Using Virtual Reality and Motion Capture as tools for Human Factors Engineering at NASA Marshall Space Flight Center

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Abstract. NASA Marshall Space Flight Center (MSFC) Human Factors Engineering (HFE) Team is implementing virtual reality (VR) and motion capture (MoCap) into HFE analyses of various projects through its Virtual Environments Lab (VEL). VR allows for multiple analyses early in the design process and more opportunities to give design feedback. This tool can be used by engineers in most disciplines to compare design alternatives and is particularly valuable to HFE to give early input during these evaluations.

These techniques are being implemented for concept development of Deep Space Habitats (DSH), and work is being done to implement VR for design aspects of the Space Launch System (SLS). VR utilization in the VEL will push the design to be better formulated before mockups are constructed, saving budget and time. The MSFC VEL will continue forward leaning implementation with VR technologies in these and other projects for better models earlier in the design process.

Keywords: Human Factors Engineering · Human Space Flight · Virtual Reality · Motion Capture · Space Launch System · Mockup · Simulation

1. Introduction

MSFC's HFE Team is responsible for all worksite analyses performed for the SLS prelaunch integration activities at Kennedy Space Center (KSC), as well as the analysis of DSH concepts. There is a wide variety of tasks, and it is important to verify early in the design process that the vehicle can be successfully integrated at KSC. If the ground support crew cannot complete the task, redesign efforts must be implemented. These worksite analyses are traditionally performed by inspection of drawings and construction of mockups to replicate the worksite. These mockups are most beneficial early in the design phase when changes to the design can be made to better meet the HFE requirements. However, the design is often so fluid that the mockup may not reflect the most recent changes.

Layout analysis of Deep Space Habitat (DSH) facilities is another field of investigation for the MSFC HFE team. These layouts are ever-changing, and VR is being used in the VEL (shown in Figure 1) to examine possibilities and make design decisions. With a small team, the group has found a process to work with the Advanced Concepts Office and other departments to minimize efforts across the center for DSH work. Being able to bring together this innovative work in a way that can be rapidly re-planned has been most helpful in designing concepts that may be used for future deep space travel.

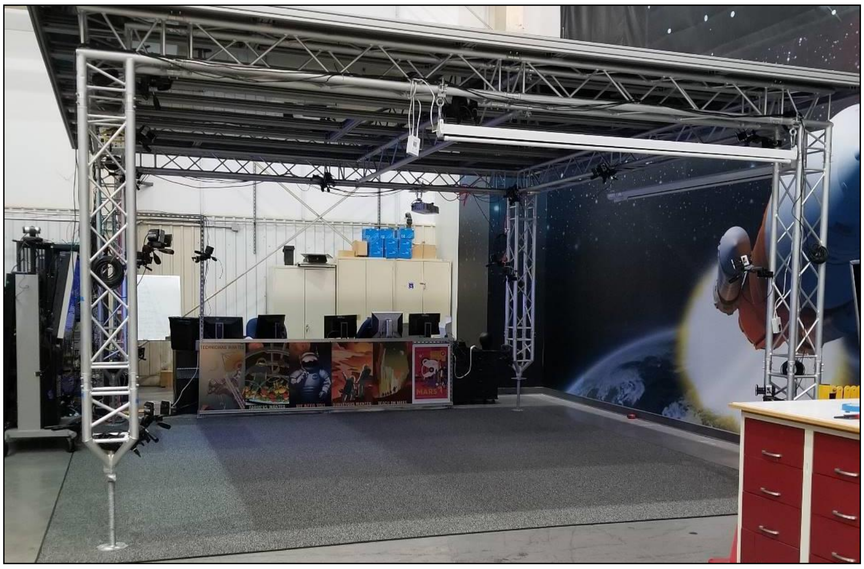

Figure 1: *Virtual Environments Lab (VEL) at NASA Marshall Space Flight Center. The VEL contains a 16 infrared Vicon motion capture camera system and VR capabilities with Oculus Rift and HTC Vive*.

