Understanding Human Movement Patterns within Cislunar Habitats

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In preparation for testing five Broad Agency Announcement (BAA) commercial cislunar habitat designs, the National Aeronautics and Space Administration (NASA) embarked on a yearlong in-house training program. This consisted of in-house testing for subject matter experts (SMEs) and crew to informed and ensure evaluation data collection techniques for each of the contractor options. Many evaluation techniques were tested with some continuing forward. Two-test conditions were employed - 1) habitat centric functions with one space element and 2) distributed functions across two or more space elements. This paper will look at one of these techniques—human circulation patterns—to assess a spacecraft habitat's internal configuration while the crew is working a three day simulated cislunar mission. Real time tracking of the crew was accomplished using the AllTraq© system of ultra-wideband frequency (UWB) receivers and radio frequency identification tags (RFID). Heat maps, Zone Time Histograms, Zone Time Utilizations Tables and Task/Time Density Tables were constructed from the collected data. Results indicated distributing functions across elements decreased crew interference and task wait times. Additionally, areas of underutilization were located, which lead to interior layout design changes.

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INTRODUCTION

The space, which determines the operational environment and overall living environment for an individual, and affects the quality of productivity of the crew and daily living onboard a space vehicle is known as the space of habitation [1]. Human movement patterns have been a technique used by architects for several years to understand the efficiencies and pitfalls of traffic flow for a certain configurational layout. Architectural flow or movement refers to the way people move through and interact with a space. In buildings, human circulation, in certain areas, is of high importance (e.g. elevators, escalators, staircases, etc.). For spacecraft, translations paths and hatches are areas of high flow importance. Elements of flow should be positioned and designed to optimize the movement of the human(s) in the designed space for the vehicle [2]. Layout and traffic flow are extremely important to any habitational configuration regardless if it is an Earth dwelling or a spacecraft. Architects and human factors engineers have employed isovist fields [3], frequency counters, functional analysis and link analysis [4] to study the way humans move through a design. Today, technology has made tracking human movement more accurate and easier with the use of radio identification (RFID) tags and computer algorithms [5].

The objective of the three-day in-house testing was to study the distribution and layouts of the functions within the cislunar spacecraft and see if it could be a predictor of crew performance and overall acceptability of two habitational configurations. The effects of these different distributions on crew performance used objective and subjective metrics to define the most acceptable distributions. If practically significant differences between different distributions of functions were found, then the objective would be accepted, and recommendations for future work would be based on preferred distributions of functions, including hybrid configurations that incorporate the most acceptable functional distributions and layouts from each option. If there were not a practically significant difference between different distributions of functions, then the objective would be rejected, and recommendations for future work will be solely based on other programmatic and cost considerations.

Investigators for this study employed the AllTraq© real-time tracking and monitoring system to track test subjects within the mocked up space habitation configuration. The AllTraq© system used an ultra-wideband frequency (UWB) receivers, RFID tags, and data security protocols for collecting human movement data. The RIFD tags, worn by the test subjects, were small and non-intrusive.

METHODS

Subjects

For the in-house study, sixteen participants took part in four separate evaluations. Of the sixteen, eight were engineers and eight were astronauts with flight experience. Each evaluation used a crew of four participants.

Test Environment and Equipment

Testing took place at NASA Johnson Space Center (JSC) in the Integrated Power, Avionics, and Software (iPAS) facility in Building 29 with ground support using the Analog Mission Control Center (AMCC) located in Building 30 (Figure 1). The mockup consisted of two elements—a main habitat module and an airlock module. The main habitat is 20.4 feet in length, which includes the end cones with a 14.04 feet diameter with a habitable volume of approximately 1,059.4 cubic feet (Figure 2). The outer shell and internal secondary structure were constructed of 80/20 aluminum framing, fireproof ½-inch gator board material and fireproof ¾-inch thick plywood. The floor was a ¾ inch thick Lexan with an aluminum supporting structure and high-resolution decals. Hatches, which were 31.5 inches in diameter, were made of foam as well as the Mid-Deck Lockers (MDL) and their electronic faces. The International Space Station (ISS) Cargo Transfer Bags (CTB) were used in conjunction with the MDL and printed decals as personal logistics, maintenance tasks and scientific payloads. Light Emitting Diode (LED) lights were used around the hatches and shelves to illuminate the mockup along with several task lighting fixtures.

