(NASA-TM-110737) APPLIED VIRTUAL REALITY IN AEROSPACE DESIGN (NASA. Marshall Space Flight Center) 6 p

N96-13397

Unclas

G3/90 0065137

NASA-TM-110737

APPLIED VIRTUAL REALITY IN AEROSPACE DESIGN

Joseph P. Hale
Crew Systems Engineering Branch/EO23
NASA/Marshall Space Flight Center
MSFC, AL 35812

A Virtual Reality (VR) applications program has been under development at the Marshall Space Flight Center (MSFC) since 1989. The objectives of the MSFC VR Applications Program are to develop, assess, validate, and utilize VR in hardware development, operations development and support, mission operations training and science training. Before VR can be used with confidence in a particular application, VR must be validated for that class of applications. For that reason, specific validation studies for selected classes of applications have been proposed and are currently underway. These include macro-ergonomic "control-room class" design analysis, Spacelab stowage reconfiguration training, a full-body micro-gravity functional reach simulator, a gross anatomy teaching simulator, and micro-ergonomic design analysis. This paper describes the MSFC VR Applications Program and the validation studies.

INTRODUCTION

A Virtual Reality (VR) Applications Program has been under development at the Marshall Space Flight Center (MSFC) since 1989. Its objectives are to develop, assess, validate, and utilize VR in hardware development, operations development and support, mission operations training and science training (Hale, 1993a). One of the goals of this technology program is to enable specialized Human Factors analyses earlier in the hardware and operations development process and develop more effective training and mission support systems (Hale, 1993b).

The MSFC VR systems reside in the Computer Applications and Virtual Environments (CAVE) Lab in Building 4610. System components consist of VPL Research, Inc. Eyephones (Models 1 and LX), DataGloves, and software (Swivel 3D, Body Electric, and ISAAC), Polhemus Isotrak and Fastrak spatial tracking systems, two Macintosh IIfx computers and two Silicon Graphics Inc. graphics computers (4D/310VGX and 4D/320VGXB). Two single-person configurations are possible. One uses the Eyephone Model 1 with one DataGlove. The other single person configuration uses the Eyephone LX with one or two DataGloves (i.e., both right and left hands, simultaneously). Both single person configurations provide stereo views. A two-person configuration is possible. It combines the two single person configurations, but provides only monocular views to each Eyephone. In the two-person configuration, both people are in the same Virtual World (VW) simultaneously and each is able to see and interact with the computer-generated image of the other.

Several CAVE Lab VR development activities are underway. EXOS, Inc. is under contract to develop a Sensing And Force-Reflecting Exoskeleton (SAFiRE) for the hand. This device will provide force-reflecting feedback to the fingers and hand as the user touches and grabs virtual objects. Tomorrowtools is under contract to develop a multi-sensor spatial tracking system. Using ultra-sonics to determine the location of each of the sensors and infrared to transmit data to the base units, this system provides an untethered method to track up to 30 body points and/or other objects simultaneously. This will be particularly useful in dynamic work envelope analyses. Tomorrowtools is also developing a capability to remotely interact with our VR system using Integrated Services Digital Network (ISDN) telecommunications. This would allow a user at a remote site to don a Head-Mounted Display (HMD), plug into an ISDN wall jack, and immersively navigate a virtual world running in the CAVE Lab. In-house, work is underway to broadcast the video signals to the Eyephones, thus removing the video cable that tethers the user to the system.

The CAVE Lab is also collaborating with the Johnson Space Center (JSC) in their efforts to develop a "long distance" two-person capability using their in-house developed VR system. This means allowing two people to see and interact with the computer-generated image of the other in the same Virtual

World, simultaneously, with one person at JSC and the other at MSFC! Basic capabilities have already been demonstrated. As VR technology evolves, this virtual link between, and eventually among, the NASA Centers will provide major foreseeable and unanticipated benefits.