Being able to quickly review new designs without the expense of a mockup could also be very beneficial to SLS. Applying strategies to design development that include HFE from the beginning of the design process leads to better designs where functional tasks can be successfully accomplished. Doing this analysis initially with VR with input given back to designers will result in more accurate mockups when physical assessments are constructed. Integrating VR at design reviews will also expedite this process through immersive visualization of the object, rather than reading a print. Challenges with changing the way these reviews have been completed in the past are present, but work is being done to show the MSFC community how helpful VR can be.

2. Current Processes

MSFC HFE has developed a reputation of producing excellent quality physical mockups that are valuable to the engineering team. The fabrication shop has the ability to produce mockups of varying fidelity, dependent on budget and schedule. Assessment of these mockups have been used for decades to give HFE inputs and determine design direction. Engineers and managers outside of the HFE team have also used these mockups to demonstrate hardware issues and make design decisions. With a need for these mockups early in the design process, there are often major changes to the design after the mockups are constructed, resulting in the need for a rebuild. It is frequently a circular need in that the mockup is desired early, needs are identified, and design modifications result from the analysis. From this new design, the mockup has to be modified or be reconstructed altogether.

While the need for physical mockups is not going away, some work can be done earlier in the design process for designers and integrators to view the object in the appropriate scale through VR immersion. Being able to see the design as it is sized and better understand accessibility and workspace volumes at the beginning of the design process can lead to improved layouts from the beginning. If a better design is present well before the Critical Design Review (CDR), more accurate physical mockups will be built without as many iterations.

3. Physical Mockup vs VR Environment

VR provides the ability to view a scene on a 1-1 ratio without building a physical mockup. When looking at a space or object, engineers can better detect potential issues and produce solutions if the space or object is on a real-world scale. For this reason, it is beneficial to use a full-scale, three-dimensional, and intractable virtual model. It is also advantageous because an interactive VR environment offers a comparable experience to a physical mockup, while saving time and money. When using an interactive VR environment, physical materials are not required. This not only saves on materials, but also saves the time a person would use in looking at drafts, creating build procedures, and building the mockup. It can be more time-effective to create an interactive VR model compared to building a full-scale mockup. With adequate computing power, a CAD model can be translated inter an intractable VR environment in a days' time. And as the design evolves, models from the designers can be continuously incorporated into the VR environment; this saves the tremendous amount of time necessary to construct new physical mockups when designs become obsolete. A VR environment is often created in hours, compared to the weeks or months it can take to machine and assemble a high-fidelity mockup.

An advantage to this approach is the ability to manipulate and/or make changes to a model quickly in order to explore possible design changes. For example: a wall has a 10-inch diameter hole where a person needs to reach though and up to a box that is attached to the wall and 6 inches above the hole. In this scenario, a full-scale mockup can be built and an analysis can be performed using participants who are between the 5th percentile female size and the 95th percentile male range, as described in the Anthropometric Survey of the US Army Personnel. (ANSUR)[1]. These participants would each try to reach through the hole and up to the box while being asked questions about the task. With the physical mockup, the hole cannot be moved or changed without several hours of work. Contrasting, if this assessment were completed using the human factors analysis program, the wall and the hole dimensions could be changed relatively quickly.

A high-fidelity physical mockup is advantageous when factors such as heavy equipment and complex movements are needed. VR environments use visual and auditory senses only. If an assessment requires data from a participant's reactions to weight or touch, a VR environment alone will not be adequate.

4. VR for Deep Space Habitats

The SLS derived DSH is a concept mockup (seen in Figure 2) that provides multiple analysis opportunities. It is a three-story habitat design with domed ends to provide for more living and storage space. The upper deck contains an exercise area and galley, the mid-deck provides living quarters, laboratory equipment, and storage space, and the lower deck provides a work area and operation components. The DSH serves as a test bed for various conceptual designs which might be used in future deep space habitats. It is more useful to think of the SLS derived DSH as a collection of parts rather than a whole. Some of its components will be utilized for NASA's eventual deep space habitat design, but likely not in the configuration that exists in the overall design of MSFC's DSH.