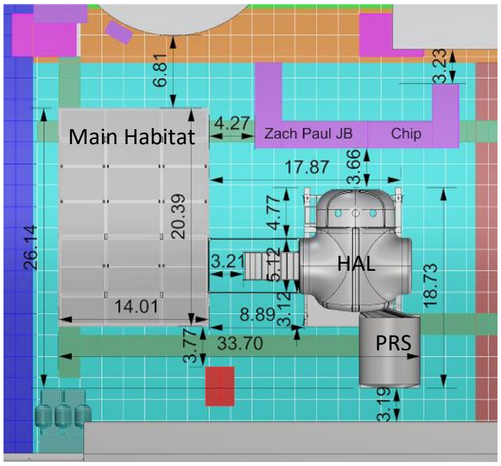

Figure 1. iPAS test area in JSC Building 29 for integrated multiple-day testing (PRS = Pressurized Rear Stowage).

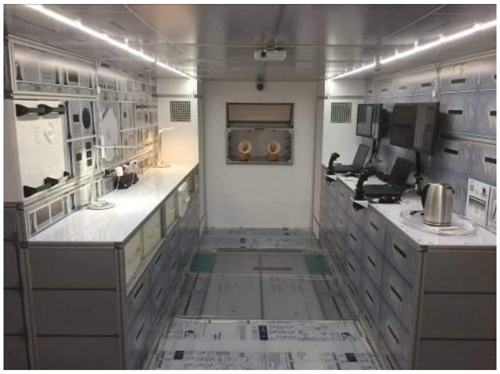

Figure 2. The Main Habitat mockup used for the evaluation located in B29.

The habitable airlock (HAL) is one of several options being considered to provide airlock capability for the main habitat. The HAL consists of a core cabin with an Environmental Control Life Support System (ECLSS), avionics and habitation systems, workstations for controlling various robotic operations, and all of the interfaces necessary to support Extravehicular Activity (EVA) prep and return (Figure 3). The core HAL cabin was outfitted with a hemispherical end cap on the nose that includes a docking port hatch. The aft bulkhead contains functional prototypes of the transfer ports, which were fitted with a logistics stowage module and a science airlock. The science airlock served as a low volume airlock capable of bringing in scientific samples, Orbital Replacement Units (ORU) and other hardware into and out of the vehicle with minimal gas losses. The dimensions of HAL are 6.97 feet in height, 11.45 feet in length and 10.73 feet in width with a habitable volume of 403 cubic feet.

Figure 3. The HAL mockup used for the evaluation located in B29.

The AllTraq© system is a real-time position tracking system that uses an UWB receivers, RFID tags, and data security protocols for collecting human movement data (Figure 4). For accuracy, stationary RFID tags were positioned within each of the habitat modules. The "Stationary Tag Accuracy" is a metric that quantifies the error in the geolocation estimate of the stationary tag. Accuracy of the geolocations were calculated by first placing the stationary tag in the habitat with the other 13 receivers (collecting approximately 27,000 data points in an 8-hour day) and then calculating a probability or confidence level for the accuracy of each pre-determined zone.

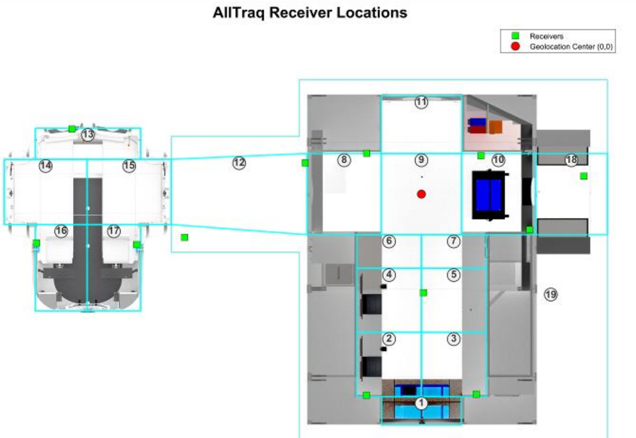

Figure 4. The AllTraq© system setup. Green squares indicate the receivers while the single red dot indicates the geolocation center (0, 0).

The small, non-intrusive AllTraq© RFID tags were worn by the test subjects at all times during testing (Figure 5). The tags have an accuracy of approximately 6-8 inches between pre-determined zones.

Figure 5. The AllTraq© RFID tags test subjects worn during testing.

