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Habitat Design and Assessment at Varying Gravity Levels

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For a number of years, the University of Maryland Space Systems Laboratory has been conducting a series of design studies and experimental assessments of space habitat designs. This year, under the support of the NASA Exploration Habitat (X-Hab) Academic Innovation Challenge 2014, UMd is performing two parallel and interrelated studies in habitat design; one-gravity investigation and assessment of habitats based on two vertical cylindrical habitat shells built at UMd under prior studies, and a new investigation of habitability aspects of microgravity and partial gravity designs tested in the UMd Neutral Buoyancy Research Facility.

Analytical studies performed by UMd as part of a NASA Exploration Systems Mission Directorate grant on the design of a minimum functional habitat element (MFHE) showed that, for most applications, a vertically-oriented habitat provided better internal utilization than a horizontally-oriented habitat such as those in the International Space Station. Two full-scale vertical cylinder habitat mockups, ECLIPSE (two floors, 3.6 meter diameter) and HAVEN (one floor, 5 meter diameter) were built by UMd for prior habitat studies, and were repurposed for the effort reported here. Various internal layouts for these facilities were developed and evaluated in virtual reality using an Oculus Rift immersive VR system. The interiors of HAVEN and ECLIPSE were remodeled to reflect the best systems found in VR, and short-term (<1 hour) simulations were conducted to allow a meaningful understanding of habitability issues arising from each design.

While one-g habitats provide easy access and an essentially unlimited body of potential test subjects, they do not allow realistic internal motion when simulating a habitat in a partial gravity environment such as Mars or the Moon, much less that of a true microgravity habitat. For that reason, a parallel research effort was conducted using an underwater habitat mockup in the UMd Neutral Buoyancy Research Facility (NBRF). Test subjects equipped with full face mask systems with two-way voice communications performed test procedures using "hookah" rigs to remote air tanks to minimize ballast effects on body dynamics. Small amounts of ballast were adjusted to provide the best simulation of microgravity; body segment parameters were used in conjunction with harness systems for individual ballasting of each of the major body segments to produce realistic simulated gravity effects for intermediate gravity levels such as the Moon or Mars. A dedicated Qualisys 12-camera underwater motion capture system was used to measure body motions and infer forces applied. Of particular relevance for this system are focused studies on aspects of habitat design specific to gravitation levels, such as investigating the best methods of providing access between different levels, and performing specific tasks such as investigating stowage systems and reconfiguring interiors with indigenous material to accommodate changes in the size or makeup of the crew mid-mission.

I. Introduction

To date, space habitats and space exploration have been mutually exclusive. Extensive experiential data on microgravity habitats has been obtained from more than thirty years operating the Space Shuttle and International Space Station in low Earth orbit. Exploration beyond LEO has been limited to date to four active years of the Apollo program, with "habitats" consisting of some combination of the crew's launch and entry vehicle and the lunar lander.

As we move forward into a phase of exploration beyond Earth's orbit (BEO), the null space between habitats and exploration will have to close. The duration of human missions to near-Earth objects or lunar bases, to say nothing of Mars missions, will demand habitats far beyond the volume of the launch and entry vehicle for crew health and performance. The almost total lack of knowledge of habitat design and habitability best practices for lunar and Mars gravity needs to be filled in in the near term, using the best available methods of Earth-based simulation until space flight opportunities arise. To this end, this paper details a low-cost, short-duration set of habitat design and habitability

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assessments performed by the University of Maryland (UMd) Space Systems Laboratory (SSL) and the 2014 ENAE 484 senior capstone course in spacecraft design, with support from the 2014 Experimental Habitat (X-Hab) Academic Innovation Challenge program, administered by the National Space Grant Federation for NASA.

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]

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

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

Figure 2. Interior of ECLIPSE habitat upper level

Figure 3. Interior of ECLIPSE habitat lower level

Figure 4. Exterior of HAVEN habitat under construction

Figure 5. Interior of HAVEN habitat

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 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.

