The Human as a System – Monitoring Spacecraft Net Habitable Volume throughout the Design Lifecycle

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Spacecraft design has historically allocated specific volume and mass "not to exceed" requirements upon individual systems and their accompanying hardware (e.g., life support, avionics) early in their conceptual design in an effort to align the spacecraft with propulsion capabilities. If the spacecraft is too heavy or too wide for the launch stack - it does not get off the ground. This approach has predictably ended with the crew being allocated whatever open, pressurized volume remains. With the recent inauguration of a new human-rated spacecraft - NASA human factors personnel have found themselves in the unique position to redefine the human as a system from the very foundation of design. They seek to develop and monitor a "not to fall below" requirement for crew net habitable volume (NHV) – balanced against the "not to exceed" system volume requirements, with the spacecraft fitting the crew versus the crew having to fit inside the spacecraft.

Introduction

The ultimate goal of monitoring NHV is to ensure that future spacecraft provide sufficient unencumbered volume for crewmembers to live and execute tasks in support of mission goals. NHV considers the operational requirements of the mission - including crew size, mission duration, acceptable crew risk, and mission objectives. If the spacecraft NHV is too small or restricted, operations will be adversely impacted.

NHV has been defined by NASA as the total remaining volume available to on-orbit crew after accounting for the loss of volume due to deployed equipment, stowage, and any other structural inefficiencies (cavities and voids) which decrease functional volume. NHV can be described as contiguous regions of volume in which the crew can work, sleep, eat, egress, ingress and perform tasks necessary for a safe and successful mission.

Structural inefficiencies are regions that are too small or poorly shaped to be counted as habitable (cavities) or are disjointed from the habitable volume (voids). Cavities should be subtracted from habitable volume and voids should be ignored.

Once the definition for NHV was decided upon by NASA, the next question was how to measure NHV so that it can be monitored and verified.

Process Innovation

Novel processes were developed to compute NHV: (1) Using computer-aided design (CAD) models and measurement tools and (2) Physically measuring mockups, sketching the raw data onto paper, and transferring the data into CAD.

CAD Measurement of Net Habitable Volume

Step #1: Define the Habitable Volume and Non-habitable Volumes using Simple Solids

A simple solid or volume envelope includes objects such as boxes, cylinders, cones, truncated cones and extrusions of outlines. These volumes will be envelopes encompassing open space to be considered habitable (see Figure 1) or encompassing equipment or space considered non-habitable (see Figure 2). In the example below, a gross habitable volume is defined to be two non-overlapping truncated cones and a non-habitable volume is the envelope around multiple pieces of hardware. The small cavities between the hardware units are captured as non-habitable volume.

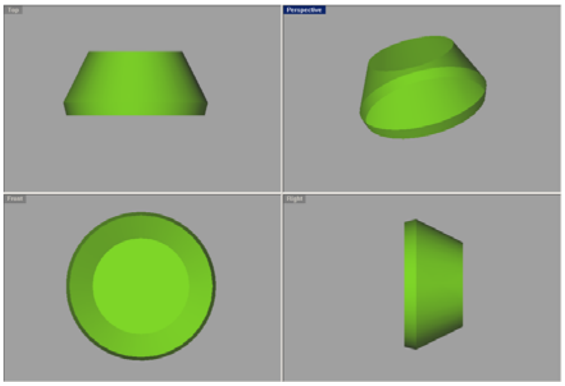

Figure 1: Initial Habitable Volume
Two non-overlapping simple solids are made from two truncated cones

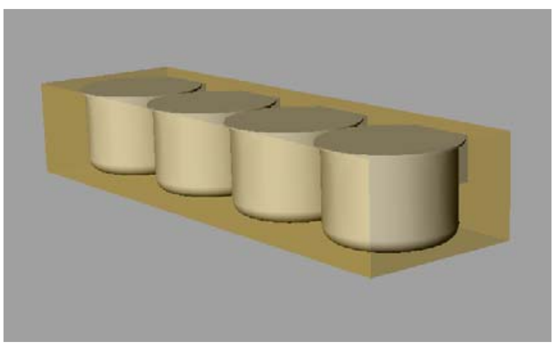

Figure 2: Non-habitable Volume
Simple solid is an brown box around 4 electronic units

Step #2: Refine the Habitable Volume by Removing Non-habitable Volumes

If a non-habitable volume intersects the habitable volume it must be subtracted using Boolean operations or an equivalent process so that only the portion of the non-habitable volume that is inside the habitable volume is subtracted from the habitable volume. If a non-habitable volume is completed enclosed by the habitable volume then its entire volume is simply numerically subtracted from the total habitable volume as it not necessary to perform a geometric Boolean operation to determine volume.

