Application of Virtual Reality Technology, Including Force Feedback, for Astronaut Training

Charles J. Gott and David J. Homan

Simulation and Graphics Development Branch
Automation, Robotics, and Simulation Division
NASA Johnson Space Center, Mail Stop ER6
Houston, Texas 77058
U. S. A.
e-mail: cgott@gp301.jsc.nasa.gov

Abstract

The application of virtual reality technology to ground-based training of astronauts in preparation for extravehicular activity (EVA) on Space Shuttle missions was initially evaluated in conjunction with the first Hubble Space Telescope repair mission in 1993. This initial proof-of-concept application was used by the remote manipulator system (RMS) operator and the EVA crew member positioned on the end of the RMS to establish and validate a command protocol for directing movements of the RMS during integrated operations. A second application was successfully developed to support training in the use of the Simplified Aid for EVA Rescue (SAFER) unit, flight tested on STS-64 in the fall of 1994. The helmet-mounted display was integrated with the SAFER avionics and hand controller hardware and flight software into a simulation which provided a 3-D graphics representation of the Orbiter payload bay and RMS configurations as seen from the vantage point of the SAFER crew member. Again, this application afforded a capability to train in an integrated environment not available in other ground-based simulators. A third capability being developed and evaluated in Johnson Space Center's Integrated EVA/RMS Virtual Reality Simulation Facility involves a force feedback device to simulate the zero-g mass characteristics of large (>500 lbs) on-orbit replaceable units. A tendon-driven robotic device provides the kinesthetic sensation of the mass and inertia characteristics of the object being handled, while the helmet-mounted display provides the virtual reality subject with a visual representation of that object and its surroundings. Results from these initial demonstrations have shown the potential for virtual reality technology to support ground-based preparation for on-orbit integrated EVA/RMS operations as well as EVA free-flyer piloting.

Key Words: virtual reality, helmet-mounted display, force feedback, astronaut, zero-g

Introduction

The remote manipulator system (RMS) is part of the overall Payload Deployment and Retrieval System on the Space Shuttle and consists of an anthropomorphic, 50 ft long, 6 degree-of-freedom manipulator whose tip position and attitude are controlled from the Orbiter aft flight deck by a crew member operating two 3 degree-of-freedom hand controllers. The primary task of the RMS is to support deployment and retrieval of payloads from the Orbiter payload bay. It was first flown on STS-2 in November 1981. In April 1983 on STS-6, the first extravehicular activity (EVA) from the Space Shuttle was performed. On STS-41B (February 1984), these two capabilities were combined using the manipulator foot restraint (Fig. 1)—a device that attaches to the end of the RMS and allows an EVA crew member to be maneuvered around on the RMS similar to the way "cherry-pickers" are used by local utility companies to position workers at work sites above the ground.

Figure 1. MFR operations.

The highly integrated nature of on-orbit EVA/RMS operations provides some unique challenges to ground-based training for flight crews, particularly when scenarios involve one EVA crew member on the end of the RMS or an EVA crew member flying free, as in the Simplified Aid for EVA Rescue (SAFER) flight demonstrations. Ground-based facilities are also limited by the amount of physical volume available in which to assemble actual on-orbit hardware configurations. Virtual reality provides a means to practice these integrated operations in an on-orbit configuration with no discomfort or risk to the crew members involved, and with no geometric limitations on the physical size of the simulated hardware configuration. The goal of the Automation, Robotics, and Simulation Division (AR&SD) at the Johnson Space Center (JSC) is to conceive, develop, and evaluate applications for virtual reality that are directly applicable to JSC's role in engineering design and crew training for human presence in space.

To date, the AR&SD has built integrated EVA/RMS virtual reality simulations for five shuttle missions: Hubble Space Telescope repair (STS-61), Wake Shield Facility contingency retrieval (STS-60), SAFER flight demonstration (STS-64), EVA Flight Demonstration Test (EFDT) 01 and mass handling demonstration (STS-63), and EFDT-02 (STS-69).