III. Simulation Technologies

Habitat simulations on Earth typically focus on field analogs, ignoring the difference in gravitation between the simulation and the target locations of the moon (0.16 g) and Mars (0.38 g). To try to make the simulations as realistic as possible, the University of Maryland team attempted to "push the envelope" in ground-based simulation of planetary gravitation levels for the research activities of this program.

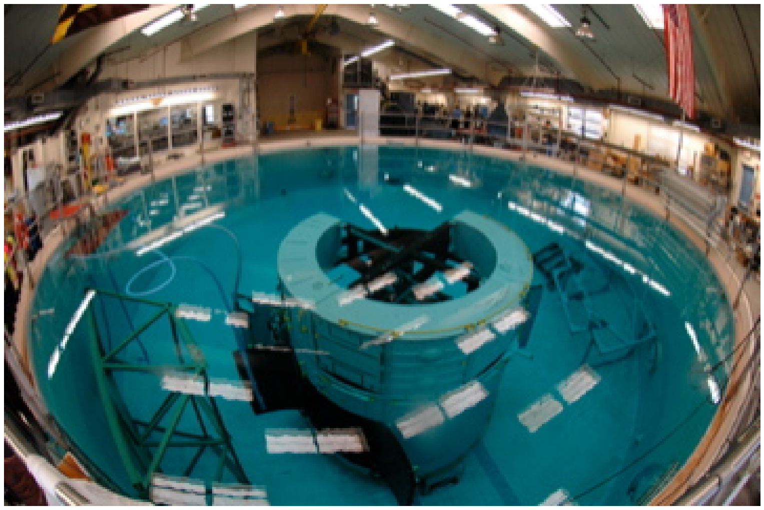

Figure 6. University of Maryland Neutral Buoyancy Research Facility with Hubble Space Telescope mockup

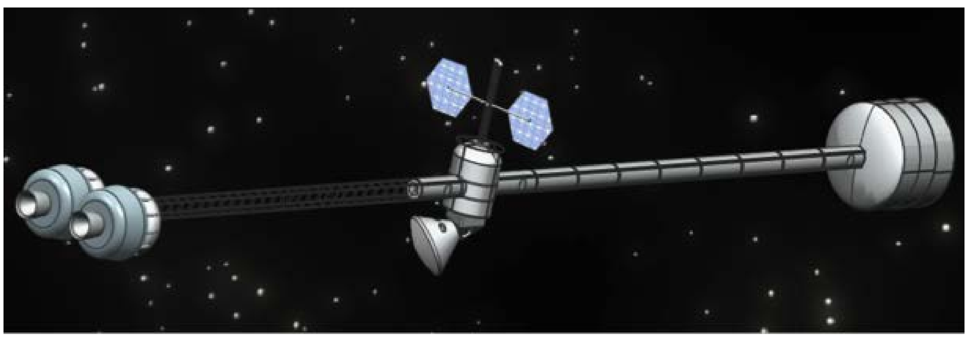

Figure 7. POLUS artificial gravity cislunar space habitat concept

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 the 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.

B. 1-G Habitat Mockups

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

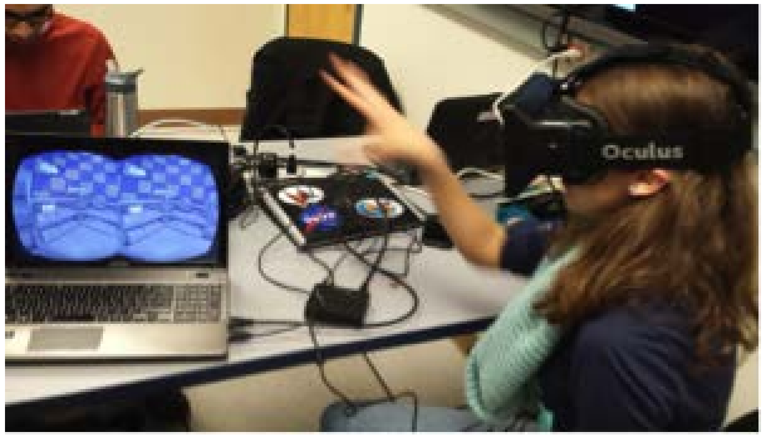

Figure 8. Early test setup with Oculus Rift for immersive simulation

has the scarring for adding the upper level; an analysis showed that attempting to add the upper floor would not be practical in the limited time of the 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.

