NASA MARSHALL SPACE FLIGHT CENTER TOOLS FOR HUMAN FACTORS ENGINEERING ASSESSMENTS FOR SAFE SLS WORKSITES

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ABSTRACT

NASA Marshall Space Flight Center (MSFC) Human Factors Engineering (HFE) Team is implementing mockup fabrication, virtual reality (VR) and motion capture (MoCap) into HFE analyses of SLS worksites through its Virtual Environments Lab (VEL). MSFC HFE Team is responsible for the Space Launch System (SLS) worksite analyses of the integration activities performed at the Kennedy Space Center (KSC). With a wide variety of tasks, it is important to verify that SLS can be safely integrated at KSC early in the design process. If the ground support crew cannot safely complete the tasks, redesign efforts must be implemented. MSFC HFE is responsible for verification through methods such as drawing inspection, observation of tasks performed, and building physical mockups. There is a need, however, for a faster analysis early in the process that can impact design safety before drawings are finalized. This need is addressed through MSFC's VEL.

1. Introduction

MSFC's HFE Team is responsible for all worksite analyses performed for the SLS pre-launch integration activities at Kennedy Space Center (KSC). There is a wide variety of tasks associated with pre-launch integration activities and it is important to verify early in the design process that the vehicle integration will be successful. If the ground support crew cannot complete the required tasks, there will be a redesign effort. Early involvement of the HFE Team into the process helps reduce redesign costs associated with rework of physical hardware. Traditionally, analyses of integration activities are done using inspection of drawings and construction of mockups. These analyses are most beneficial early in the design phase when changes made to the design have little impact and take into account the HFE requirements. However, the early design phase is often so fluid that a mockup may not reflect the most recent design configuration.

VR allows for multiple analyses early in the process and more opportunities to give feedback to designers. Engineers can use this capability to compare design alternatives, but it is particularly valuable for HFE to provide recommendations for design improvement and safety input during the evaluation of these alternatives. With the near-term flight of SLS, VR is useful in the context of safety, HFE, and important milestone reviews. MSFC HFE is currently implementing these VR technologies for SLS worksite assessments. Physical mockups are still necessary for many task analyses, but VR can provide more insight in the early design changes. Sole use of VR analyses are very effective for some situations, such as providing early feedback during the design process, which can lead to a better-developed physical mockup. However, the need for physical mockups is still very real for assessments, which need to provide a feel for space constraints and multi-task evaluation.

Within the last year at MSFC, engineers developed a procedure for integrating Computer Aided Design (CAD) models into a VR environment. In order to conduct adequate HFE analyses, the VR environment provides an experience as close to reality as possible. VR use for HFE analyses at MSFC is proving valuable for engineering and safety efforts, especially during the early design phases. VR development will better influence the design before becoming a formal program, saving budget and time. The MSFC HFE VEL (shown in Fig. 1) will continue to implement VR technologies in these and other projects for better designs for safe assembly by ground crews.

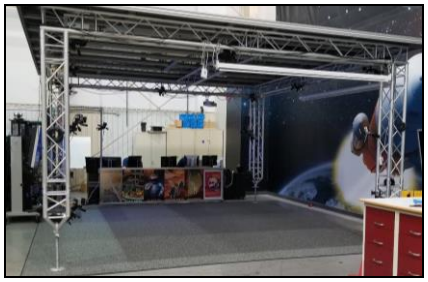


Figure 1. Virtual Environments Lab (VEL) at NASA's Marshall Space Flight Center. The VEL contains a 16 infrared Vicon motion capture camera system and VR capabilities with HTC Vive.

2. Current Processes

The MSFC HFE fabrication shop produces high quality physical mockups that are valuable to the engineering team. Fidelity of mockups depends upon budget, schedule, and type of assessment being performed. The HFE Team have performed assessments using physical mockups for decades, to provide recommendations to engineers for improving human accessibility and usability of their designs. Engineers and managers outside of the HFE team utilize these mockups to demonstrate hardware issues and make design decisions.

Mockups are often necessary early in the design process to demonstrate task difficulty and positively impact the next revision of a design. After the initial construction of a mockup and an analysis is completed, any change to the design can result in the need to update the mockups or build a new one before repeating the analysis. Finding a balance between the early requirement for a mockup and budget-saving measures can be difficult because of the sometimes costly modifications required to keep a physical mockup current with the design as it evolves. This can cause a circular need in the design process for constant updates to mockups.

While the need for physical mockups is not diminishing, designers can alternatively view their designs through VR immersion. This capability enables engineers to interact with their designs at full scale, providing them with a better understanding of user accessibility and workspace volumes at the beginning of the design process. This tool leads to improved layouts and a more informed engineering/management team. Fewer iterations of physical mockups are necessary if well planned designs are present prior to Critical Design Review (CDR).

