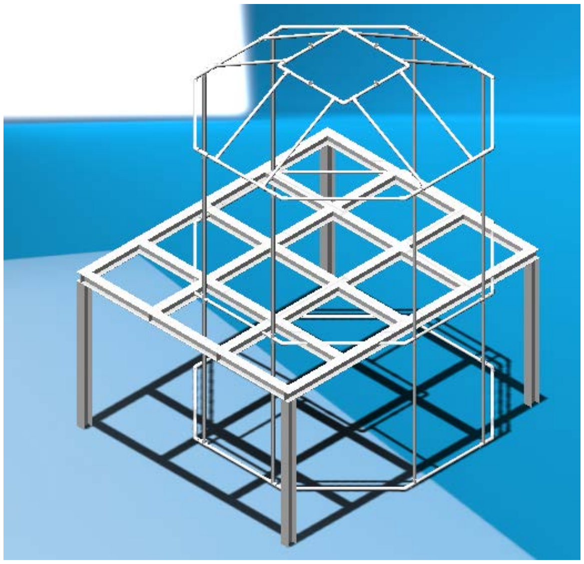

Figure 17. Structural deck in underwater hab (vertical orientation)

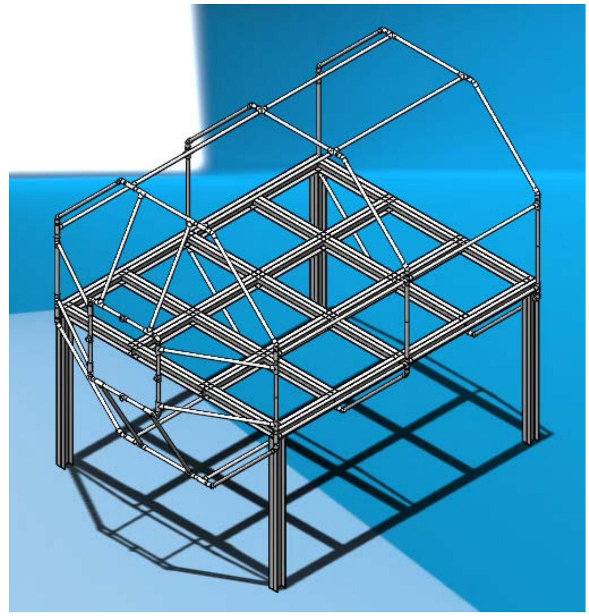

Figure 18. Structural deck in underwater hab (horizontal orientation)

a time, little substantive data exists to support a methodology for habitat design at 1/6 G. Things are clearly worse for Mars, with no experience whatsoever on living and working at 3/8 G. In neither case is there any data on long-term effects of partial gravity on human physiology, or on the optimum design for partial gravity habitat in either the near or long term.

Short of a variable-gravity space station of the type designed by the UMd ENAE 484 class, one of the best analog simulation environments for better understanding partial gravity is ballasted underwater simulations. Body segment parameter data is used to ballast the human body at the torso (generally including the mass effects of the head), upper legs, and lower legs, as per the distribution listed in Table 1. Upper and/or lower arm segments can be proportionately ballasted as well, although they generally only require one or two kg, and have been left unencumbered in these studies to eliminate the restriction of weight systems on arm motions. Figure 19 shows the addition of ballast to torso packs, which are mounted on the front and back of the test subject. Figure 20 shows the same process for the leg, and illustrates the incorporation of retroreflective markers for the Qualysis 12-camera motion tracking system in the NBRF. Figure 21 shows a ballasted test subject walking on an underwater treadmill, using motion capture to quantify gait and fundamental dynamics. Analysis indicates that quasi-static tasks such as walking on a treadmill provides realistic motion with a minimum of hydrodynamic drag interference.[5]

Table 1. Distribution of planetary body weight for underwater simulation

Weight Location	Weight Distribution
Front torso	31%
Back torso	31%
Left thigh	13%
Right thigh	13%
Left calf	6%
Right calf	6%

Figure 19. Adding ballast weight to test subject's torso

Figure 20. Ballast packages and retroreflective tracking targets for lower limbs

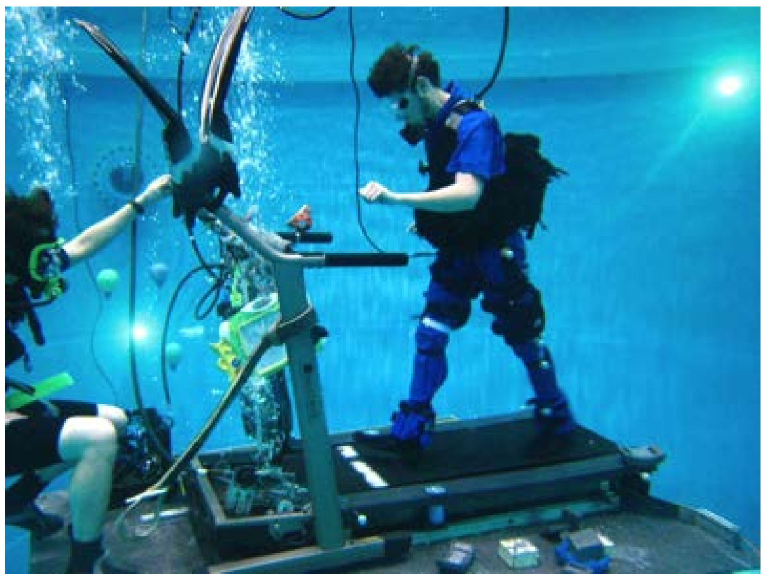

Figure 21. Underwater gait analysis of ballasted test subject at lunar gravity. Note lights from motion capture cameras used to illuminate tracking targets for position measurements.