Figure 2: *The physical SLS derived Deep Space Habitat (DSH) mockup. This mockup includes a galley and exercise area on the upper deck, crew quarters and laboratory equipment on the mid-deck, and a work area on the lower deck.*

During the process of developing procedures to convert CAD files into VR environments useful for HFE analyses, the SLS derived DSH was converted into a VR format (shown in Figure 3). The use of VR is particularly useful in the context of the SLS derived DSH for many reasons. Because the SLS derived DSH is used primarily as a conceptual test bed, there is less funding associated with it for the purpose of building mockups and conducting analyses. Since using VR is often more cost and time effective than building physical mockups, using VR in conjunction with the DSH allows for more work to be performed with the design.

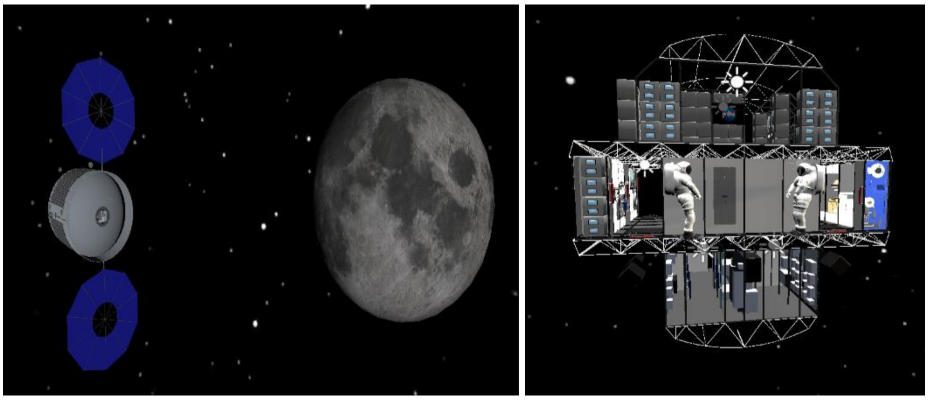

Figure 3: *Outside (left) and inside (right) views of the VR mockup of the DSH. Using VR allows for more design features to be included in the VR mockup (such as the end domes and solar panels) than are feasible in the physical mockup.*

Another reason to use VR in conjunction with work on DSH model**s** is VR's ability to allow for micro-gravity simulation. The DSH will operate in space, so its inhabitants will be living in a micro-gravity environment; simulating micro-gravity environments on earth is often difficult and requires expensive infrastructure, so the use of VR provides a relatively quick and inexpensive alternative. In the VEL, the HTC Vive (shown in Figure 4) is used in conjunction with Unity 3D software. Unity 3D allows for features to be added through code in the languages C# and JavaScript; scripts written in these languages allow for micro-gravity to be utilized in VR environments.

Figure 4: *A participant using the HTC Vive VR console to view a VR model*

The use of micro-gravity simulation in HFE analyses is very valuable when examining the way astronauts would use a system while in space. Many aspects of HFE analysis would be affected by the lack of gravity; being able to simulate microgravity allows for engineers to better anticipate design features which might need to be changed. Beyond the scope of HFE, VR micro-gravity simulations are also useful in the context of crew training and public education; VR technology today provides for an immersive experience which feels very realistic to the user.

There are some disadvantages to using micro-gravity simulations in VR. Creating an accurate micro-gravity environment through coding is difficult and time consuming during the development phase. Furthermore, some users find the simulation disorienting**.** Because VR feels so real to the user, it can be hard to feel as if you are floating in the virtual environment while still being affected by gravity in real life. It takes a bit of work by the user to adjust to the headset and avoid feeling motion sick; most users are able to get used to it rather quickly, but those prone to motion sickness may prefer to avoid these simulations.

The VR environments created for work on the DSH were built from scratch using Unity3D. A CAD model of the DSH existed in a different software, which was exported piece by piece and added to the environment in Unity 3D. Building the scene in this way allows the creator to tailor the environment to fit the specific needs of an assessment. As each piece of the model is added into the environment, the creator can add different characteristics to the piece and manipulate it's behavior so that it closely mirrors the scenario being assessed. For example, an environment in low earth orbit would behave differently than an environment located on the moon, or on Mars; the VR environments must closely resemble the environment being assessed. The freedom associated with this method is very valuable when considering that NASA engineers often have a need to evaluate environments drastically different than what is experienced on earth. This method is time-consuming, as each part of the model must be given characteristics and added to the scene individually.