C. 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 9, 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.

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 10). 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 11).

D. 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 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.

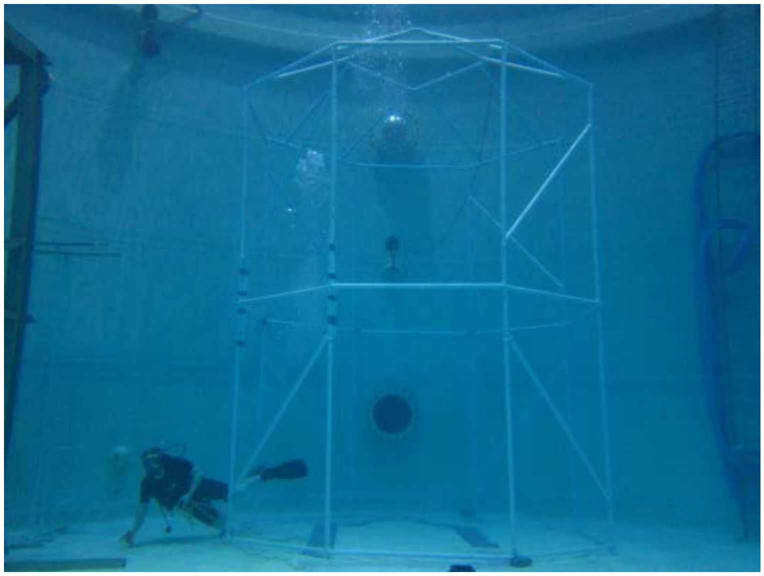

Figure 9. Underwater habitat pressure hull representation in NBRF tank

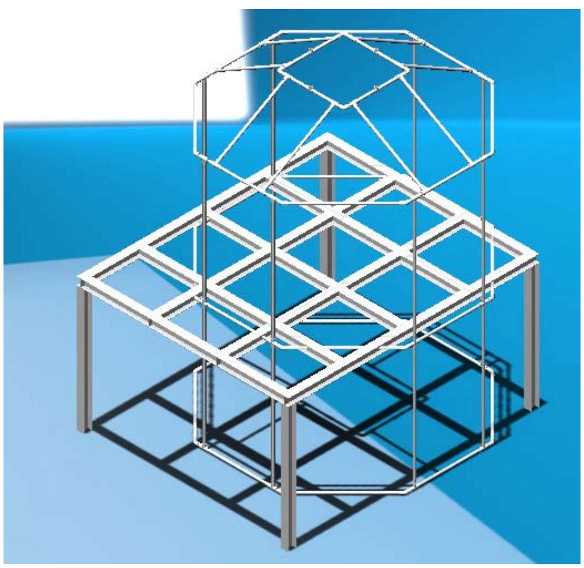

Figure 10. Structural deck in underwater hab (vertical orientation)