Figure 3 shows a refined habitable volume (green) intersected by the displays and control panel (orange) and by stowage volumes around the base (blue and silver) and on top (purple).

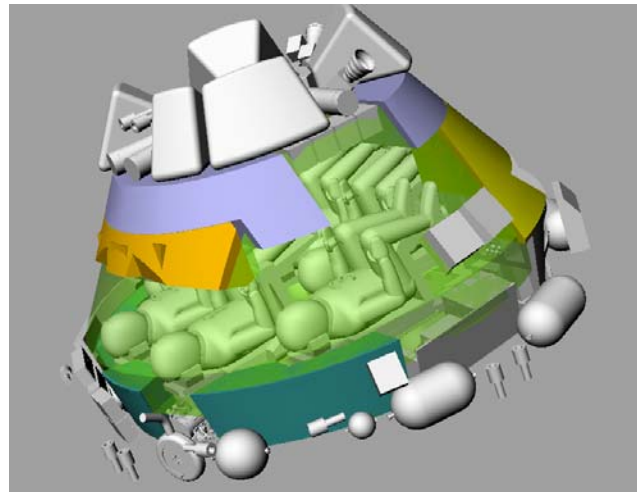

Figure 3: Refined Habitable Volume with Intersecting and Enclosed Volumes

Step #3: Address Cavities and Voids

The model will have cavities and voids that were not captured by the initial habitable volume assessment. Many of these cavities are too small to be counted as habitable or are disjointed from the vehicle's NHV and should be subtracted from NHV calculations and shape assessments. Rules of thumb regarding these include:

- A volume is considered habitable and should be included if it is possible to place a human body completely inside.
- If a volume is too small to place a human body completely inside, it is still habitable if it is possible to place a human limb inside, while the rest of the human body is contained within an adjacent, contiguous volume. However, only the portion reachable by the limb should be included. For example, a 10 ft long tube with a radius of six inches can accommodate a human arm, but only the portion that could actually contain the arm is considered habitable.
- Examples of non-habitable volume are stowage, seats, electronics systems, electrical systems and hygiene systems.
- Cavities between equipment, stowage, etc. should not be considered habitable if it is unreasonable to expect a person to nominally

place a body part inside that volume during nominal task execution.

- Cavities must be touching or connected to the vehicle's NHV to be considered part of it otherwise it is to be considered a void.

The final volume, with all non-habitable sections removed via subtraction or Boolean operations, provides the NHV.

Physical Measurement of NHV

As a vehicle design matures, mockups of varying levels of fidelity will be constructed to assist with the development. The NHV must be physically measured in these mockups, as well as within the resulting spacecraft, in order to verify that the vehicle meets design requirements.

Step #1: Define the Habitable Volume using Simple Solids

Begin with simple solids. After a visual assessment, break up the volume to be measured into manageable blocks and three dimensional volumes that are as simple in geometry, and as large as possible (e.g. cylinders, cones, and rectangular solids) but are able to be combined to capture the complexity of the entire interior shape. A photographic record and sketches of the interior are extremely useful in reconstructing the measurements into an integrated volume. These volumes should be calculated and added together.

In certain cases, a space cannot be divided into simple solids alone, and an advanced method must be used to calculate more complex interior geometry. For this scenario, a lofting technique is suggested. The complex 3D shape can be divided into parallel planes, spaced according to reference features such as hatches, displays and controls, etc. Second, a section view must be drawn out at each plane with special attention to the lengths and angles between walls as well as the distances between planes. Once all of these measurements are taken, the planes and sections must be input into CAD software and the sections lofted together to create a 3D model of the space (see Figure 4).

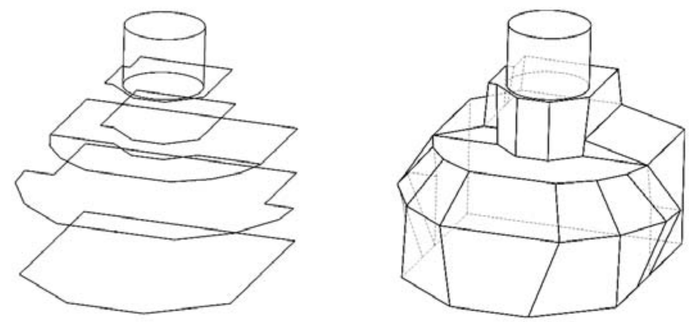

Figure 4: 2-D sections of the Apollo Command Module in CAD, lofted to create a 3-D model

Step #2: Refine the Habitable Volume

In most scenarios, objects will protrude into the previously measured simple or complex solids. Account for extraneous hardware, stowage, and other protrusions into the NHV based on awareness of the operations planned in the vehicle. All non-habitable volumes must be accounted for and subtracted from the NHV. In particular, awareness of protrusions that will sub-divide the NHV into potentially unusable volumes is critical. Only volumes of appropriate size to accommodate the human crew or that are nominally used by crewmembers during operations should be included in the Habitable Volume.