C. Habitat Interior Robotics

Under support from DARPA and NASA, the University of Maryland recently completed the initial development of Exo-SPHERES, a free-flying robotic system designed to operate external to ISS for operational sorties up to eight hours in duration. As part of this program, the SSL also developed EUCLID, an underwater full-scale version of Exo-SPHERES for use in neutral buoyancy simulations. Figure 22 shows an image of EUCLID being remotely controlled to fly interior to the underwater jab mockup,simulating flight activities including maneuvering the vehicle through the common berthing mechanism hatch-sized passageway at the top of the habitat mockup when in the vertical orientation. EUCLID was used in conjunction with microgravity test operations in the underwater habitat to provide remotely-commanded views of the test operations, and to investigate the interactions of the free-flier and human subjects in the restricted habitat volume.

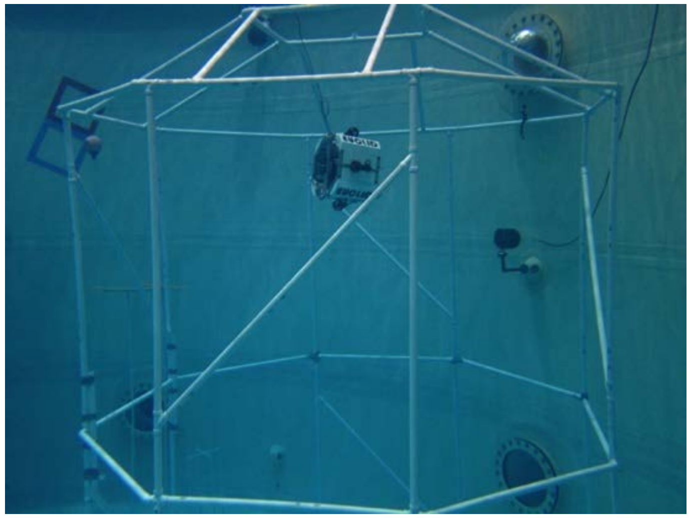

Figure 22. EUCLID vehicle performing controlled flight inside the underwater habitat mockup

D. Underwater Work Stations

One of the major challenges of underwater testing is the ability to provide meaningful tasks for test subject performance within the restrictions of the underwater environment. To this end, the UMd team developed a test protocol based on the use of tablet computers (iPads) in underwater housings to represent tasks for habitat test subjects. Initial testing demonstrated that the commercially-available underwater housings did, indeed, provide protection to the tablets, which ran the preloaded application throughout the test series (Figure 23). However, the effects of water pressure and capacitance saturated the touch screen, making all attempted touch command interfaces unusable. These results have delayed the availability of the interactive underwater control stations pending the development and testing of a more elaborate system, incorporating liquid crystal displays in a waterproof housing, along with underwater-functional switches, knobs, and buttons for test subject input. In lieu of operational underwater computer work stations, simulated work stations using laminated static images were adopted for the early test series.

Figure 23. Tablet in waterproof housing during initial operational testing

E. Multilevel Mobility and Human-Robot Interaction in Microgravity

The underwater habitat outer envelope truss structure was used to investigate mobility inside the habitat, as well as potential collaboration between a human test subject and a remotely controlled free-flying robot. A set of six simulated control panels were placed around the interior of the habitat mockup for the second set of tests. Each panel contained either images of gauges and switches, or a 5x5 table of numeric data values. The goal of this test was to assess mobility interior to a habitat for both the human and the free-flying robot. A test director, acting as ground control, gave the subject a task, such as, Go to Panel 3 and verify that slide switch B is on setting 4. When the task was complete, another task was given until all six were completed. The task panels were distributed evenly at 120 intervals around the vertically-oriented cylinder, with one set three meters vertically above the other. These tasks required the test subject to traverse around and along the habitat, which was done by using the frame structure as handrails. The times for each task and total sequence time were recorded.

EUCLID performed the same set of tasks in the same order and, as expected, took more time to complete the series of tasks. As Tables 2 and 3 show, one sequence took EUCLID twice as long as the IVA human subject, and the second sequence took it three times longer. Some individual tasks had high variations in repeated performance by EUCLID; these were when the remote operator had trouble locating the panel with the onboard cameras, which have limited fields of view and only face forward and aft. These tests demonstrated that EUCLID needs much wider-angle lenses on the cameras, and a larger number of cameras to enhance situational awareness. Despite the longer completion times for EUCLID as compared to the human IVA test subject, on orbit this would still free up the astronauts to perform other tasks.