COMPUTATIONAL HUMAN FACTORS

Human Factors issues and considerations in hardware and operations development present a large class of potential VR applications. VR technologies and techniques currently provide some limited ergonomic analytical tools for consideration of operational, viewing, and reach envelope requirements in both one-gravity and micro-gravity environments. Combined with scaleable user anthropometry, micro-ergonomics analyses for workstation spatial layout enables the consideration of fields-of-view from a variety of eye reference points and reach envelopes from a variety of shoulder and seat reference points and/or foot restraint locations, using a range of virtual anthropometric sizes.

The capability to perform specialized Human Factors analyses earlier in the hardware and operations development process is required to better refine and validate requirements during the requirements definition phase. This leads to a more efficient design process where perturbations caused by late-occurring requirements changes are minimized. A validated set of VR analytical tools must be developed to enable a more efficient process for the design and development of space systems and operations.

Many Human Factors analyses that currently use full or part-scale "Fomecor" mockups, the KC-135 (provides approximately 30 seconds of weightlessness during each cycle of parabolic flight), or the Neutral Buoyancy Simulator (NBS) (underwater facility for simulating weightlessness) are candidates for VR. It is not that VR would completely replace these other technologies and techniques, but adds another tool to the analytical toolkit. Because VWs are nothing more than computer files, design changes can be done faster and more candidate configurations can be subsequently analyzed than is currently possible with existing, "standard" Human Factor tools (e.g., Fomecor mockups).

In some instances, VR might be considered for use in an analysis that would have otherwise not be undertaken. Resources (time, people, materials, etc.) required for a "standard" simulation or mock-up analysis may be greater than the expected return. In this case, VR, due to its relatively low utilization costs, would surpass the cost/benefit ratio threshold and enable an analysis that would have otherwise been forgone.

Similarly, VR can enhance and enable more effective utilization of standard simulations and mock-up analyses. By preceding these analyses with preliminary VR analyses, both the hardware and operations can be refined so that the return from the standard analyses is increased. This is accomplished by either reducing the magnitude or number of standard analyses and/or improving the fidelity of those analyses with a more mature design. For example, the first NBS dive of a four-dive series could be replaced by a VR simulation to checkout and refine preliminary procedures, verify locations of foot restraints and translation aids, and modify worksite configurations. It could even be used to brief the dive support cadre and pre-determine desirable swim camera (video) and still photography views.

VALIDATION STUDIES

Before VR can be used with confidence in a particular application, it must be validated, or calibrated, for that class of applications. The approach of the MSFC VR Applications Program is to develop and validate appropriate virtual environments and associated object kinematic and behavior attributes for specific classes of applications. These application-specific environments and associated simulations will be validated, where possible, through empirical comparisons with existing, accepted tools and methodologies. These validated VR analytical tools will then be available for use in the design and development of space systems and operations, and in training and mission support systems.

One class of VR applications is as a Human Factors design analysis tool for work areas and other architectural spaces. The use of VR in the macro-ergonomic analyses of work area topological design enables the consideration of the fields-of-view from a variety of eye reference points and can include operationally-driven components such as translation paths among the various worksites. Examples of "spaces" include control rooms, space stations, and orbiting telescopes (Null and Jenkins, 1993).

A validation study for "control-room class" ergonomic applications, to help characterize possible distortions or filtering of relevant perceptions in a virtual world, was recently completed (Hale and Dittmar, 1994; Dittmar and Hale, 1994). Two existing control rooms and their corresponding virtual counterparts were used to collect subjects' qualitative and quantitative judgments on a variety of measures. The Spacelab Payload Control Room (PCR) and Simulation Control Room (SIM) were selected, based on their apparent separation on a variety of continua (e.g., large/small, spacious/cramped, aesthetically well/poorly designed, etc.). Corresponding Virtual PCR (VPCR) and Virtual SIM (VSIM) were developed that contain the basic elements (e.g., tables, monitors, printers, communication panels, etc.) and spatial layout of their real world counterparts.