This excludes, for example:

- Volume that appears free in the mockup but is planned for use during a mission. For instance, much of the volume beneath the Apollo Command Module seats was used to pack supplies and equipment, excluding that volume from a NHV assessment
- Volume occupied by hardware that may be reconfigurable but must be accounted for in the NHV (e.g. the seats themselves)
- Small corners or slivers of volume created by hardware protrusions (e.g. stowage lockers, shock-absorbing struts).

Step #3: Add Component Volumes

The measured volumes should be integrated and measured in CAD software or a comparable tool.

Add volume from Step #1 and subtract volumes from Step#2 to arrive at a final NHV.

Findings

To validate the accuracy and clarity of the two processes developed to compute NHV, three groups of individuals used the processes to compute NHV for the ISS configuration of NASA's Crew Exploration Vehicle (CEV). The results were compared to determine the repeatability of the processes. Two different CAD packages were also used to further verify repeatability.

In addition, two of the groups computed net habitable volume of the Lunar configuration of CEV. One group used the same CAD measurement process used for ISS configuration while the other group used a process individually developed but based on a similar concept.

CAD models were provided by the CEV Cockpit Working Group. Physical measurements were accomplished in the Habitability Design Center (HDC) mockup in JSC Building 15.

Teams worked independent of one another and were also asked to provide comments and recommendations regarding the process itself.

For example, one of the important lessons learned was that it is critical to clearly define what is considered "habitable". An area may not be considered habitable if it is used for temporary stowage of equipment or items which must be removed to displace another volume in order to be accessed.

ISS Configuration of CEV		
Cubic Feet		
313.21	**Group 1**	Computed using CAD measurement process
315.61	**Group 2**	Computed using CAD measurement process
308.76	**Group 3**	Computed using CAD measurement process
300.00	**Group 1**	Computed using Physical measurement process

Lunar Configuration of CEV		
Cubic Feet		
317.34	**Group 1**	Computed using CAD measurement process
311.33	**Group 2**	Computed using similar concept to CAD measurement process

The results show that the CAD Measurement process is sufficiently repeatable for computing net habitable volume and sufficiently accurate when compared to another independently developed process used for the Lunar configuration.

The variations of the computation are due to the interpretations of what is to be habitable volume and how that volume is to be represented and computed. For example, there were differences in the estimations of the volume of seats and the volume of the space required for using the waste and hygiene unit.

The relatively small differences between the ISS and Lunar configuration volumes are probably due the fact that the reduced number of seats (Lunar configuration has 4 seats, ISS configuration has 6 seats) offset increased stowage volume for the ISS mission because of the longer duration mission.

Discussion

When calculating NHV for any vehicle, assumptions regarding what areas are considered to be "habitable" and which are excluded should be clearly stated. Equally important to ensure a consistent determination is a clear statement of assumptions for crew provisions, stowage allocations, and measurement of intrusions such as seats and other rigid structures within the vehicle that will be subtracted from the gross NHV. These should all be clearly defined prior to the calculation, and included in the results.

The human should be regarded as a “system” with key functions, requirements, and interfaces to vehicle systems. Habitable volume is a key enabler of the human system’s ability to meet its requirements safely and effectively to accomplish mission goals. Volume allocations for crew, stowage, equipment, and seat stroke are interdependent and should be managed as an integrated solution, instead of four separate elements. Fixed and reconfigurable vehicle structures should also be taken into consideration.

As vehicle missions and systems mature, task analysis should be performed to further refine the required amount of volume and the shape of the volume. Quantitative analysis and modeling techniques and qualitative evaluations should be performed to identify any potential hazards or interface conflicts to other systems. Translation corridors within the habitable volume must also be established to reduce crew risk during a contingency such as pad egress, fire, or off-nominal landing.

As key system designs such as suits and seats mature, NHV should be reassessed for specific impacts associated with these systems.   Oversight of the internal volume allocations and layout is critical and role ensures that both the intersection and unions of these volumes (habitable and non-habitable) will be monitored and managed within the available cabin volume. Potential conflicts and disconnects must be monitored and identified not only early in the design, but throughout the design life-cycle and operational phases.