Procedures

Subjects participated in a high fidelity, integrated simulation of a cislunar human mission. Using a core mission timeline, which was developed by integrating the Human Exploration and Operations Mission Directorate (HEMO) exploration objectives, ISS Exploration Capability Study Team objectives and input from NASA subject matter experts (SME), subjects tested the functional arrangement of each habitat configuration. The test consisted of two conditions that were executed to evaluate the allocation of habitat functions across modules. The first condition, the Habitat-Centric Functional Allocation, assumed all the require habitat functions were co-located in a single habitat module. The second condition, Distributed Function Allocation, spread the required habitat functions across multiple modules (Figure 6). During the three-day test, subjects worked inside the mockup spacecraft-executing portion of the detailed timeline. Day 1 tested the habitat-centric condition, while Day 2 tested the distributed condition. Day 3 tested EVA tasks and will not be discussed in this paper.

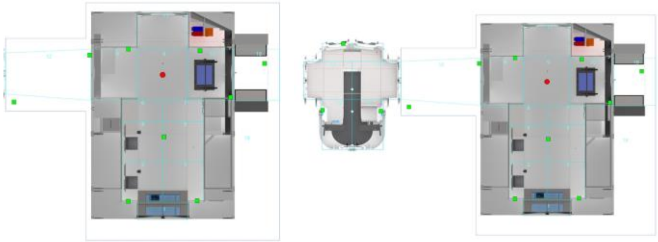

Figure 6. HAB-Centric setup on the left. Distributed Function Allocation setup on the right.

RESULTS

During four three-day testing sessions, both subjective and objective data was collected on the test subjects as for their movement patterns and behavior in two test conditions. For subjective data, a 10-point scale of acceptability, which was developed and used by the Exploration Analogs and Mission Development (EAMD) project during several analog field tests between 2008 to the present, measures the acceptability of different prototype systems and operations concepts, and informs requirements for improvements when necessary. The scale consists of five categories: totally acceptable with no improvements necessary, acceptable with minor improvements desired, borderline with improvements warranted, unacceptable with improvements required, and totally unacceptable with major improvements required (Figure 7). Any rating of four or lower is considered acceptable. From these ratings, investigators were able to evaluate the acceptability of each proposed habitation configuration. A categorical difference in acceptability and a 10% difference in performance metrics were considered practically significant.

Totally Acceptable		Acceptable		Borderline		Unacceptable		Totally Unacceptable		No Rating
No improvements necessary		Minor improvements desired		Improvements warranted		Improvements required		Major improvements required		Unable to assess capability
1	2	3	4	5	6	7	8	9	10	NR

Figure 7. Acceptability Rating Scale describing practically significant (i.e. categorical) differences.

The subject location frequency distribution zones for the tested habitat configuration are provided in Figure 8 and Table 1, respectively. Each zone corresponds to a specific functional element. For example, Zone 3 and Zone 9 for the habitat configuration, respectively, correspond to the port science bay multi-purpose area 1 and translation path 1 areas; Zone 13 and Zone 16 for the airlock configuration contained the HAL Aft area and the HAL Starboard area. Zone numbers were assigned in a linear direction when viewed from above; where practical, the same zone number was assigned to a given function for both configurations. For example, Zone 1 contained the glovebox while Zone 8 contained the medical area/translation path 2 in both habitat configurations.

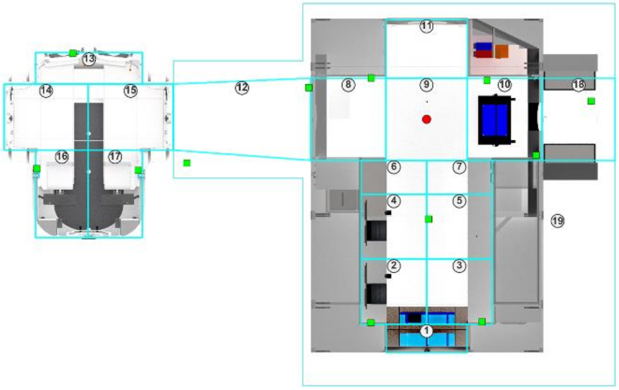

Figure 8. The plan view of the test mockup configuration divided into functional zones (indicated by white around dots with numbers).