A 2x2(x2x2) , full-factorial experimental design with 2 within subjects variables and 2 blocking variables was employed. In addition, two pairs of crossed two-level within subjects variables were nested in one of the "main" within subjects variables. The overall Independent Variables (IVs) were World (Real/Virtual) and Room (PCR/SIM) with Gender and World Order (Virtual-Real/Real-Virtual) as blocking variables. Nested within Room were range and relative range estimations. Range estimations, where subjects estimated the range to specified items in the room, took place in the SIM/VSIM and were comprised of two IVs: 1) Item (Object/Surface) and 2) the Item's Range from the observer (Near/Far). A second, partial, range estimation condition was constructed in which rooms (PCR/SIM) were compared with World and Range, with only objects being involved in the estimates. This second set of conditions was employed to examine the effects of room context on the other variables. The relative range estimations, where subjects were required to make a forced choice of which object of a pair of objects was closer, took place in the PCR/VPCR and were also comprised of two IVs: 1) Field-of-View (FOV) (Same/Different, i.e., whether or not the subject can see both objects simultaneously in the same FOV) and 2) the objects' Distance from the observer (Close/Away). Range estimation, relative range forced choice, and elapsed time to answer range and relative range questions were collected as dependent variables. Thirty-two subjects (sixteen males and sixteen females) participated in this study.

The results indicated that choosing which of a pair of objects is closest when their relative range from the observer differs by only 2 inches appears to be relatively easy when they both appear in the same FOV, but quite difficult when they appear in different FOVs. This is true regardless of whether the observer is in the "real" or "virtual" worlds. For the same FOV, subjects did as well with near objects as they did with far objects. For different FOVs, subjects in the real world did no better than chance in choosing the closest object and actually chose the wrong object in the virtual world. For far objects, subjects actually chose the correct object in the real world, but did no better than chance in the virtual world. Thus it appears there is some degree of perceptual filtering or distortion occurring within the virtual world. Even though subjects had a somewhat difficult time in the real world with different FOVs, they did less well in the virtual world with different FOVs.

Although this is an initial estimate and should be refined in future studies, it appears a 2 inch differential is clearly discriminable for objects in the same FOV, regardless of world; barely discriminable in the real world in different FOVs; and not discriminable in a virtual world in different FOVs. This suggests some limits to which one can confidently rely upon perception and analyses in virtual environments.

Subjects were also more accurate in estimating ranges to objects than to surfaces. It is suspected that this is related somewhat to both the object's smaller size and the subjects' greater familiarity with notebooks. The former permits perception of more contextual cues (e.g. on a table), the latter offers object size consistency cues (i.e., changing retinal image size is attributed to change in range rather than change in size). Further, lack of textures for the virtual surfaces removes important contextual cues for range estimation. Finally, women underestimated distance more in the real world, whereas men underestimated in the virtual world. This is the only significant gender-related finding in this study and, lacking other corroborating evidence, it would appear more than likely to be an artifact. However, it will be interesting to see if this reappears in future studies.

In terms of elapsed time, subjects took longer to make relative range choices for objects in the different FOVs and in all cases, subjects took longer to respond in the virtual world than in the real world. Part of the different FOV finding would be expected since subjects had to repeatedly turn their heads to compare the two object ranges. But overall, these findings suggest subjects had to gather and/or process more perceptual cues to make a determination. In the different FOVs, the pairs of objects lacked the shared occlusive and parallax attributes of the pairs of objects in the same FOV. As for the virtual world, it is not as rich in textures, shadows, and "clutter" as the real world.

The primary objective of this experiment was to begin the process of validating and calibrating the use of VR as a Human Factors analytical tool. Overall, there appears to be little difference between real and virtual worlds in one's ability to differentiate and estimate distances at approximately three and six feet. This is also true for discrimination of 2 in differentials at those distances with objects within the same FOV. For different FOVs, this discrimination ability starts to deteriorate in the real world and is lost in the virtual world. Thus, analyses using this technology that depend upon gross range estimations seem permissible, but those relying upon fine range perceptions should be approached with caution.