VR environments can also be created through the use of HFE software. Using HFE software allows VR environments to be created in very little time by simply translating the model into a different file format. This option has stricter limitations which depend on the parent HFE software, and is therefore much harder to customize. From the perspective of worksite analyses, using an HFE software should be preferred. Using HFE software allows engineers to examine a high-fidelity CAD model with many useful features and engineering tools that collect assessment data.

Creating a VR environment from scratch is more useful when examining a model in a conceptual way and while evaluating its general functions. It is also preferred when evaluating gravity environments other than that on earth. These models can be created to have very high fidelity, but the increased fidelity means more time spent on the project; in the fast-paced world of human space flight, by the time a VR environment is created in this way the design might be outdated. In the context of engineering analysis, HFE software provides an excellent option for generating VR mock-ups quickly and to the fidelity of thorough HFE assessments. It is this method which is used to evaluate the worksite analyses for NASA's upcoming SLS rocket.

5. VR HFE Analyses for SLS

In HFE at NASA MSFC, analyses are performed to assess if a task can be completed within the project requirements and performed without damage to the flight article. NASA considers personnel safety and flight article protection top priorities. It is important to understand that it is necessary to take measures to ensure the safety of the technicians and engineers involved in the product life cycle of SLS in order to safeguard mission success. Using VR in the design and verification processes allows the engineer to see and interact with an environment before it is built. This lets the engineer see potential issues early, allowing time to find a solution before a particular task needs to take place.

Because the SLS is such a large project, it is hard to know the anthropometrics of the person who will be performing a certain task at KSC. KSC is responsible for the ground processes of SLS including (but not limited to) stacking of the rocket, installation of payloads and hardware, and cable connections between hardware and elements. The SLS ground crew is comprised of a variety of people, therefore the requirements state that systems should be designed for assembly by 5^{th} female to 95^{th} male percentiles.

The HFE assessment begins with a breakdown of functions and their associated tasks to be performed, along with the type of analysis to be performed. Types of analyses can be an inspection where drawings or documents are evaluated, demonstrations such as physical mockups or VR experiences, and/or tests where a process is completed using mockups or interactable VR environments. The functions and tasks are then placed in a table where each task is lined up with SLS requirements to see if the requirement is applicable to the task. If nothing other than visual confirmation is needed, then a VR assessment will proceed. In this case, the CAD model is converted to an interactive VR environment for the engineer to experience.

The majority of HFE assessments at MSFC involve a reach analysis. For an SLS VR assessment, a SLS element CAD model will be converted and uploaded into the human factors program. Within this program, avatars can be inserted and manipulated to obtain an idea of task feasibility. These avatars are programmed to have the limitations of a human body. For example, a human arm cannot rotate 360 degrees around the shoulder socket. This limitation is applied to the avatars providing a more realistic scenario. After the avatars and necessary objects are added (such as platforms or tools), the virtual environment is converted into a VR environment. The user can then see the model on 1-1 scale with ability to explore and manipulate the environment and model.

In the VR environment, the participant can use the controllers to manipulate the environment, models, and avatars. The user may 'teleport' to any location in the environment then walk anywhere within the boundaries of the physical space where the user is operating the VR system, which changes the viewed environment to a new location within the model. The primary VR technology at MSFC is the HTC Vive headset using Steam gaming software and HP Z VR computers designed specifically for VR. The HTC Vive headset and controllers are tracked using two lighthouse sensors. The Vive controllers allow for several options. One of these options is the ability to separate parts of a CAD model. This is beneficial because in the HFE program the user can pick a specific part, pull it towards him/her, inspect all sides, and place it back on the model. This function saves time as there is no time required to build or assemble/disassemble a model in the VR environment. The program also allows the user to use tools such as a flashlight to illuminate shaded areas and a 'mark up' pen to save notes or design ideas.

The physical mockups and VEL technologies can also be combined for a more thorough assessment. By using physical mockups, the participant has the advantage of being able to feel a tangible object while performing the task or viewing the model. The physical feedback is often necessary when completing an HFE assessment, as it can be important to record realistic reactions from a participant. Some aspects of reality are lost while using the HFE program used for assessments: for example, the user is able to walk through hard boundaries, as the model doesn't obey the laws of physics. For example when objects are released they do not fall to the floor of the model due to gravity nor do they stop when they interfere with a surface. Without this physical feedback, it can be difficult to record realistic reactions from participants. In the VR environment, the user can see interferences between the avatar and the model by the model changing color when it detects collisions, but there is no physical (haptic) feedback. Haptic feedback is important because it would let the participant know if he/she is reaching through a boundary (like a model wall or shell).