3. Physical Mockup vs VR Environment

VR provides the ability to view a scene at a 1:1 ratio without building a physical mockup. When viewing a work volume or object, engineers can better detect potential issues and produce solutions if the workspace or object is at full scale. For this reason, it is beneficial to use a full-scale, three-dimensional, and interactive virtual model. It is also advantageous because an interactive VR environment offers a comparable experience to a physical mockup, while saving time, material, and money. 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 into an interactive VR environment in a day. As the design evolves, models from the designers can be continually incorporated into the VR environment; this saves the tremendous amount of time necessary to construct new physical mockups when designs are incorporated. 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 capability to manipulate and/or make changes to a model quickly in order to explore possible design changes. For example, a wall with a 10-inch diameter hole that is designed for a person to reach though to access a component will require weeks or months of preparation to build a physical mockup and plan for an assessment. Participants within the 5^{th} percentile female and the 95^{th} percentile male range, as described in the Anthropometric Survey of the US Army Personnel database [1]. Fig. 2 shows these height differences in a virtual environment and Fig. 3 shows a 5th percentile female participant reaching for the top of a physical mockup of the same design.

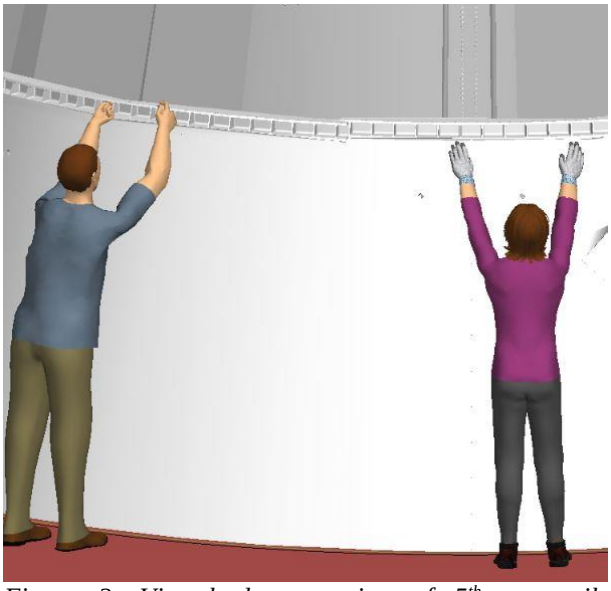


Figure 2. Virtual demonstration of 5^{th} percentile American female vs 95^{th} percentile American male



Figure 3. Demonstration of 5th percentile American female subject interacting with physical mockup

Participants would each try to reach through the hole and up to the box while being asked questions about the task. However, if a design modification is needed in order to improve accessibility, with a physical mockup, the hole cannot be revised without several hours or days of work, requiring a follow up assessment at another time. Contrasting, if this assessment were performed using human factors analysis software such as Siemens Jack or Process Simulate Human, the wall and the hole dimensions can be modified relatively quickly and, depending on complexity, during the assessment.

High-fidelity physical mockups are advantageous when factors such as heavy equipment and complex movements by the participants need to be analyzed. Most 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 HFE Analyses for SLS

Within the HFE Team at MSFC, engineers assess the success of a task within the project requirements and the ability to perform that task without damage to the flight article. NASA considers personnel safety and flight article protection to be top priorities. It is important to take steps to ensure the safety of the technicians and engineers involved in the life cycle of SLS in order to safeguard mission success. Using VR for design and verification processes allows the engineer to see and interact with an environment before construction, allowing the engineer to see potential issues early. This provides the engineer time to find a solution before a particular task needs to take place or a design is finalized. For example in Fig. 4, the HFE Team recommended adding a platform that allows the integration crew to more easily reach a part of SLS and successfully complete the needed task.

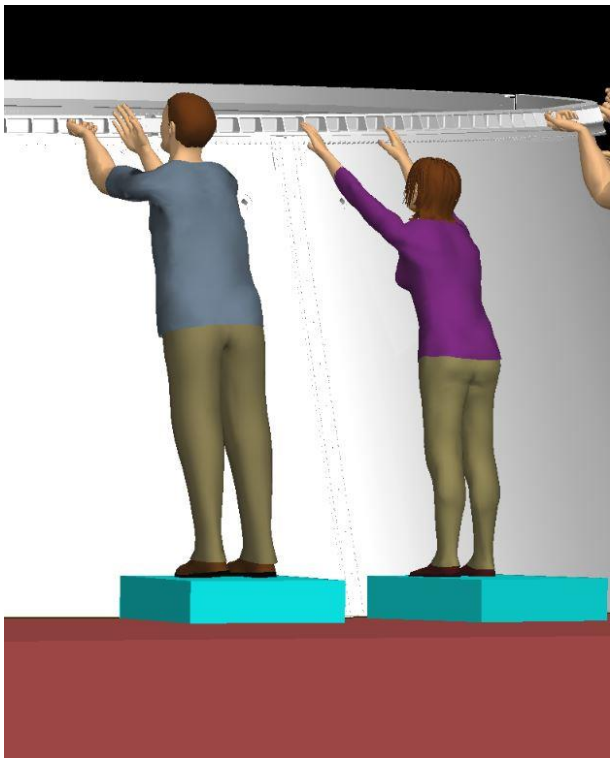


Figure 4. Demonstration of recommended platform heights to reach SLS parts when stacking SLS.