Ground-Based Training Constraints

Training for an EVA that does not involve RMS operations and (vice versa) training for RMS operations that do not involve EVA crew members are fairly straightforward and are accomplished in part task trainers. The bulk of EVA training is done in the neutral buoyancy facilities located at JSC and the Marshall Space Flight Center. The Weightless Environment Training Facility (an 80 ft x 30 ft x 25 ft deep water tank at JSC) and the Neutral Buoyancy Simulator (a 75 ft diameter x 40 ft deep water tank at Marshall Space Flight Center) provide excellent training for EVA work, but because of limited volume cannot encompass the entire RMS reach envelope to provide adequate RMS training.

EVA crew members use the neutral buoyancy facilities to rehearse detailed procedures and scenarios for performing nominal and contingency extravehicular tasks in and around the Orbiter payload bay. The Weightless Environment Training Facility and the Neutral Buoyancy Simulator both contain mechanical representations of the RMS to provide integrated EVA/RMS operations training; however, several shortcomings do arise. Prior to the fall of 1993, neither manipulator was capable of operating in the same manner as the RMS. (The manipulator in the Neutral Buoyancy Simulator has since been modified to make it more flight-like in its operating characteristics.) The manipulators were operated one joint at a time, not in six-joint coordinated motion as is the case with the Orbiter RMS on orbit. In addition, the manipulators in the neutral buoyancy facilities did not use the same control algorithms or reach limit annunciations as the actual RMS, thus allowing the facility manipulators to attain configurations that were not acceptable for on-orbit operations. Another drawback is that the amount of the actual Orbiter/payload configuration that can be accurately simulated at any one time is limited by the physical volume of each facility. Figure 2 shows the on-orbit payload bay configuration for the Hubble Space Telescope repair mission as compared to the volume of the Neutral Buoyancy Simulator at Marshall Space Flight Center. Figure 3 makes the same comparison with the Weightless Environment Training Facility at JSC. The volume limitations of the facilities are accommodated by rearranging the components to fit within the confines of the tank, as in Figure 4 which shows the training configuration for the Hubble Space Telescope at the Neutral Buoyancy Simulator.

One obvious problem that occurs in training for integrated EVA/RMS operations in this situation is evident when comparing the on-orbit configuration (Fig. 2) with the training configuration (Fig. 4). The top of the telescope is physically in a different place in the training set up than it is in the real world, thus leading to completely different RMS configurations to support training and on-orbit work at the same location on the Hubble Space Telescope.

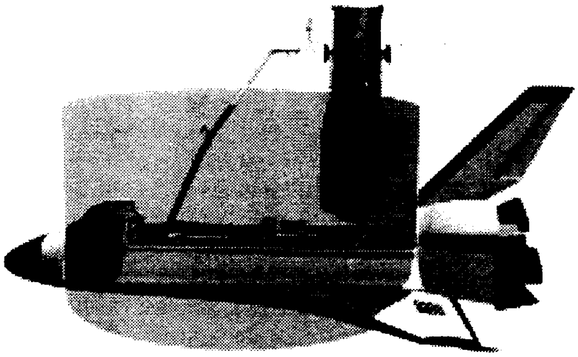

Figure 2. NBS at MSFC.

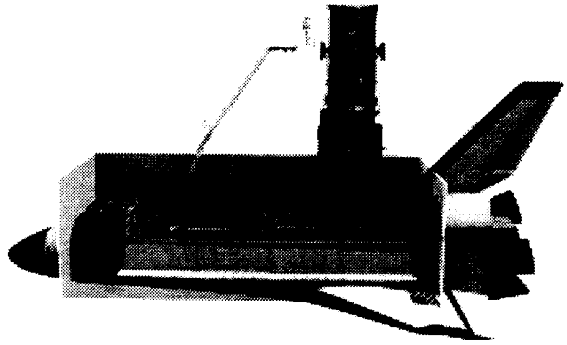

Figure 3. WETF at JSC.