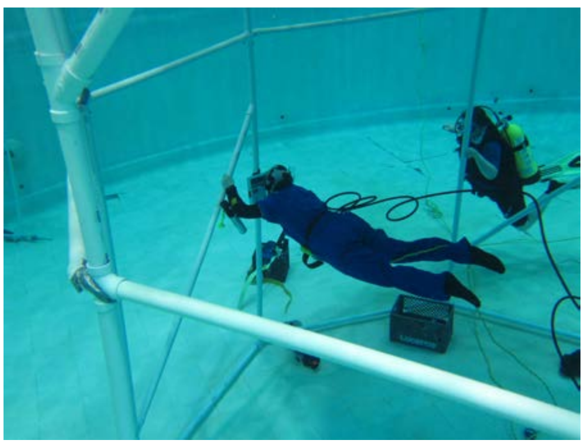

Figure 24. Human test subject checking simulated test panel

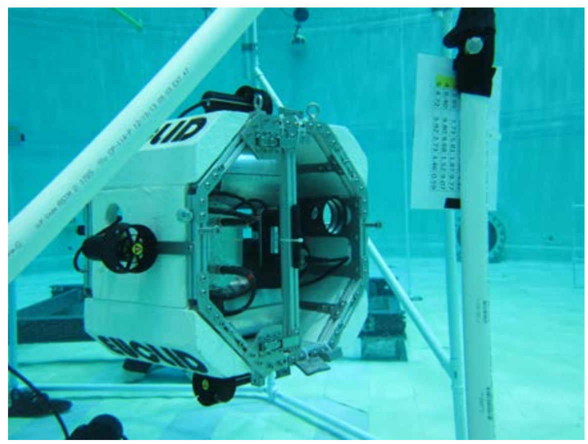

Figure 25. EUCLID providing view of simulated test panel

Table 2. Task times for first sequence in underwater habitat mockup

Task Set 1	Human solo	EUCLID solo	Human/EUCLID
Panel 1 - read value	11.1	8.3	17.6 (human)
Panel 4 - check switch position	18.5	64.4	16.7 (human)
Panel 2 - check switch position	32.5	62.6	20.6 (human)
Panel 5 - read value	22.4	41.7	15.0 (EUCLID)
Panel 6 - check switch position	24.5	50.2	11.4 (human)
Panel 1 - check switch position	28.5	42.6	22.9 (human)
Total time (seconds)	137.5	269.7	104.1

In the second part of this test, the astronaut and EUCLID worked collaboratively to complete the series of tasks as a team. EUCLID and the IVA crew were each given tasks to do independently, with the next task in sequence given to the first agent (human or robot) which completes the current task. For the first sequence, EUCLID performed one task while the human completed the other five; overall, the human-robot team finished quicker than when the human performed the tasks alone. In the second task sequence, EUCLID finished in time to be given a second task, which led

Table 3. Task times for second sequence in underwater habitat mockup

Task Set 1	Human solo	EUCLID solo	Human/EUCLID
Panel 1 - read value	5.9	6.7	10.4 (human)
Panel 2 - check switch position	15.2	50.0	22.2 (human)
Panel 3 - check switch position	32.9	37.6	20.1 (human)
Panel 5 - read value	36.7	177	14.3 (EUCLID)
Panel 4 - check switch position	23.6	48.7	79.7 (EUCLID)
Panel 1 - read value	7.7	37.5	16.1 (human)
Total time (seconds)	121.9	357.5	162.8

to the human subject being done with the other four substantially before EUCLID finished its second. This sequence took somewhat longer overall than the case for the human alone, but was still much more productive than with the robot alone. The test subject reported that they had no problems with a robot flying in the same space, and that they barely noticed the vehicle, since they were traveling around the outside whereas the robot traveled in the middle.

While these tests clearly indicated that a free-flying robot could be beneficially used both alone and in collaboration with humans inside the habitat mockup, the research team plans to increase the fidelity of the testing for future similar studies. The original intent was to have interactive task boards using iPads in waterproof housings; while the housings did protect the tablets, the water pressure prevented the touch screen system from registering any level of touches at all. Future task boards have been designed with LCD screens for data readouts and waterproof physical buttons and switches for user inputs. In addition, a planar structure is under construction to provide a "floor" inside the habitat, which is adaptable to serve as a habitat floor for a horizontally oriented cylinder (e.g., ISS) or for a vertical orientation (e.g., Skylab). This will allow the provision of through-deck passages of various sizes, shapes, and locations, and will increase the fidelity of the habitat simulation. It is also planned to extend these tests to multiple humans, both with and without robotic augmentation.

F. Neutral Body Postures in Varying Gravities

Workstation design is predicated on some repeatability in neutral body posture, which has been repeatedly shown to substantially differ in microgravity from 1-G. No data of any sort exists on neutral body posture in gravity levels between 0-G and 1-G. To address this, the University of Maryland performed a series of investigations of neutral body posture in varying gravity levels. Test subjects were directed to fully relax while reading a piece of paper held in their hands, with body restraint provided by a pair of "toe-loop"-type foot restraints. Subjects were breathing from a "hookah" rig, with a 5-meter hose between the subject and the remote scuba air supply, to remove the mass and apparent weight of the air tank from their body. The subject adjusted their overall buoyancy to achieve neutral buoyancy; for lunar and Mars gravities, appropriately scaled ballast weights were added to pouches on the test subject's front and back torso and upper thighs, and to weight belts around each ankle. Body pose was captured by orthogonal underwater cameras, as well as tracked in real time by the Qualysis motion tracking system using optical targets mounted on the torso and each major limb segment. Examples of neutral body posture at each gravity level for two test subjects are shown visually in Figure 26, and postural data from the motion tracking system is shown in Figures 27 and 28.