Although KSC is responsible for the ground processing of SLS, engineers at MSFC are responsible for building the elements and verification of the design, including HFE requirements. The requirements state that tasks shall be successfully completed by technicians that range from 5th female to 95th male percentiles. These standards are used to ensure that the technicians can safely perform the integration tasks, such as stacking of the elements, installation of payloads and hardware, and connecting cables between elements.

The HFE assessment begins with a breakdown of functions and their associated tasks, along with the type of analysis related to the assessment. Analyses can be performed by methods that include inspection of drawings, demonstrations using test articles or flight hardware, and/or tests where a process is completed using mockups or interactive VR environments. Functions and tasks, placed in a matrix, outline each task and how it lines up with SLS requirements to see if the requirement is applicable. Once an assessment plan is in place that verifies these requirements, it can be determined if a VR assessment is appropriate. If VR is an advantageous assessment medium, the CAD model is converted and imported into the VR environment. The participant then can then using the VEL.

The majority of HFE assessments at MSFC involve a reach analysis. For an SLS VR assessment, an SLS element CAD model is converted and uploaded into the human factors program. This program utilizes avatars and manipulates them to obtain an idea of task feasibility. These avatars are pre-programmed to have the limitations of a human body. For example, a human arm cannot rotate 360 degrees around the shoulder socket. This applied limitation to the avatars provides a more realistic scenario. The Human Factors Engineer imports the necessary objects (such as platforms and tools) into the software and integrates them with human avatars in the VR environment. The user can then experience the model at full scale with the ability to explore and manipulate the environment and model.

In the VR environment, the participant uses hand controllers to manipulate the environment, models, and avatars while wearing an immersive headset. 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. At the writing of this paper, the primary VR technology used by the HFE team at MSFC is the HTC Vive headset using Steam gaming software and HP Z VR computers (Fig. 5) designed to handle large amounts of data.



Figure 5. HP Z portable backpack computer with docking station and backpack



Figure 6. HTC Vive Lighthouse

The Steam gaming software uses two lighthouses (Fig. 6) to track the HTC Vive headset and hand controllers (Fig. 7). 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 schedule, 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 (Figs. 8 and 9).



Figure 7. Vive Pro HMD and Controllers

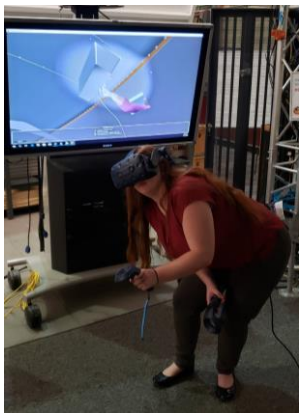


Figure 8. Flashlight tool

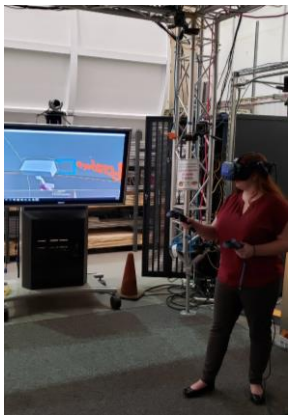


Figure 9. Markup tool

Integrating physical mockups with VEL technologies can result in a more thorough assessment than by using either of them independently. By combining physical and virtual mockups, the participant has the advantage of being able to feel a tangible object while performing a task or interacting with the model. This physical feedback is often necessary when completing an HFE assessment, as it is important to record realistic reactions from a participant. However, the features of the physical mockup can be low fidelity since the VR model is providing the visual details as an overlay on the physical mockup.

Aspects of reality are sometimes lost when performing a virtual assessment. For example, the user is able to walk through hard boundaries, as the model does not properly obey the laws of physics. In addition, released objects 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 is 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 they are reaching through a boundary (like a model wall or shell). The changing color can indicate where procedural improvement is essential to avoid a safety violation where technicians could injure themselves while performing a task.

The Motion Capture (MoCap) system can track the reactions and movements of participants during a combined physical/VR assessment. The VEL contains 16 infrared Vicon cameras that track reflective markers on a spandex suit designed for use with MoCap (Fig. 10).