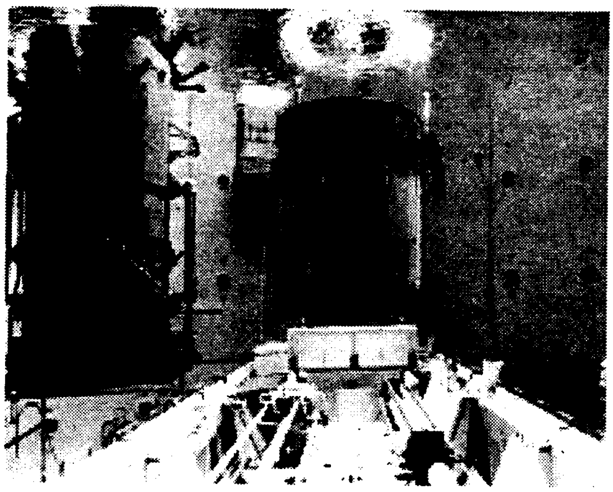

Figure 4. HST configuration in the NBS.

The other side of the training coin (RMS training) has similar shortcomings when it comes to integrated EVA/RMS scenarios. RMS training is accomplished in a number of man-in-the-loop simulators that range from graphics computers on a desktop to the Shuttle Mission Simulator, which has a high fidelity aft flight deck mock-up with graphically generated out-the-window scenes, to the Manipulator Development Facility, which is a full-scale aft flight deck and payload bay mock-up with a hydraulic manipulator to mimic real RMS operations. The Shuttle Mission Simulator produces high fidelity training in the use of the RMS and other intravehicular activity tasks that support EVAs, but the EVA crew members are left out of the equation. Likewise, the Manipulator Development Facility provides high fidelity training for the RMS operator but since the hydraulic manipulator is not man-rated, the EVA crew member on the end of the "arm" is replaced by an inflatable mannequin, and the real EVA crew member is positioned on the catwalk extending along the side of the payload bay mock-up and tries to imagine being on the end of the "arm." This approach works reasonably well until the person on the end of the RMS is put into a position other than vertical, at which time the mental gymnastics required to envision the correct view from the mannequin's vantage point become cumbersome and confusing to both the real EVA person and the RMS operator. The Manipulator Development Facility and the Shuttle Mission Simulator at JSC provide excellent RMS training but do not support EVA training.

Virtual reality was first applied by the AR&SD at JSC to bridge this gap between EVA and RMS part task training for integrated scenarios.

Integration of Virtual Reality Environment Into Astronaut Training

Looking past all the hype of virtual reality today, it is obvious that the technology to create the "holodeck" on the *Starship Enterprise* still lies in the distant future. In fact, a good analogy puts it comparable to being at the Wright Flyer end of the spectrum heading toward the Space Shuttle. However, the current capability of virtual reality technology does offer a useful solution to the problem of ground-based integrated training for EVA/RMS operations on Space Shuttle missions, and it offers this capability at a reasonably low cost—a factor to be considered in light of today's declining budgets.

In 1992, AR&SD's Integrated Graphics Operations and Analysis Laboratory (IGOAL) initiated work on a prototype concept for integrating virtual reality components and graphics systems with the existing RMS part task trainer to develop and evaluate potential applications for virtual reality technologies. The RMS part task trainer (Fig. 5) was developed for RMS training in 1988 as a fully functional, kinematic simulation of the Shuttle RMS and served as the RMS portion of the integrated virtual reality simulation. This simulation provides the RMS operator with:

- A functional representation of the RMS control panel which includes numerical displays, rotary dial switches, rate meters, and caution and warning alarms and lights used in the operation of the RMS.
- Access to the Orbiter general purpose computer display pages used during RMS operations.
- Two 3 degree-of-freedom hand controllers (rotational and translational) for making position and orientation commands to the RMS.
- Stereo, out-the-window views.
- Graphically generated camera views from any of the standard payload bay and/or RMS cameras.

The objective of integrating virtual reality technology with the RMS part task trainer was twofold: To create a virtual reality operating system that could generically control and synchronize commercially available

Figure 5. RMS part task trainer.

hardware and merge it with existing graphics software packages and simulation capability, and to develop an application for virtual reality that would benefit the NASA JSC mission.