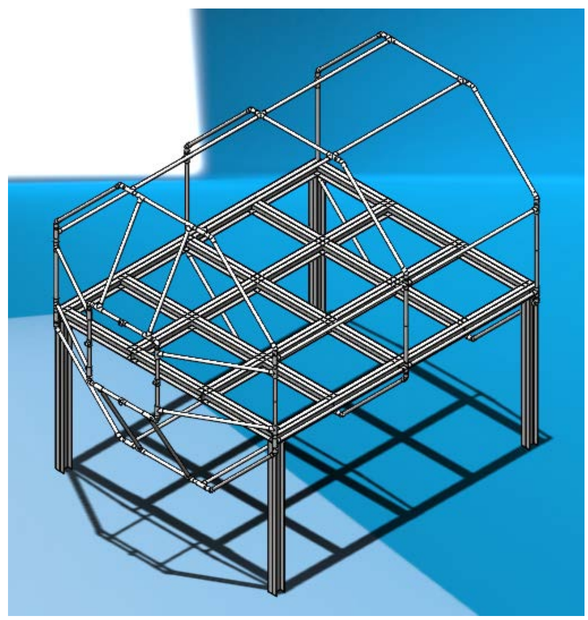

Figure 11. Structural deck in underwater hab (horizontal orientation)

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. Upper and/or lower arm segments can be proportionately ballasted as well, although they generally only require one or two kg, and are frequently left unencumbered to eliminate the restriction of weight systems on arm motions. Figure 12 shows the addition of ballast to torso packs, which are mounted on the front and back of the test subject. Figure 13 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 14 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]

Figure 12. Adding ballast weight to test subject's torso

Figure 13. Ballast packages and retroreflective tracking targets for lower limbs

Figure 14. Underwater gait analysis of ballasted test subject at lunar gravity. Note lights from motion capture cameras used to illuminate tracking targets for position measurements.

E. 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 15). 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 early test series.

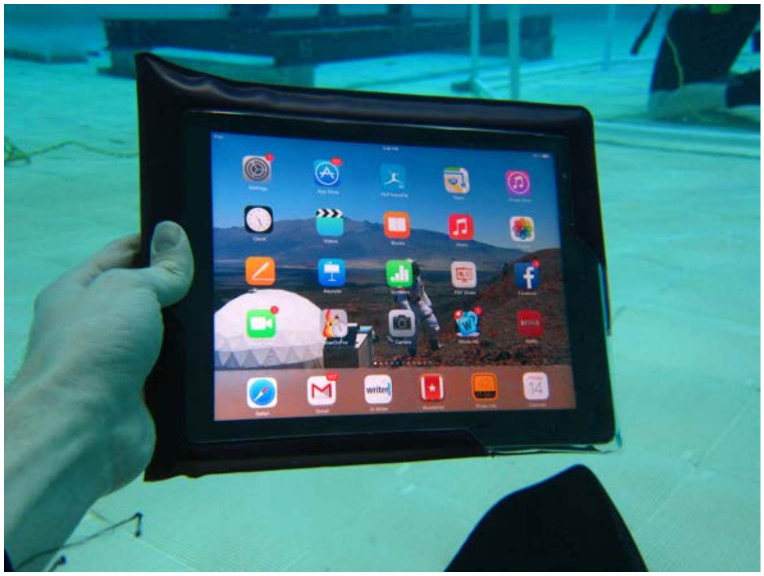

Figure 15. Tablet in waterproof housing during initial operational testing

F. 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 have been 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 collaboration. 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. Linear actuators drive successive pitch joints, 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, currently under development, 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.

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 16 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.

G. 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 17, the frame is 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 are currently being rectified via the use of modified track mounting hardware. When this is completed, simulated logistics material in cargo transfer