Figure 10. A participant using the MoCap system wearing the Vicon suit

The system also utilizes Synertial Cobra gloves that record the hand position in the environment and feeds that information back into the MoCap system. This allows for analysis of tasks that require finger manipulations and hand movements. This is often needed for maintenance type tasks where components within a systems are removed and replaced.

The Vicon Blade program tracks and records a participant's movements while simultaneously communicating with the HFE program. This allows the avatar to move within the environment. Physical mockups used in the VEL need to allow optimum tracking. Selecting non-reflective mesh netting allows reflections to pass through the area of the mockup (example in Fig. 11). This allows the cameras to track the movements of participants as they move within the physical mockup.

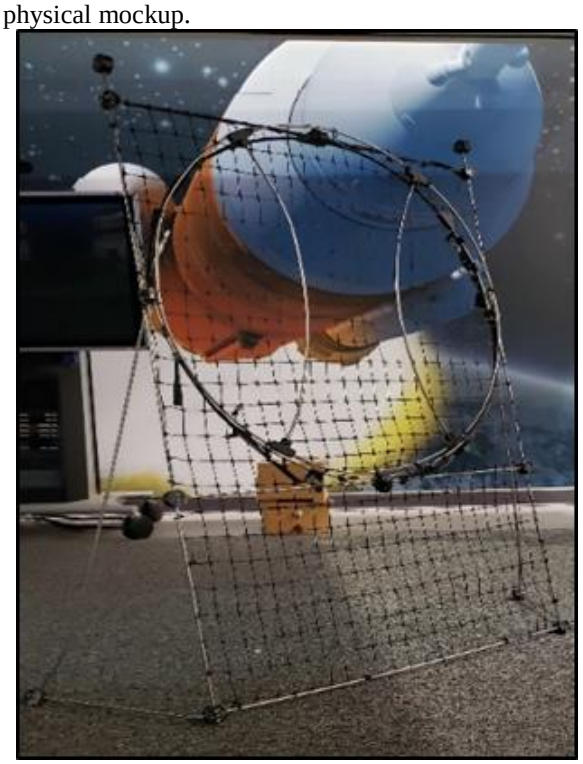


Figure 11. Mesh mockup of a hatch design used in an HFE assessment. Mesh mockups are compatible with the MoCap markers.

An example assessment utilizing both a mockup and VR can be seen in Fig. 11-13. Here a participant would open a hatch door, set it to the side, and step 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 without damage to hardware. The participant would wear the MoCap suit, Synertial gloves, and VR headset while performing the tasks. The Blade program tracks the movement of the

participant (shown in Fig. 12) while he/she sees the hatch (as in Fig. 13).

The mesh mockup real world environment and the VR environment boundaries align so that the participant touches the mockup as they see it 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 view later for use in design reviews, design feedback, and/or training.

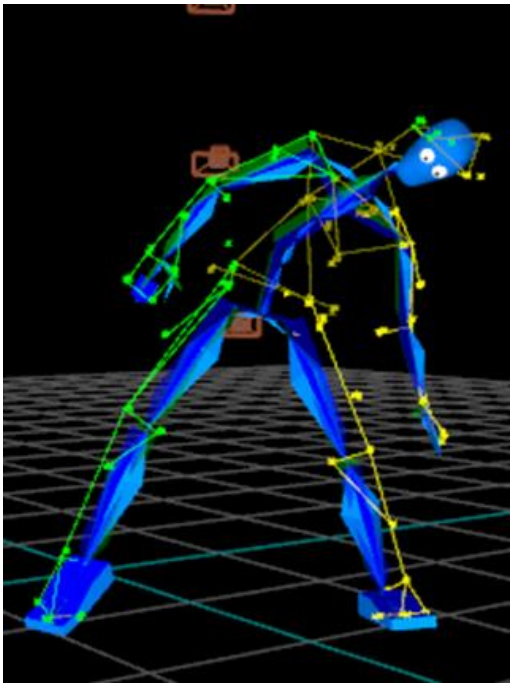


Figure 12. The Blade program tracking the markers on a MoCap suit



Figure 13. HFE program avatar moving with the real-time MoCap tracking info sent from Blade

5. Conclusions

The VR work performed by the HFE team at MSFC has allowed fast changing layouts to be analyzed by various departments with minimal impact to cost or schedule. Implementing these methods for SLS allows for VR use in early design cycles, saving time and budget. Utilizing the resulting HFE analyses improves usability and safety. Ultimately, the goal is to provide a safe environment for the technicians assembling the vehicle and the astronaut crew at launch.

6. References

1. US Army NATICK Soldier RD&E Center: 2012 Anthropometric Survey of U.S. Army Personnel: Methods and Summary Statistics: (NATICK/TR-15/007) Updated December 2014

2. Vicon Blade, https://www.vicon.com/products/software/blade

3. Wallace, Brianna: Virtual Reality Conversion Manual. (2018). Technical report, NASA Marshall Space Flight Center