Table 1. *Functional Zones of the Tested Habitat Configuration*

Zones	Zone Description
1	Glove Box
2	Starboard Multi-purpose Workstation 1
3	Port Science Bay Multi-Purpose Area 1
4	Starboard Multi-purpose Workstation 2
5	Port Science Bay Multi-Purpose Area 2
6	Galley
7	Port Science Bay Multi-Purpose Area 3
8	Medical Area/Translation Path 2
9	Translation Path 1
10	Exercise
11	Hygiene/Maintenance
12	Tunnel
13	HAL Aft Area
14	HAL Starboard Side Hatch Area
15	HAL Port Side Hatch Area
16	HAL Starboard Area
17	HAL Port Forward Area
18	Logistics Module

Each zone is subdivided into a grid of 10 inch by 10-inch squares. The amount of time spent in each 10-inch square can be inferred from the density of the geolocations within that area. In order to visualize the time spent by each test subject in a particular area, heat maps were constructed; the color gradation scale ranges from white (representing 0 minutes spent in that area) to dark red (representing 60 minutes). (Figures 9 and 10).

When interpreting the heat map data provided in the subsequent figures, there are a few important considerations related to the timeline and tested habitat layout. The multi-person mission timeline was designed to follow the flow of an expected day-in-the-life cislunar mission, beginning with post-sleep activities, system status checks, and a daily planning conference (DPC) with the ground, followed by various science, robotics, and habitation tasks.

The time that each test subject spent in each zone on each day was collected using the AllTraq© system with the objective of assessing the efficacy of subject time/motion as they executed the timeline. The heat maps show a clear reduction of cumulative zone utilization time in the tested habitat configuration. This trend was also supported by a significantly more acceptable ratings of the overall layout in the multiple habitat modules versus a single habitat module. For the multiple habitat configuration, timeline execution was improved due to the addition of redundant multipurpose workstations and better access to work surfaces. This enabled the crew to perform identical tasks simultaneously, increasing overall timeline efficiency. These observations were also reflected in the subjects' acceptability ratings.

Figure 9. The composite heat map of all test subjects for the single habitat-centric configuration.

Figure 10. The composite heat map of all test subjects for the distributed functions habitat configuration.

Histograms were generated to show the relative distribution of high- and low-use zones; an equal distribution reference line was added that represents the total amount of time that would be spent in each zone if the crew spent an equal amount of time in each zone (Figures 11 and 12). This data provides insight into cabin layout, volume utilization, and efficiency of task/function distributions throughout the configuration to further inform functional requirements and habitation design refinements. Furthermore, areas of a habitat that may be underutilized could potentially be repurposed or eliminated.

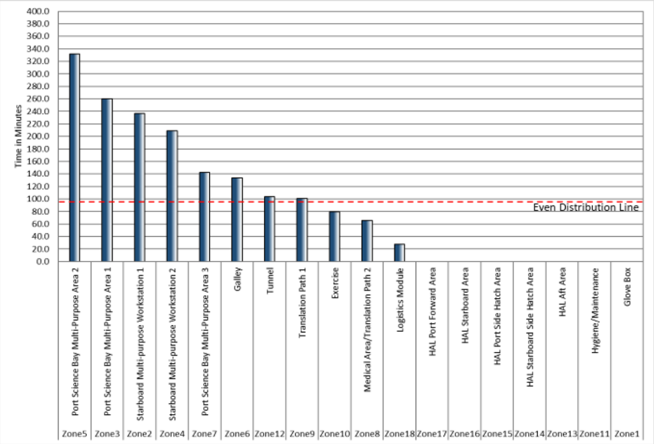

Figure 11. Crew time utilization rank order histogram per zone for the single habitat-centric configuration.

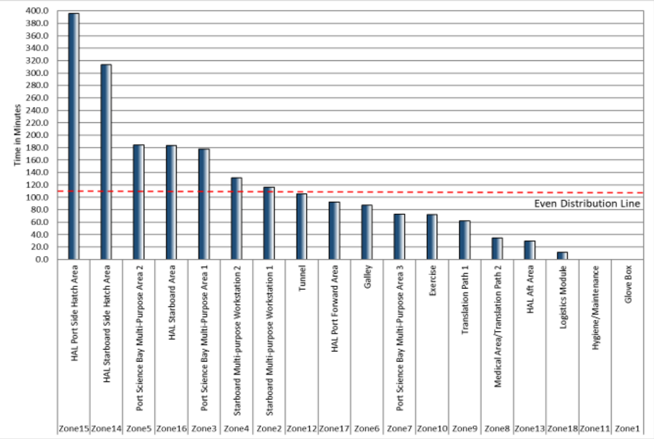

Figure 12. Crew time utilization rank order histogram per zone for the distributed functions habitat configuration.