The very clear main effect of World (increased time to make judgments in the virtual world) provides guidance as to when and when not to use this technology as an analytical tool. If task times, for example, are a critical component of the analysis, the use of this technology should be carefully considered.

However, these cautions will naturally be relaxed as the technology evolves. Texture mapping, a feature now generally available but not a part of this study's VR system, is an example of a technological advance that should modify these cautions and enlarge the set of VR application classes.

Three VR studies are currently underway in the CAVE Lab. The first is a Spacelab Stowage Reconfiguration Trainer. The essential feature of this application is a Virtual Spacelab Module (VSLM). It involves using this VSLM during the last nine-to-six months before launch. There are always late changes to on-board stowage. As changes are made, the MSFC Payload Crew Training Complex (PCTC) Training mock-up is updated. It is desirable to allow the crew the opportunity to tour the mock-up to "see" the latest stowage configuration. This helps to "internalize" the location of items within the Spacelab module. Unfortunately, as the launch date approaches, access to the crew becomes more and more limited, particularly during the last three months when the crew is dedicated primarily to the Johnson Space Center (JSC).

A VSLM with the updated stowage configuration would enable a more convenient, even remote, method to "visualize" changes in stowage locations. Updated VSLM files could even be electronically transmitted to JSC for the crew to "tour" on the JSC VR system. To further enhance this training application, using both the MSFC and JSC VR systems simultaneously, the users could enter and interact within the same VSLM at the same time, even though they are physically located in different states. This would permit, for example, a Mission Specialist at JSC to be accompanied by the stowage manager or a Payload Specialist at MSFC for the stowage "walk-thru."

The pathfinder Spacelab for this VR application is the second International Microgravity Lab (IML-2). A VSLM with two "stocked" lockers has been developed along with application-unique kinematic and object behavior attributes. The simulator is currently being evaluated and refined.

The second ongoing VR study is a full-body micro-gravity functional reach simulator. In one-gravity, one's side-to-side and front-to-back unrestrained full-body reach envelope is constrained to keeping one's center of mass over one's feet; otherwise you fall. In micro-gravity with the feet in foot restraints, one is able to sweep a "hemi-ellipsoid-ish" surface while pivoting about the feet, constrained by the various joint ranges-of-motion. In this study, the "hemi-ellipsoid-ish" functional reach surface was first approximated using Mannequin Designer, a computerized 3-D anthropometric modeling application by Biomechanics Corp. of America. As of this writing, these data points are being used to define curves that will then be incorporated into a virtual world to give the egocentric perception of a full-body micro-gravity functional reach envelope. This fall, more precise data will be gathered in the Neutral Buoyancy Simulator (NBS) using a 3-D underwater measurement system designed by Marquest Group under the NASA Small Business Innovative Research (SBIR) program. This system has been designed to take up to six point measurements twice every second. These data will be used to validate and refine the VR model.

The third study is related to science training. It will assess the use of VR to help teach gross anatomy. A "virtual cadaver" with abdominopelvic organs is now being developed. This fall, it will augment current teaching methods at a local college. Assessments will include whether the students learned faster, gained a deeper level of understanding, and/or had longer retention.

An additional study is being planned that involves a proposed redesign of the Crew Interface Coordinator (CIC) console. In this study, VR will be evaluated as a micro-ergonomics analysis tool to consider operational, viewing, and reach envelope requirements in the spatial layout of workstations and worksites. It will include scaleable user anthropometry attributes. An algorithm has been developed to rescale user anthropometric attributes to any desired virtual anthropometry. Thus, a 95^{th} percentile male could view and reach as a virtual 5^{th} percentile female and vice-versa.