The Hubble Space Telescope repair mission afforded a unique opportunity for this endeavor: It occurred in the correct time frame, and it required significant amounts of EVA time in conjunction with coordinated RMS operations to accomplish its planned objectives. Another factor in the decision to pursue a virtual reality application for the Hubble repair mission was the fact that there were available two Shuttle crews who had firsthand experience with the telescope in particular and spaceflight in general. These were the crew that deployed the telescope in 1990 (STS-31) and the crew that was training to repair it in 1993 (STS-61). An important aspect of building the virtual reality simulation was to intimately involve the ultimate users in the development of the simulation itself. This was done to take advantage of their on-orbit experience as a guide to incorporating into the simulation what they considered to be the most important features or "sensations." It was also done to make them aware of exactly what the limitations of the technology were as well as what to legitimately expect of the technology in the near term.

Initially, the hardware available for virtual reality in the IGOAL consisted of one VPL data glove, two Polhemus FastTrack sensors, one Virtual Research head-mounted display, and two Silicon Graphics Inc. (SGI) 310 VGX computers. This equipment was augmented by additional hardware and software resources under development in the IGOAL; i.e., graphics programs, graphics support libraries, and the RMS part task trainer and its associated hardware and software.

The data glove was disassembled and reassembled into a pair of gloves using 5 (there were 10 on the original glove) of the fiber-optic sensors on each glove. The lower fidelity gloves were acceptable for this application, since finger dexterity was not important to the EVA simulation. It was more important to be able to perform the opening and closing gesture with either hand.

A number of helmet-mounted displays were evaluated with ease of donning and wearing comfort being the major factors in the selection of the Virtual Research helmet. The display resolution was of concern, but not a driving factor at that time, since all used similar liquid crystal display technology.

A set of four Polhemus FastTrack electromagnetic sensors were used to track the motion of the virtual reality subject's head, right and left hands, and the object being handled by the EVA crew member.

Figure 6 shows a functional diagram of the hardware/software configuration for the Hubble Space Telescope trainer. In this configuration, one graphics display is used by the RMS simulation, while the other two displays are used to drive the head-mounted display system.

Figure 7 depicts the physical configuration of the virtual reality simulation used for integrated EVA/RMS training in preparation for the Hubble mission.

Using Virtual Reality to Train Astronauts for the Hubble Repair Mission

The virtual reality simulation to be discussed was not intended to be a formal part of the STS-61 crew training schedule. Crew members did, however, use the system on 8 occasions for a total of 16 hours of preflight work.

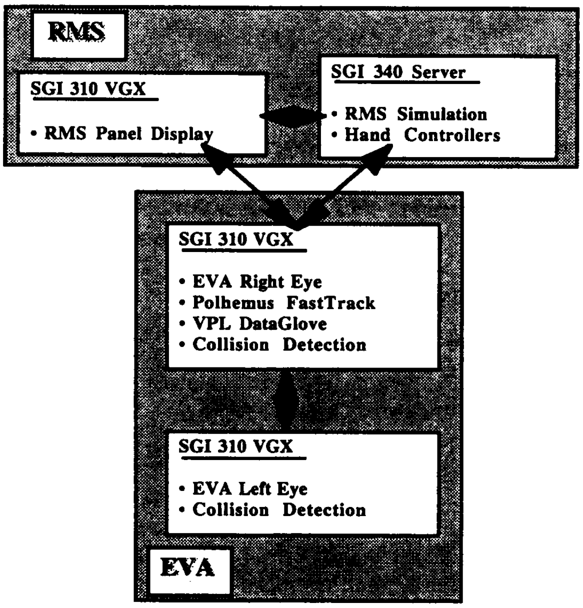

Figure 6. HST simulation block diagram.

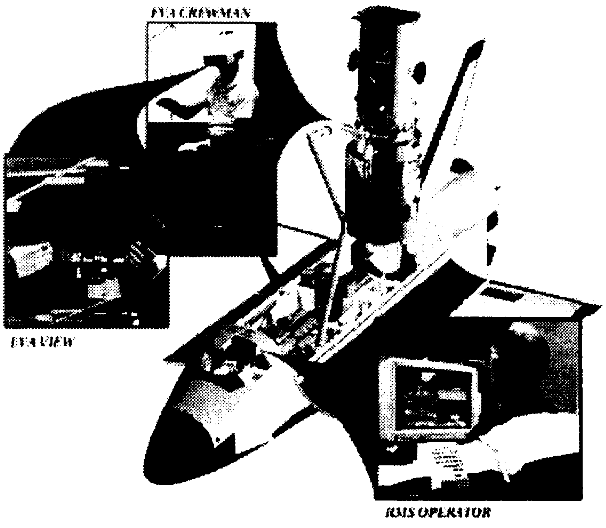

Figure 7. Integrated EVA/RMS VR simulation for HST.