The resulting analysis indicates the test subjects preferred the distribution functionality of having multiple habitat modules especially in regards to habitation and science functions. This concurs with the overall acceptability scores with the HAB-Centric condition receiving a borderline rating and the Distributed Function condition receiving an acceptable rating. Acceptability ratings were not collected for individual zones. Separating these functions aided in minimizing cross contamination of food, sweat (from exercise), noise, etc., with science payload activities. Additionally, duplicating devices, such as workstations, helped minimize interference and task wait times as subjects could work on tasks simultaneously. In fact, the Alltraq© data indicated lower spikes in frequently used zones when multiple habitat modules were used. In the tested habitat design, the sleep stations were designed to be deployable and were located in areas that had the most activity, Zones 2 through 5, while Zones 8 and 9 were underutilized. Both the AllTraq© data and subject acceptability comments recommend moving the sleep stations to Zones 8 and 9 and make the sleep stations permanent instead of deployable. This would give a cislunar mission crew access to their sleep stations during the day for privacy without disrupting others that were working. Furthermore, keeping translation paths through the hatches clear for daily use was deemed important. However, with habitat volume at a minimum, trade-offs were made. Subjects recommended moving the exercise device to Zone 8, which is the Orion docking hatch, and keeping Zone 10, which houses the Logistic Module hatch, clear as a cislunar crew will tend to be in the Logistic Module more throughout the day bring in science payloads or crew logistics. The hatch to Orion will nominally be closed and a crew will only need to go into Orion very rarely during a 30-day mission; thus, moving the exercise device in that location was optimal. Lastly, relocating the galley area away from the exercise and science to isolate the galley, minimize cross-contamination risk and reduce interference of galley operations while other experimental tasks were being performed. Volume in the original area was small that by relocated the galley to Zone 1, where the glovebox was originally located, gives a cislunar crew more flexibility in preparing crew meals, a cleaner environment and would provide a dedicated galley/meeting table. Figures 13 and 14 illustrates the recommended design changes from the test habitat to a post-test data-driven habitat design. It should be noted that the recommended changes did not affect any of the systems or subsystems architecture and layout.

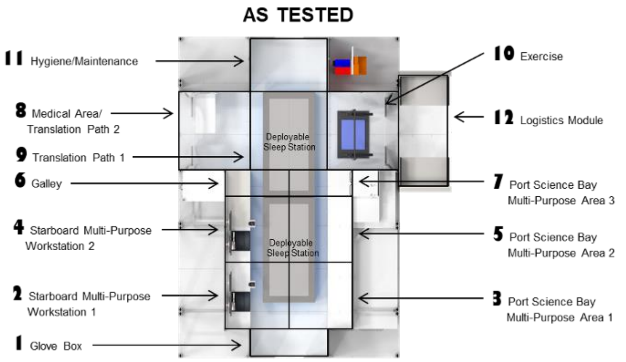

Figure 13. The As Tested habitat design and layout.

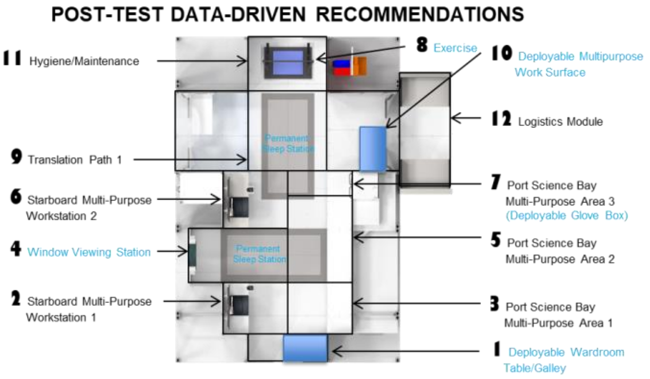

Figure 14. The Post-Test Data-Driven habitat design and layout.

CONCLUSIONS

Habitability is about quality of life [6]. Testing using the AllTraq© tracking system along with subjective acceptability data provided human factor engineers both objective and subjective data on human movement in a cislunar habitat both in a singular configuration as well as in a multiple element configuration. Movement data showed lower spikes in frequently used zones when tasks were distributed across elements compared to a single habitat, which increased crew efficiency. Both underutilized zones and highest density zones were identified by also using this method. Furthermore, the movement and frequency data collected enable human factors engineers to make data-driven design recommendations to improve the layout configuration for optimal crew performance. With the success of the in-house testing, this technique was include in the test data collection package for NASA's BAA contractors. Over the past year, the collection of human movement data in various sized habitats was successful in optimizing the BAA cislunar habitat internal configuration and in developing standardized design guidelines for future vehicles.

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