The study will compare the proposed redesigned CIC console with a Virtual Crew Interface Coordinator (VCIC) console. Test scenarios will be performed on both a "Fomecor" mock-up of the CIC console and the VCIC console and their results compared to ascertain what, if any, distortions arise in a VW. The test scenarios focus on the fields-of-view from a variety of eye reference points and the reach envelopes from a variety of shoulder reference points using a range of real and virtual anthropometric sizes. Results of these analyses are also compared to determine the relative merits of VR vis-a-vis an existing, "standard" Human Factor's tool (i.e., "Fomecor" mock-up).

"REAL WORLD" APPLICATIONS

The MSFC VR capability has already been utilized in two activities. Both primarily involved immersive visualization of architectural spaces. One supported the recent move of the CAVE Lab into its new quarters, the other supported the 30% design review of the late Space Station *Freedom* Payload Control Area (PCA).

In support of the CAVE Lab relocation, two different lab floor plans were developed and modeled in VR. Several of the lab staff then "entered" the virtual lab designs and evaluated the configurations as both users and visitors. Due to the extensive CAVE Lab communications and computer networking requirements, it was very important to settle on a layout before the move started. All of the cabling and ports had to be in place before the move, to minimize downtime. Similarly, to reconfigure the Lab after the move would require extensive re-cabling and further downtime. During these evaluations, potential design problems that were not apparent on the floor plans became evident. The layouts were then modified near real-time and re-evaluated. Based upon these evaluations, one modified layout was chosen and implemented.

In a second activity, support was provided to the 30% design review of the late Space Station *Freedom* Payload Control Area (PCA). The PCA will be the payload operations control room, analogous to the Spacelab POCC. Several configurations of the console floor plan layout, large video screens, and Public Viewing Area were modeled in VR. Engineers, management, and the Public Affairs Office (PAO) utilized the system to immersively visualize the options. Engineers and management were able to focus on the operationally-driven design features, such as the team-based grouping and layout of the consoles. PAO evaluated the view from the Public Viewing Area, considering what a range of visitor sizes (e.g., 3.5 ft six year olds, 6.5 ft adults) might be able to see from a range of viewing area floor heights. PAO was also able to perform a preliminary camera viewing analysis, "flying" to various possible camera locations to inspect the composition of the possible camera fields-of-view. The ability to pan and tilt and change "lens" (i.e., narrow to wide angle fields-of-view) in real-time was especially useful.

FUTURE APPLICATIONS

A demanding and comprehensive application for VR is support of unplanned In-Flight Maintenance (IFM). That is, subsets of the features and VR capabilities required to support this application are used in a variety of other applications. Support to unplanned IFM requires Human Factors analyses (e.g., viewing, reach, and dynamic work envelope analyses), operations development, training, and mission support. It could even require those developing and assessing the procedures to simultaneously be in the same virtual environment even though they might be in different geographic locations.

An example of an unplanned IFM occurred on Spacelab 3. This actual Spacelab mission experience will also be used for comparison in the validation of this application. The goal would be to actually recreate the IFM environment and operation, then compare this virtual IFM experience with the actual flight experience. This would include reference to video and audio recordings of the on-board operation, written logs, and participation of the actual Spacelab crew involved in the IFM operation.

During Spacelab 3, the Drop Dynamics Module (DDM) developed a problem with a power supply module. One of the three DDM AC power supplies had failed. There were no procedures or plans developed pre-mission for this particularly malfunction, nor were there any spare power supplies stowed. It was decided to cut the wires from the failed power supply and re-route them to one of the other power supplies that could handle the extra load. Procedures had to be developed and validated on the ground and approved by both MSFC and JSC before they were uplinked to the crew. The procedure required removal of the rack front panel before the Payload Specialist (PS) entered head first. Only his legs remained visible outside of the rack. Inside the cramped rack interior, the PS successfully re-wired the power supply modules and continuation of the science objectives resumed.

It is anticipated that enhanced VR would have been capable of supporting many of the activities and analyses that occurred on the ground during this unplanned IFM. Viewing analyses, reach envelope analyses, and, with an incorporated anthropometric model, dynamic work envelope analyses can be achieved concurrently with procedure development. Although much of this can be done in an engineering mock-up, VR offers several unique capabilities.