To date, two subjects have been tested across all three gravity levels. A number of issues have been identified, such as the use of wet suits (due to a breakdown in the NBRF tank heater) affecting the neutral position of the limbs. Also, all subjects expressed apprehension when testing at the microgravity data point, as the toe loops did not provide positive restraint, and they were uncomfortable with being unrestrained in the water without some amount of downforce to prevent "floating off". These tests will be repeated with a larger number of test subjects when the tank heater is repaired and the water temperature is high enough to make wet suits unnecessary. The revised test sequence will use modified molded in-line skate boots with EVA foot restraint-compatible interfaces to allow positive retention of the subjects' feet during the neutral body pose.

In a related test, the subjects were directed to perform a maximum-effort standing hop from the neutral body position. Past SSL studies have analyzed potential biomechanics of jumping motions in various gravity levels as a way to ascertain desirable ceiling heights in habitats on the moon and Mars. Tests were inconclusive, as the subjects

Figure 26. Neutral body posture in simulated microgravity (left), lunar (center), and Mars (right) gravity levels

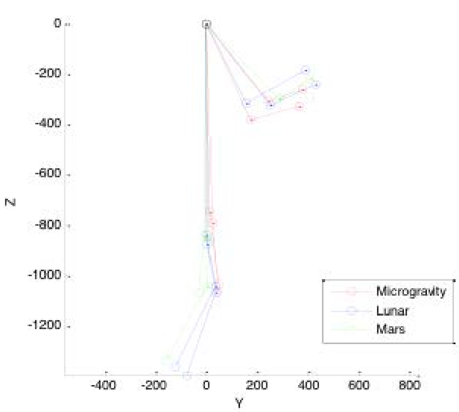

Figure 27. Side view of test subject digitized pose

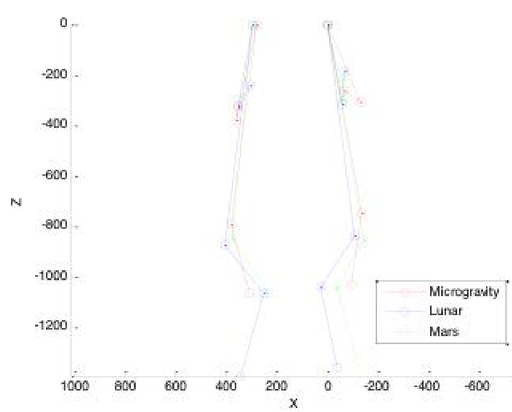

Figure 28. Front view of test subject digitized pose (note leg displacement due to rotation of knee optical marker to the front of the leg)

were reluctant to jump at anywhere near their maximum capacity given their training as scuba divers to restrict ascent rates for safety. These tests will be repeated under more controlled circumstances, including a tether to limit motion to no more than a meter or so of travel off of the bottom of the water tank. The use of the motion capture system will allow the direct measurement of jumping velocity at the point of separation from the floor, which is the desired data for more accurate biomechanics models of both jumping and various gaits in microgravity.

G. Multi-Level Access Studies

A significant issue for multilevel habitat design is the access between levels, and how the optimal form of interlevel transport varies based on gravity conditions. Using the underwater habitat deck structure described above, subjects were asked to translate up and down between the floor of the NBRF tank and the deck, a vertical difference of three meters. Systems to be tested include vertical ladders, ramps, and stairways of varying steepness. The interlevel translation tasks were performed at microgravity, lunar, Mars, and Earth gravity levels.[1] Since an important reoccurring task is to transport materiel between levels, the tests were repeated while the subject carried a "filled" CTB, ballasted to reflect the appropriate apparent weight for a CTB with a mass of 32 kg.

For the initial series of tests, climbing was performed using the vertical egress ladder secured to the wall of the NBRF tank, and an aluminum extension ladder secured to various rungs of the vertical ladder to represent different slopes. After some experimentation, tests standardized on 90° (vertical, Figure 29), 67° (Figure 30), 57° (Figure 31), and 35° (Figure 32) angles. Since these tests proved to take more than two hours and were physically taxing to the test subject, the 67°case was later dropped, as it was deemed to be too similar to the vertical ladder to justify a separate test series.