During those sessions, the crew was able to rehearse complete EVA/RMS tasks by taking advantage of the system's capability to present the on-orbit configuration which allowed the full range of the RMS to be simulated. This allowed the EVA person on the end of the RMS to be placed in the position that would be required during the flight, but that was not attainable in the ground-based facilities (Fig. 1). Not only could the RMS operator see the correct RMS configuration, but the EVA person could also see the configuration from the correct vantage point. By integrating the two simulation capabilities, the RMS operator and the EVA person were also able to develop a command protocol and be confident that each knew what the other meant when the maneuvers were performed during the actual EVAs. Because the EVA crew member could get a realistic view of the Shuttle and payload bay in the virtual reality simulation, different positions and views could be explored to determine the best method for performing a specific task, thus greatly increasing the efficiency of use of the neutral buoyancy facilities. A number of task procedures and RMS positions derived in the neutral buoyancy facilities were changed when the integrated virtual reality simulation showed them to be unsuitable for achieving the task. One other added benefit noted by the crew was that when using virtual reality, the EVA crew member relies only on visual cues to determine orientation (as when in space) instead of the gravity cues received in the neutral buoyancy facilities. The sessions were also used to suggest potential improvements and refinements to enhance the simulation capability.

Removal and temporary storage of the high speed photometer (HSP) was an EVA scenario on which the crew spent a majority of its virtual reality sessions and is a good example for discussing the various capabilities of the virtual reality simulation.

The on-orbit configuration shown in Figure 8 consisted of the Hubble Space Telescope securely attached to the Orbiter payload bay by the flight support structure and rotated so that the bay containing the HSP pointed directly forward. (For reference, the photometer was approximately the size of a telephone booth and had a mass on the order of 700 lbs.) The doors of the lower portion of the Hubble Space Telescope were in the open position to provide clear access to the HSP while an EVA crew member was located on the MFR at the end of the RMS. The scenario was:

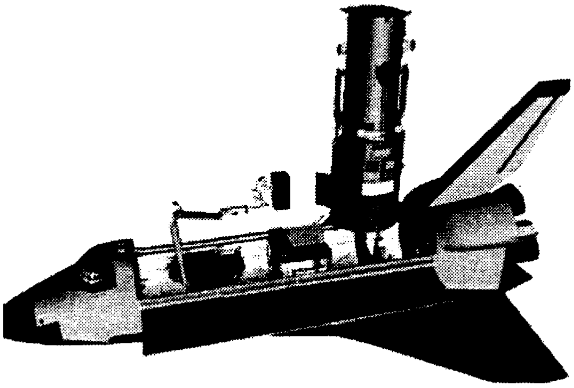

Figure 8. HSP removal.

- The RMS operator maneuvered the EVA crew member into the open bay of the Hubble Space Telescope.
- The EVA crew member grasped the handholds located on the HSP.
- The RMS operator extracted the EVA crew member holding the photometer.
- Once clear of the telescope, the RMS operator maneuvered the EVA crew member to the correct position and attitude above the temporary storage location on the port side of the on-orbit replaceable unit carrier.
- During the maneuver, the EVA crew member reoriented the photometer by rolling it 90 degrees clockwise.
- The EVA crew member attached the photometer handles to the temporary storage device.
- The RMS operator then maneuvered the EVA crew member to a position above the Corrective Optics Space Telescope Axial Replacement (COSTAR) unit located in its carrier on the on-orbit replaceable unit carrier.
- The EVA crew member grasped the handholds located on the COSTAR.
- The RMS operator raised the EVA crew member holding onto the COSTAR until clear of the surrounding structure.
- The RMS operator maneuvered the EVA crew member and the COSTAR to a position that allowed the reverse of the extraction process for the photometer to be performed.

Since the HSP and COSTAR completely obstructed the view of the EVA crew member holding them, the second EVA crew member was responsible for being in position to observe clearances and assist in directing the RMS operator.