First, VR could provide a timely and safe method to enable the various advantages and disadvantages of reaching and maneuvering in a micro-gravity environment, including body attitudes and positions difficult to recreate in a one-G environment. This would be superior to existing methods for simulating micro-gravity because existing methods can not be used in a timely manner and are of limited duration (KC-135), or require ancillary equipment (Neutral Buoyancy Simulator), that can interfere with operations in restricted volumes. Second, VR would permit anthropometric sizing to reflect the dimensions of the on-board crew – particularly useful for operations being planned in relatively tight spaces.

Since a payload IFM procedure has to be approved by MSFC and JSC before it can be implemented, VR would offer mission and payload managers the ability to visualize the procedure and environment to gain a faster and more in-depth understanding of the operation – all while sitting at their consoles in the control center. Further, managers at both centers could enter the VW simultaneously to review and discuss the operation. This capability for direct mission support would be unprecedented, though the possibilities are not limited to unplanned IFMs.

Pre-mission operations development and validation could also be carried out in the same manner, even though the rapid turn-around capability of VR is not necessarily a requirement. Pre-mission crew training could use the same VWs developed to support procedure development. This would prove particularly beneficial for operations where the various advantages and disadvantages of reaching and maneuvering in a micro-gravity environment make a difference.

Enhanced VR technologies and techniques could also provide unique capabilities not presently possible with current simulation technologies. Currently, there is no way to practice the logistics of handling multiple, mobile objects in a simulated micro-gravity environment. The duration of the micro-gravity periods on the KC-135 are too short (approximately 30 seconds) and the viscous drag and motion-induced turbulence in water makes neutral buoyant methods unsuitable. VR, with suitable tactile and force-reflective feedback and a physics properties simulator reflecting physical laws concerning motion and collisions, could prove to be a valuable operations development and training tool for applications requiring dexterous, fine-motor movements.

SUMMARY

This paper has described the VR Applications Program at MSFC, including objectives and approaches. Current and planned applications and associated validation approaches were presented. Viewing analyses, reach envelope analyses, and dynamic work envelope analyses can be achieved concurrently with procedure development. VR can provide a timely and safe method to enable the various advantages and disadvantages of reaching and maneuvering in a micro-gravity environment. This would be superior to existing methods for simulating micro-gravity because existing methods can not be used in a timely manner and are of limited duration. Even where the KC-135 and/or the Neutral Buoyancy Simulator are appropriate, prior utilization of virtual mockups can result in more efficient use of these micro-gravity simulators. Hardware and operations design can be more mature, resulting in fewer and/or more productive simulator sessions.

REFERENCES

Dittmar, M. L., and Hale, J. P. (1994). Virtual reality as a human factors design analysis tool for architectural spaces - control rooms to space stations II: Subjective measures. In Proceedings of the Human Factors Society 36th Annual Meeting, Santa Monica, CA: Human Factors Society. (in press)

Hale, J. P., and Dittmar, M. L. (1994). Virtual reality as a human factors design analysis tool for architectural spaces - control rooms to space stations II: Objective measures. In Proceedings of the Human Factors Society 36th Annual Meeting, Santa Monica, CA: Human Factors Society. (in press)

Hale, J. P. (1993a) Marshall Space Flight Center's virtual reality applications program In Proceedings of the 1993 Conference on Intelligent Computer-Aided Training and Virtual Environment Technology, (pp. 271-276). National Aeronautics and Space Administration, Lyndon B. Johnson Space Center .

Hale, J. P. (1993b) Virtual reality as a human factors design analysis tool. In Proceedings of the Southeastern Simulation Conference, (pp. 140-144). Huntsville, AL.

Null, C. H. and Jenkins, J. P. (Eds.) (1993) NASA virtual environment research, applications, and technology. National Aeronautics and Space Administration