Figure 29. Descending a vertical ladder in microgravity carrying a CTB

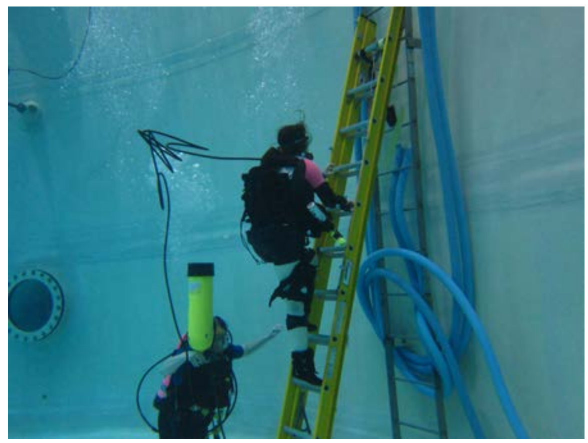

Figure 30. Ascending a 67° stairway in Mars gravity

Figure 31. Ascending a 57° stairway in Mars gravity carrying a CTB

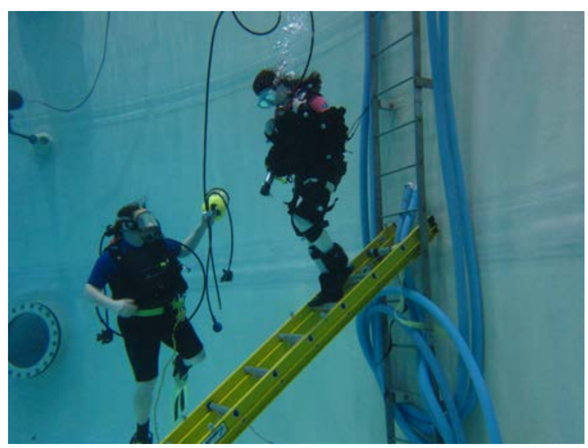

Figure 32. Descending a 35° stairway in Mars gravity

[1]As an aside, it is an interesting coincidence that the ratio between lunar and Mars gravitational accelerations is 2.4, nearly identical to the ratio between Mars and Earth gravities which has a value of 2.6.

Based on observation and post-test debriefing of the test subjects, all ladder access angles were feasible for interdeck transit. Subjects tended to behave more similar to vertical ladder climbing as body forces increased, whether due to increasing simulated gravity levels or increased downforce due to a CTB payload, or both. Earlier tests had indicated that, in lunar gravity, a typical interdeck vertical transit could be performed by having a single intermediate platform to break the upwards transit into two "hops". These more extensive tests demonstrated that, as total downforce increased, the tendency of the subject was to shorten strides to more closely approach conventional step intervals in Earth gravity. Thus, while a single intermediate platform might be adequate for a well-conditioned test subject without external load under lunar gravity, carrying supplies or other items upwards would be better facilitated with more conventional stairs or a vertical ladder.

For the case of the vertical (90^o) ladder (Figure 33), the test subjects only used their hands for transport in microgravity, and rarely used their feet except occasionally when transporting a payload up or down. Subjects noted that a vertical rail or handrail would be sufficient, rather than the full ladder with cross-rungs. Subjects could also pull themselves along the ladder under lunar gravity, although the use of feet and the ladder cross-rungs were more prevalent. Some subjects though it was easier to pull themselves in lunar gravity than microgravity: they could more easily adjust the force they needed, and didn?t have to worry about going too fast. However, subjects also generally used the rungs and their feet to climb. One subject reported that, "My favorite method of traversal was climbing normally, just faster and with less effort. I could skip rungs if I wanted to, but not skipping was easier and more stable." Climbing a ladder in Mar?s 3/8 gravity was very similar to climbing a ladder in earth gravity: all test subjects climbed the ladder like one would on earth, using hands and feet. Test subjects did not seem to have a problem with skipping or missing rungs.

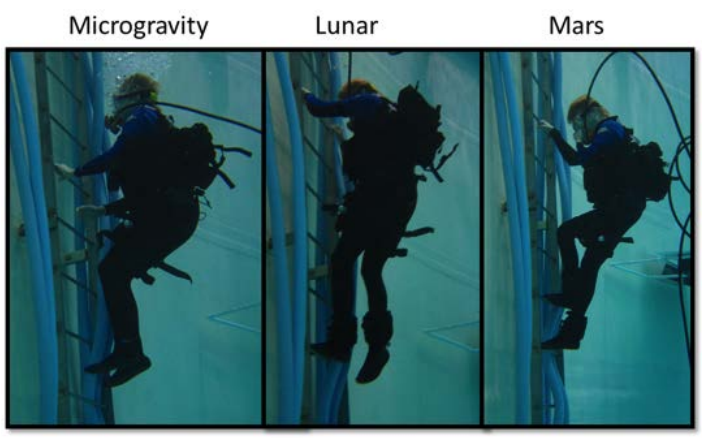

Figure 33. Climbing a vertical ladder in simulated microgravity (left), lunar (center), and Mars (right) gravity levels

The 67^o ladder case, which is approaching the upper limit of "steep ship's ladders" on Earth, was functionally identical to the vertical ladder for lunar and Mars gravities. Subjects tended to climb the ladder using both hands and feet, and strongly preferred descending while facing the ladder. The addition of the CTB ballasted to full Mars weight was destabilizing, and subjects adopted a single-handed "quick grab" strategy for climbing with one hand occupied by the CTB. (Subjects also complained about the weight of the CTB, and the fact that the fabric bag deformed under the ballast weight, making it even harder to carry.)

The 57^o ladder represented a transition case between a staircase/ramp and a vertical ladder (Figure 34). Subjects could ascend using only their legs and descend facing forward and away from the ladder, but only with some care; the preference (particularly in Mars gravity) was definitely to ascend using hands and feet, and to back down the ladder in the same manner. At lunar gravity, the subjects were more comfortable with descending facing forward, particularly when carrying the CTB. (Subjects were much more comfortable with CTB transport at lunar gravity than they were at Mars.)

The 35^o stairway (Figure 35) was much more similar to a terrestrial staircase or ramp, with subjects ascending and descending facing the direction of travel. This allowed easier use of both hands for transporting the CTB, and the test protocol in all cases asked the subjects to perform both single-handed and dual-handed transport of the CTB when it could be safely accomplished.