Figure 9 shows one of the crew members "suited-up" for a virtual reality session. The helmet provides a 3-D stereo image with a 160 degree field-of-view. Figure 10 shows a portion of the graphics image viewed by the EVA crew member, including the graphics representation of the subject's gloved hands.

Figure 9. STS-61 Crewman in VR.

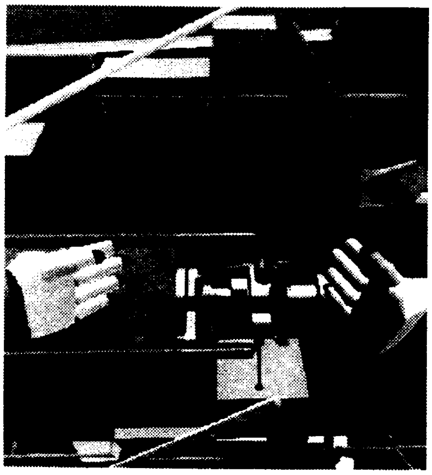

Figure 10. HMD view.

The motion of the right and left hands of the EVA crew member was tracked, as was the head motion, by the electromagnetic sensors attached to each. This motion was displayed to the EVA crew member in the helmet-mounted display and viewed by the RMS operator in whatever scene, or combination of camera displays, that was called up on the RMS simulation. In the virtual reality environment, the EVA crew member could not only move the hands and open and close the fingers, but also grasp objects displayed in the virtual environment. This was accomplished through a software module that ran in parallel with the simulation and looked for contact between each graphics hand and other objects in the scene. Since there was no force or tactile feedback in the simulation, contact between an object and either hand was indicated to the virtual reality subject by changing the color of the object to bright green. At that time, the crew member could close whichever hand was in contact with the object and grasp that object. The object would then change color to indicate which hand had control of it: red in the case of the right hand and blue in the case of the left hand. If both hands grasped the same object, the color displayed (red or blue) indicated which hand grasped it last. The motion of that hand was then the motion that controlled the movement of the object in the virtual reality and RMS displays. Not apparent from Figure 10 is that the gloves/hands in the scene were transparent. This was done to allow the virtual reality subject to detect contact with and grasping of objects which would normally be obscured by the gloves where, in the "real world," touch would be used to sense the objects.

During the initial evaluation of the simulation, it was determined that using the hand trackers to provide position and attitude data for displaying the motion of the object being handled was not the proper approach, especially when both hands were used for grasping the object. Two problems were created: The relative spacing between the hands could not be held constant, and the attitude of the hands could be changed dramatically without significant change in position.

The first problem was solved by assembling a frame of PVC pipe (hanging in the background of Fig. 9) that represented the correct spacing for, in this case, the handholds on the high speed photometer and COSTAR. This allowed the "graphics hands" to remain correctly attached to the on-orbit replaceable unit handles displayed in the helmet-mounted display. Adding a fourth tracker to the PVC handles solved the second problem by tracking the position and attitude of the object being handled. Once the handholds were firmly grasped, the RMS operator maneuvered the EVA crew member and the high speed photometer out of the telescope. In the real world, the photometer was restricted from moving side-to-side or up and down by guide rails within the base of the Hubble Space Telescope. In the virtual reality simulation, the motion of the photometer was constrained by software limitations until it was free of the guides. At that time the EVA crew member had complete control over the motion of the photometer. All movements were seen in the helmet-mounted display and by the RMS operator. The RMS operator then positioned the RMS, with the help of commands from both EVA crew members, to allow the photometer to be placed in the temporary holding fixture. Figure 11 shows the crew of the STS-61 mission interacting during a typical virtual reality session.