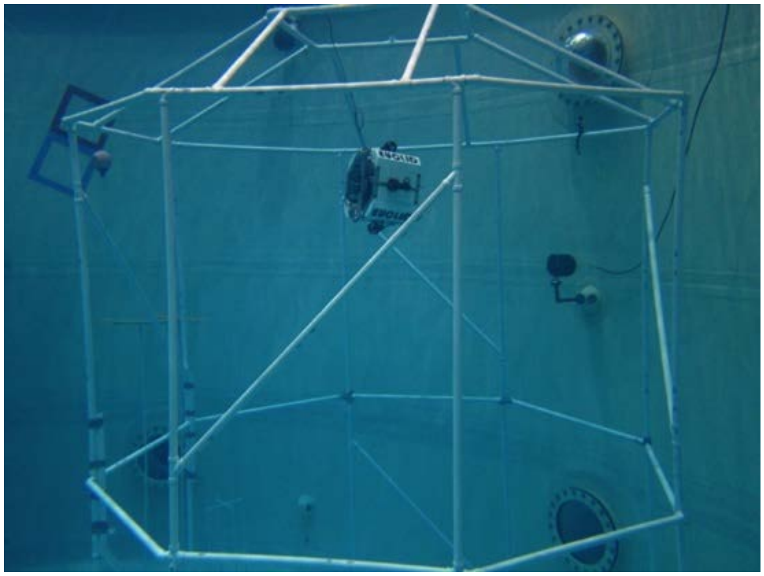

Figure 16. EUCLID vehicle performing controlled flight inside the underwater habitat mockup

bags (CTBs) will be mounted on the linear panels, and the system tested underwater to investigate the utility of reconfigurable stowage systems in the microgravity environment. Given NASA's recent focus on "Logistics to Living (L2L)", in a separate test series the RAF frame and moving panels will be covered with unfolded CTBs to form an individual crew living quarters after the system is no longer needed for logistics storage.

IV. Experiments

While the previous section focused on the hardware designed and developed for these studies, the underlying objective is to perform experiments which yield quantitative data on habitat design and operations for on-orbit, lunar, and Mars conditions. This section addresses the protocols and results for experiments performed to date, and discusses plans for further testing.

A. 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 a single test subject are shown in Figure 18.

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

Figure 17. JPL Random Access Frame for logistics stowage

of the subjects' feet during the neutral body pose.

B. 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.[a] 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^{o} (vertical, Figure 19), 67^{o} (Figure 20), 57^{o} (Figure 21), and 35^{o} (Figure 22) angles. Since these tests proved to take more than two hours and were physically taxing to the test subject, the 67^{o}, case was later dropped as it was deemed to be too similar to the vertical ladder to justify a separate test series.

Based on observation and post-test debriefing of the test subjects, all ladder access angles were feasible for inter-deck 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.

[a]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.

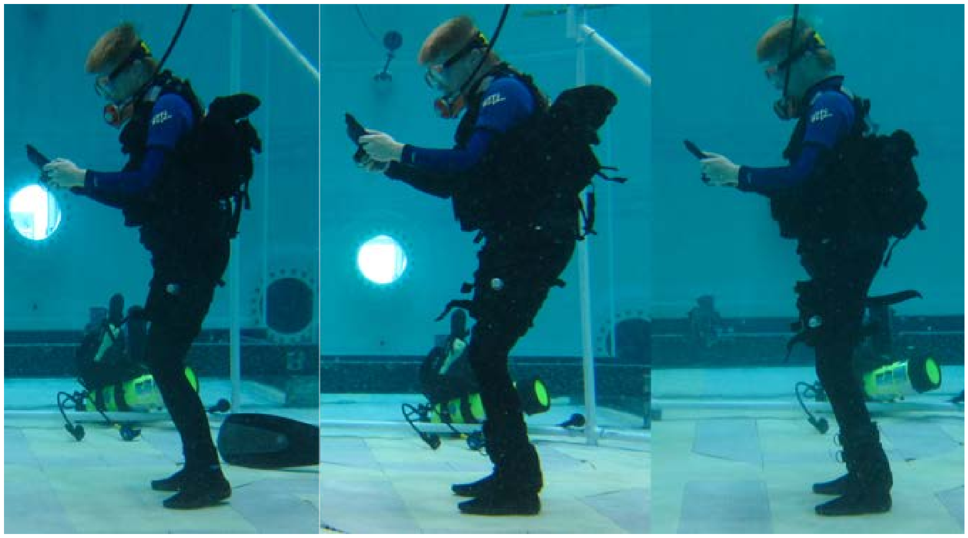

Figure 18. Neutral body posture in simulated microgravity (left), lunar (center), and Mars (right) gravity levels

Figure 19. Descending a vertical ladder in microgravity carrying a CTB

Figure 20. Ascending a 67° stairway in Mars 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.