During a combined mockup/VEL assessment, recording the reactions and movements of a participant can be done using a MoCap system. The VEL contains 16 infrared Vicon cameras that track markers on a spandex suit specifically designed for use with MoCap (Figure 8). The Vicon Blade program can track and record a participant's movements while simultaneously communicating with the HFE program. When mockups are used in the VEL they must built to allow optimum tracking, which is why mesh is often chosen to construct the mockups (example in Figure 8). The mesh surface is necessary to permit the infrared light to continue tracking the markers. An example assessment is a participant opening a hatch door, setting it to the side, and stepping through the opening. The goal of this assessment is to determine if a participant can successfully remove the hatch door and step through the opening safely and easily. The participant would wear the MoCap suit and VR headset while performing the tasks. In the HFE program, the Blade program will track the movement of the participant (shown in Figure 6), while he/she sees the hatch (as in Figure 6). The mesh mockup real world environment and the VR environment boundaries are aligned so the participant touches the mockup as she/he sees in the VR environment. This allows the participant to feel as though they are in the environment where the task will actually take place at KSC. Both Blade and the HFE program can record scenes to be viewed later and used in design reviews, design feedback, and/or training.

Figure 8: *A participant using the MoCap system wearing the Vicon suit and trackers.*

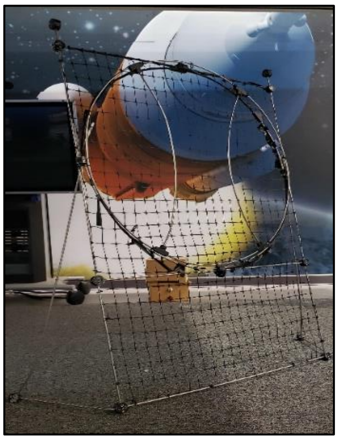

Figure 8*: Mesh mockup of a hatch design used in a HFE assessment. Mesh mockups are compatible with the MoCap trackers.*

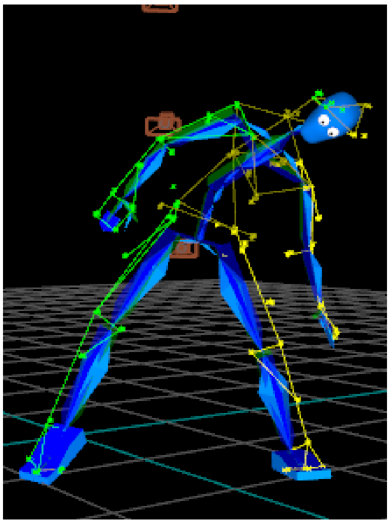

Figure 6*: The Blade program tracking the sensors on a MoCap suit*

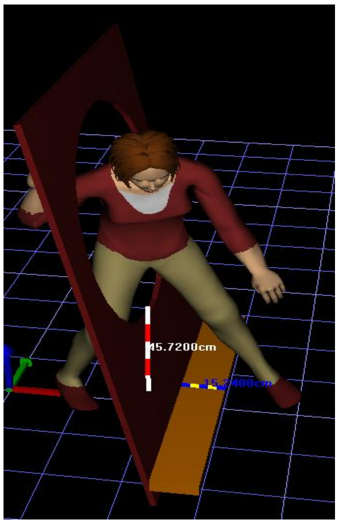

Figure 6: *HFE program avatar moving with the real-time MoCap tracking info sent from Blade*

6. Conclusions

The VR DSH work being performed at MSFC has allowed for fast-changing layouts to be analyzed by various departments without causing heavy impact to cost or schedule. These same techniques are being investigated for large programs, such as the SLS. Implementing similar methods for SLS will allow for VR use in early design cycles, saving schedule and budget. HFE analysis of these early designs will allow designs to be more thoroughly evaluated before physical mockups are built and, ultimately, improve usability and provide for a superior design.

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