The fidelity of the virtual reality simulation was sufficient for the crew members to correlate their positions throughout the maneuver with what they expected to see based on their previous work in the neutral buoyancy facilities. Also, timelines for the RMS motion could be accurately evaluated because actual RMS rates were used to drive the simulation, and the simulation was synchronized to "clock time." The

Figure 11. Typical VR training session.

refresh rate of the graphics displays averaged approximately 3.5 Hz. This update rate was a function of the number of polygons displayed and, therefore, the fidelity of the graphics scenes. Normally, this amount of lag in the visual system would produce a physiologically unacceptable display for the virtual reality subject; however, the crew members were willing to trade update performance for graphics model fidelity based on the fact that in zero-g, they moved their heads slowly anyway. Another interesting comparison to the zero-g conditions on orbit came from the realization that in virtual reality, like in zero-g, the crew's only attitude cue was a visual one. In other words, since the gravity vector remained constant, the only indication that the RMS had placed the virtual reality subject in an upside down orientation with respect to the surroundings was that the orientation of the objects in the display had changed. This is unlike other ground-based facilities where the effects of gravity (such as the blood rushing to the head) provide unrealistic cues to the trainees. Virtual reality provided the STS-61 crew the luxury of practicing integrated EVA/RMS operations in the on-orbit configuration prior to the actual flight with no discomfort or risk.

The results from the STS-61 crew participation in the development and evaluation of the integrated EVA/RMS virtual reality simulation were extremely positive. While the virtual reality technology will not replace any of the ground-based training simulations anytime soon, it will enhance the training provided in those facilities and most importantly it will help fill in the gaps that result from part task training in a number of simulators.

Wake Shield Facility Satellite Training

As a result of the success of the integrated EVA/RMS virtual reality simulation in supporting preparations for the Hubble repair mission, the crew of the STS-60 mission, which flew in January 1994, requested simulation time to help them evaluate a possible contingency that could occur following the deployment of the Wake Shield Facility. The virtual reality simulation was reconfigured to include the dynamic motion of a tumbling Wake Shield Facility satellite and was used to familiarize the RMS operator and an EVA crew member on the end of the RMS with possible contingency recovery scenarios. After deployment of the Wake Shield Facility, had its attitude control system failed and caused the satellite to tumble as the Orbiter approached to recapture it, the crew would have attempted to recover it by placing an EVA crew member on the end of the RMS to stabilize it. The virtual reality simulation was reconfigured as shown in Figure 12.

The motion of the Wake Shield Facility was driven by a dynamic simulation that could make it tumble about multiple axes at different angular rates. Using the virtual reality capability (as viewed from the vantage point of the EVA crew member at the end of the RMS and the RMS operator), the STS-60 crew familiarized themselves with three aspects of this scenario.

- How would the Wake Shield Facility tumble as the result of various rate/axis combinations.
- Based on the motion of the satellite, when would it present itself favorably to the EVA crew member or what attitude it would be in at any given time during its rotation cycle.
- How would the RMS be maneuvered to a predicted position/attitude (based on knowledge gained in step 2) of the satellite to allow the EVA crew member multiple chances at capturing the satellite.

The contingency situation did not arise on the flight of STS-60, but the crew stated in postflight debriefings that the virtual reality simulation was a valuable tool and its use should be continued.

Virtual Reality Development for Simplified Aid for EVA Rescue Training

The development of the virtual reality simulation capability expanded to support EVA/RMS training for the STS-64 mission on which a new manned maneuvering unit called the SAFER was tested. For SAFER training, the simulation software had been restructured and rehosted on new hardware. The new simulation

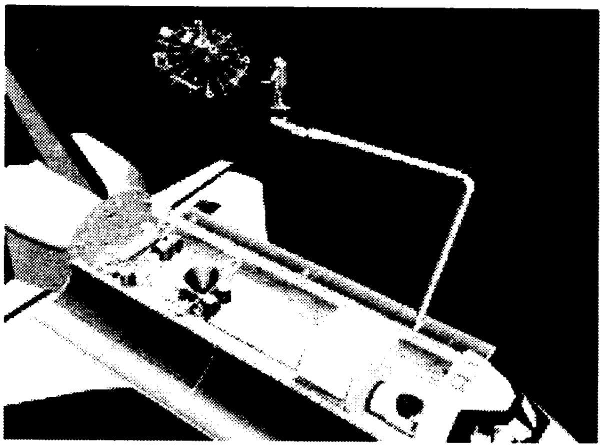

Figure 12. STS-60 configuration.

configuration is shown in Figure 13. The new architecture uses a central control process to integrate all aspects of the simulation. The most important and computer-intensive processes are run on dedicated central processing units in the multiprocessing system, and all communications are routed through the central control process. The new hardware/software configuration increases the performance by a factor of at least five over the Hubble Space Telescope configuration. The new system also provides graphics fidelity enhancements such as texture mapping and anti-aliasing with no performance penalty.