The 67° 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 35° stairway 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.

The 57° ladder represented a transition case between a staircase/ramp and a vertical ladder. 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

Figure 21. Ascending a 57° stairway in Mars gravity carrying a CTB

Figure 22. Descending a 35° stairway in Mars gravity

same manner. At lunar gravity, the subjects were more comfortable with defending facing forward, particularly when carrying the CTB. (Subjects were much more comfortable with CTB transport at lunar gravity than they were at Mars.)

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 is 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.

At the time of publication, the results are necessarily based on subjective evaluation on the part of both the test subjects and test observers. 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 the tank, providing visual access to the entire camera system. An additional four Qualisys cameras are on order, and when installed later this summer should provide high-resolution target locations throughout the tank volume.

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.

C. 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 1 and 2 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.

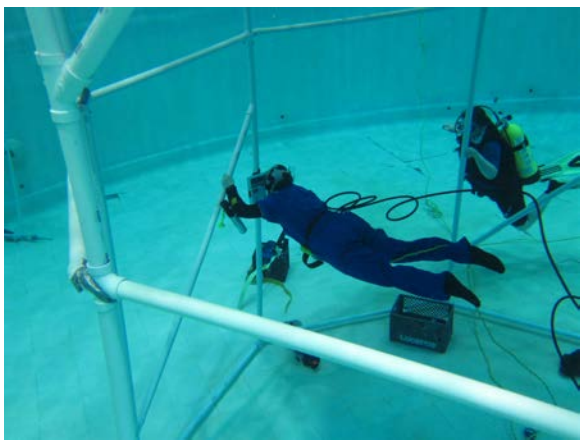

Figure 23. Human test subject checking simulated test panel

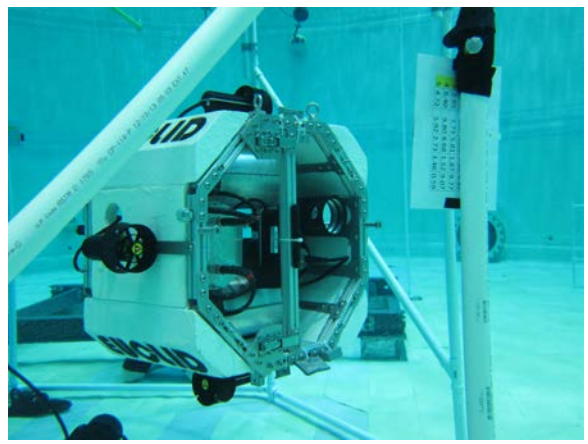

Figure 24. EUCLID providing view of simulated test panel

Table 1. 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 2. 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.

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, the focus was on the provision and use of common work and living areas, rather than sleeping quarters or other private volumes. 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 25) would also participate in the cases of 2, 3, and 4 occupants (Figure 26). Habitat operations to be conducted include 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.)

The tests conducted by the students to date have been pathfinders for more elaborate 1g habitat testing 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.

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

Figure 25. Habitat operations with solo test subject

Figure 26. Habitat operations with four test subjects

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.

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 will continue throughout the summer of 2014 under the auspices of the UMd Space Systems Laboratory. Simulations of day-long habitat activities in the HAVEN module will be performed to obtain data on the effect of habitat area/volume per person on the overall performance of the test subject teams, and architectural modifications made to ameliorate those effects to the amount practical. Results to date from underwater testing of habitat elements, such as mobility and transport between vertical levels, have already yielded interesting results in how habitat design needs to vary with gravity levels; future testing will be focused on refining and extending the quantitative results of these studies, and using the infrastructure developed to specifically examine the relative merits of vertical and horizontal orientations of the habitat shell on the utility of the interior layout.

While the total funding for all of the activities covered in this paper was only $25K, 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.

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