Test subjects were asked to carry an appropriately ballasted cargo transfer bag (CTB) as they climbed the ladder.

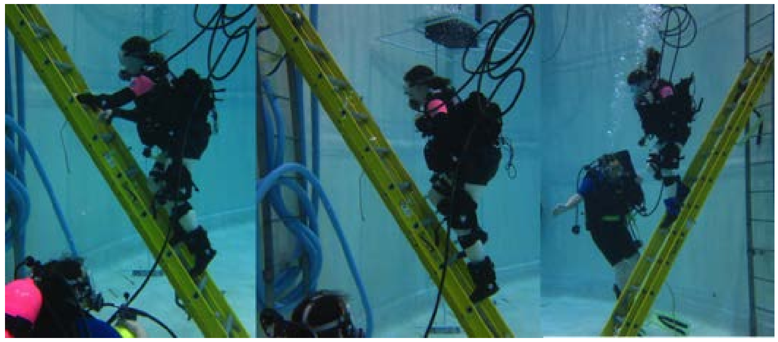

Figure 34. Climbing a ladder at 57° angle under lunar gravity. Conditions include climbing with both hands and feet (left), feet alone (center), and descending facing outwards on ladder (right).

Figure 35. Climbing a ladder at 35° angle under lunar gravity.

The test subjects were asked to carry the CTB both using a handle with it hanging down by their side, like a brief case, and using two handles with the CTB horizontal in front of them, like carrying a box. It should be noted that the weight in the CTB was not evenly disturbed, and was able to shift as it was tilted.

Test subjects were able to carry the CTB on the ladder under all three slopes. Subjects reported that the heavier gravities took more effort, as was expected. In general, the subjects preferred to carry the CTB with a single handle. This may have been a result of an uneven weight distribution that shifted as they tilted the CTB in the two-handed carry; however, it is likely that CTBs or other cargo bags would be packed for flight to preclude mass shifting, as well as deformation of the bag shape under load.

Figure 36 is an image of a test subject carrying a CTB up a 35 sloped ladder in Mars gravity. Starting the climb, the subject slipped and had to grab the ladder to steady himself. From there he proceeds with caution, turned around at the top, and walked down. The Qualysis data in Figure 37 shows the motion of the tracking targets on the subject's body during the climb. The test subject later repeated this test without turning around, going down the ladder facing the ladder rather than the direction of motion. The climb down in that case was slower and more cautious.

Unlike the previous case carrying the CTB by the handle one-handed, the subjects demonstrated less stability transporting the CTB two-handed like carrying a box in front of them. While climbing the ladder holding the CTB flat, test subjects were less steady since it was harder to see the steps. As shown in Figure 38, one test subject fell off the ladder and had to start over; the motion capture data of the same event as can be seen in Figure 39. It should be

Figure 36. Climbing a ladder at 35^o angle under Mars gravity while carrying a loaded CTB

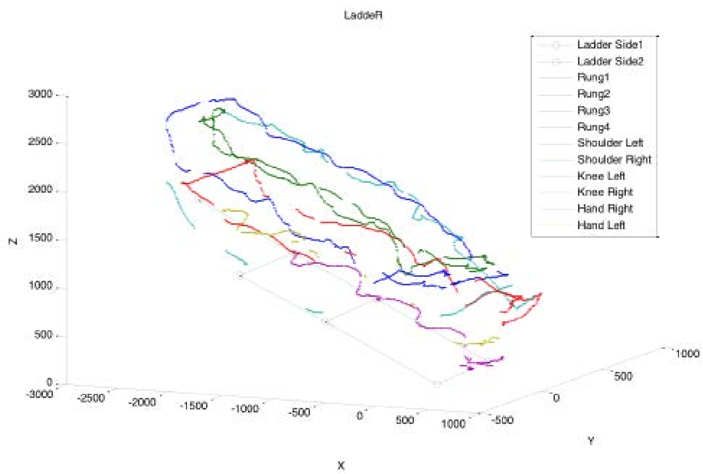

Figure 37. Climbing a ladder at 35^o angle under Mars gravity.

noted again, the fully loaded CTB is not an insignificant amount of weight, particularly in Mars gravity.

Transport in all cases in microgravity was generally performed with the hands, as the feet do not provide a positive restraint in the absence of downforce. It was clear that the vertical ladder is preferred in microgravity, as it provides the minimum translational distance from one level to another, and does not require rotating the body forward to grasp a low-angle ladder. Translation was generally accomplished with a pull-and-drift strategy, which required more frequent intervention underwater than it would in space due to hydrodynamic drag.

Vertical transport in lunar gravity was much less structured than Mars or Earth, with the test subjects frequently skipping one or more steps on ascent, and sometimes coasting downwards without using the feet while controlling descent rate with the hands alone. With the addition of the requirement to transport the loaded CTB, the subjects tended to resort to a more conventional ladder-climbing strategy, although some evidence of “fireman’s pole” descents down the vertical ladder were still seen.

The preliminary results from this testing indicate that the best architecture for moving between different levels is a function largely of downforce, induced by a combination of local gravity and additional payload transported. It was always clear that microgravity differs greatly from Earth norms; what was surprising is that lunar and Mars gravities not only differ from microgravity, but from each other as well. More structure is clearly needed to allow crew to move themselves and cargo between levels in lunar gravity than microgravity, which really has no transport infrastructure required beyond a plethora of planned or impromptu grasp points. However, lunar gravity is low enough that it has more similarity to microgravity than to Mars gravity, which if anything would seem to be well served by traditional Earth-based architectures.

The Qualisys underwater motion tracking system was used to quantify body motions, but the data has proved difficult to reduce due to the proximity to the tank wall, reducing the number of cameras with functional views of the test setup. When the underwater habitat structural platform is completed, these tests can be moved into the center of

Figure 38. Climbing a ladder at 35^o angle under Mars gravity while carrying a CTB horizontally. Left, subject falls off the ladder; right, subject descending cautiously.

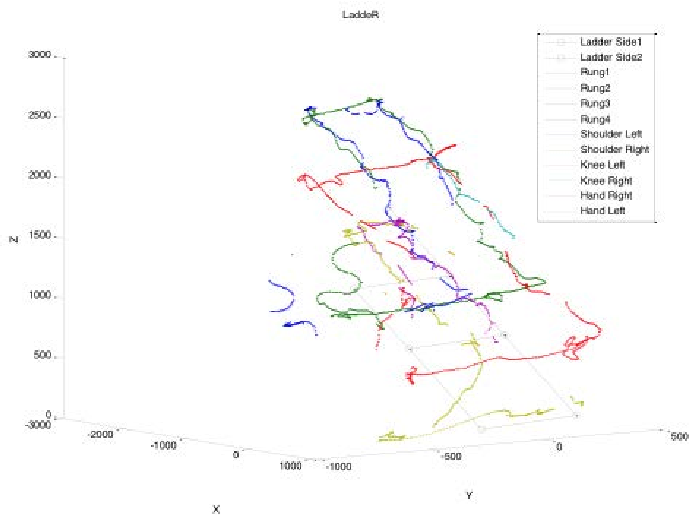

Figure 39. Qualisys motion capture data for event shown in Figure 38

the tank, providing visual access to the entire camera system. An additional four Qualisys cameras were procured and recently installed, bringing the system up to 16 cameras, which should provide high-resolution measurements throughout the tank volume.

It appears that, of the cases tested, a ladder at a 57^o slope is preferred to a 35^o or 67^o slope, or a 90^o vertical ladder. Subjects were able to climb a ladder at 57^o holding a CTB with two hands, which they were unable to do on a 90^o ladder. Test subjects had difficulty on the 35^o slope and felt the need to watch their feet, to ensure they weren?t missing a rung. When unable to watch their feet, subjects had more difficulties climbing the lower angle ladder and stumbled more, and even occasionally fell.

The testing to date has used the vertically mounted ladder on the tank wall and a commercially available extension ladder, both with a 12-inch rung spacing. The ideal test hardware for this study would be a ladder with variable rung spacing and slope angle, designed to transition between the tank floor and the habitat deck. While a number of designs have been considered for this, the overhead required to change rung spacing and ladder angle in the middle of a test run have been deemed unworkable. The current plan is to focus in on 2-3 different ladder designs, and fabricate specific structures for testing each. These will include handrails, which are required by code for steep stairways on Earth, but have not been implemented in the tests to date.

H. Random Access Frame

As an additional detailed test objective under X-Hab 2014, the Jet Propulsion Laboratory (JPL) developed and supplied to the SSL a prototype “random access frame” (RAF) for habitat storage. As shown in Figure 40, the frame was outfitted with two flat panels mounted via wheeled tracks, which can be manually moved back and forth at will. Early systems testing identified some issues with the implementation of the track system, which had to be rectified via the use of modified track mounting hardware.

Figure 40. JPL Random Access Frame for logistics stowage

1. Slider Calculations

After many attempts to find configurations of the wheeled tracks that did not bind when sliding the RAF panels, inear sliders from 80/20 were used instead of wheels. These sliders held the structure in place, and resisted moments better than the wheels. The sliders were placed on the ends of a bar, spreading them apart. Spreading the sliders apart ensured the structure would slide rather than tip when a force was applied. The length of these bars was determined using the following derivation, based on the geometry of the divider as shown in Figure 41.

The moments at the corner results in the equation (1). The $F_{gravity}$ term is due to the mass and $F_{applied}$ is due to the force required to push the divider.

$$F_{gravity} * a - F_{applied} * h > 0 \quad (1)$$

It is assumed the restraining forces on top are zero. This is a conservative estimation, as this would only occur in the worse case. This also implies that the friction forces on the top are also equal to zero.

$$F_{restrain1} = F_{restrain2} = 0 \quad (2)$$

$$F_{friction1} = F_{friction2} = 0 \quad (3)$$

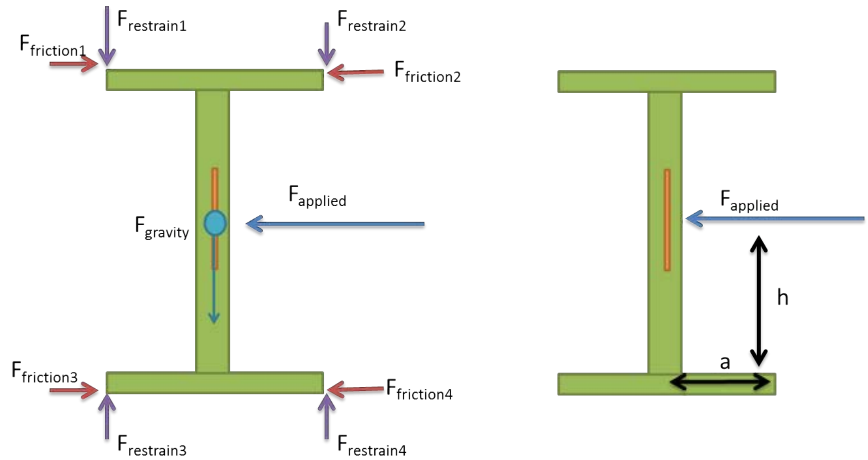

Figure 41. Free-body diagram for forces on RAF sliding panels

The force applied must be at least that of the friction force in order for the divider to move.

$$F_{applied} = F_{friction3} \tag{4}$$

$$F_{friction3} = F_{gravity} * \mu \tag{5}$$

$$F_{applied} = F_{gravity} * \mu \tag{6}$$

Substituting (6) into (1) results in a relationship between slip and tip based on the geometric properties.

$$F_{gravity} * a - F_{gravity} * \mu * h > 0 \tag{7}$$

$$a - \mu * h > 0 \tag{8}$$

$$a > \mu * h \tag{9}$$

A friction coefficient of 0.2 and a height of 3 feet were used. This results in a being a minimum of 0.6 feet. A factor of safety of two was applied and each slider bar, twice the calculated a, was made to a total length of 2.4 feet. This distance also ensured that if CTBs were attached to the frame and the divider they wouldn't be crushed into each other.

2. *Neutral Buoyancy Testing of the RAF*

The RAF was tested with three cargo transfer bags (CTBs). The goal of the test was to slide the divider in order to access and remove a CTB. The test subject was weighted so they were neutrally buoyant. Three CTBs were placed on the structure, two on the divider and one on the frame itself.

In order to slide the divider, the test subject grabbed the side of the RAF structure and the divider and pulled them together (Figure 42). It was noted that in doing this action, the test subject's unrestrained feet would float into the structure. Currently, the divider is supported by linear sliders on spreader bars, which prevents the divider from sliding into the frame. This slider bar prevented the test subject's feet or any CTBs from being crushed. During some of the tests, the test subject tucked their feet under the frame to prevent them from going inside.

Drag is not insignificant, especially with CTBs attached, and it took an effort to move the divider underwater. The test subject used the side of the frame to help pull the divider, which wouldn't be an option if the track was longer. In that case, additional handholds or footholds along the frame would be required.

In order to remove a CTB, the test subject had to reach into the frame. There should be enough space for a person to enter the structure to remove a CTB (Figure 43). This would also mean the CTB doesn't need removed to be accessed, assuming the interior access zipper(s) are on the exposed side of the CTB as mounted in the frame. This is especially true if the frame gets deeper, or if larger CTBs are used. A second divider, with CTBs on both side, would not allow much travel room or human interior access in the current configuration.

Figure 42. Using RAF fixed structure to slide the access frame

Figure 43. Accessing CTB contents from inside the RAF

V. Conclusions

There are unique benefits and challenges to merging sponsored research with an academic capstone design course. While the opportunity for students to get integrally involved with the design and execution of the research is both a strong motivator and unique educational tool, the demands of the academic year make it problematical to maintain the initially planned schedule. While this program was initially planned to be completed at the end of the Spring 2014 academic year, the research activities continued throughout the summer of 2014 under the auspices of the UMd Space Systems Laboratory.

While the total funding for all of the activities covered in this paper was only $, this activity demonstrated the benefit of using multiple simulation environments to address varying aspects of a single space architecture problem. By taking advantage of recent advancements in virtual reality and underwater instrumentation, as well as making maximum use of preexisting hardware such as the HAVEN habitat mockup and ECLIPSE robotic vehicle, this paper illustrates that even a tiny amount of research funding can be leveraged in the academic environment to provide support for a critical technology area which is perennially neglected in NASA funding.

Acknowledgements

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Appendix A

Students involved with X-Hab 2014 at the University of Maryland

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Chandan Kittur
Douglas Klein
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Sahin Kunnath
Sarin Kunnath
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Benjamin Mellman
Atin Mittra
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Oliver Ortiz
William Ouyang
Pegah Pashai
Mihir Patel
Brandyn Phillips
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1-G Spacecraft mockup
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Lisa Krayer
Lauren Walter

Volunteer Student Mentors
Katherine McBryan
Nicholas Limparis
Christopher Carlsen
Kevin Davis

Appendix B

Papers published based on X-Hab 2014 activities

David L. Akin, Katherine McBryan, Nicholas Limparis, Nicholas D'Amore, and Christopher Carlsen, "Habitat Design and Assessment at Varying Gravity Levels" ICES-2014-264, *44th International Conference on Environmental Systems*, Tucson, Arizona, 13-17 July 2014

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David L. Akin and Mary L. Bowden, "Design of an Affordable Near-Term Variable Gravity Research Facility in Cislunar Space" AIAA 2014-4197, *AIAA Space 2014 Conference and Exposition*, San Diego, California, 4-7 August 2014