The test flight involved integrated operations with the RMS, an EVA crew member on the end of the RMS, and the EVA crew member flying the SAFER unit (Fig. 14). SAFER (a nitrogen gas-propelled backpack) will let EVA crew members inadvertently separated from the Space Station fly back to it. Crew members trained in the virtual reality simulation for about 30 hours each. They practiced separation maneuvers and precision maneuvers involving staying one foot from the RMS while flying from the RMS shoulder up to its elbow poised high above the bay, back down to the wrist, over to the aft flight deck window, and then holding that position for 30 seconds. Using virtual reality for SAFER training was particularly valuable in that during the rescue demonstration, one EVA astronaut standing on the RMS foot restraint grasped the other crew member with the SAFER backpack and imparted a spin rotation. The spinning astronaut was able to realize the sensation of the rates as well as the type of response that could be expected from the SAFER to stop the rotation. This was not possible in other simulators.

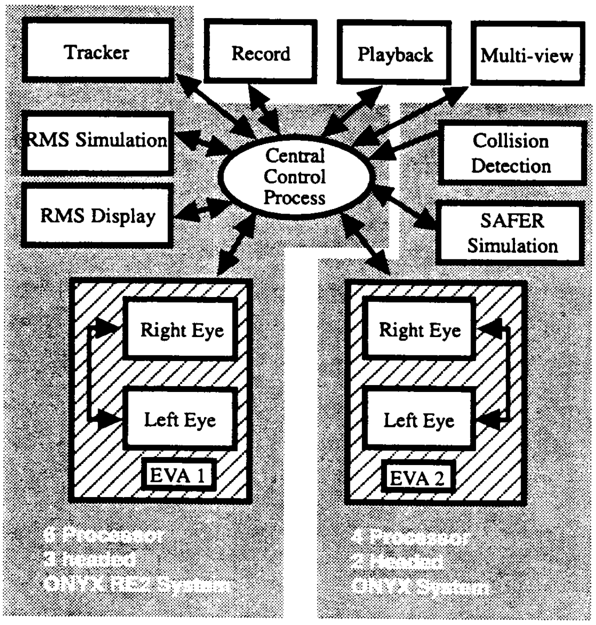

Figure 13. Upgraded VR simulation block diagram.

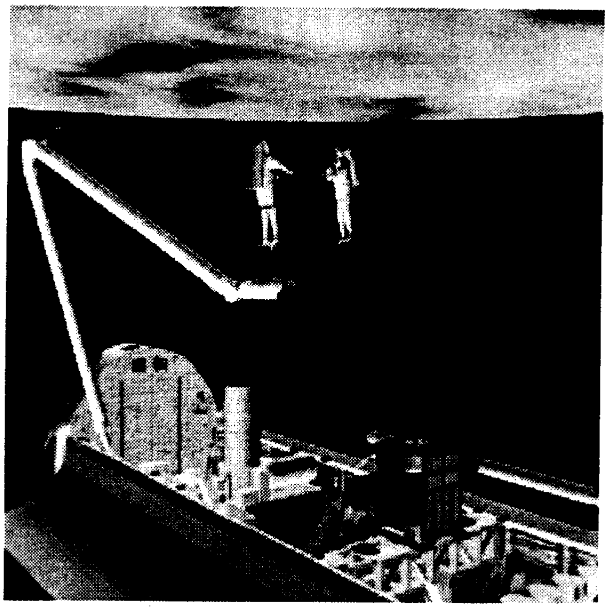

Figure 14. STS-64 SAFER test configuration.

After the flight, the crew reported that the ability to fine-tune maneuvers was attributable to the virtual reality training which "actually makes you feel like you're flying." Crews are currently using the integrated virtual reality system for training on a regular basis, and future plans call for supporting future EVA flights to develop Space Station assembly techniques.

Integration of Force Feedback Into Virtual Reality

One of the most important aspects of EVA is the physical handling of objects such as on-orbit replaceable units. Present day virtual reality technology (including high performance computer graphics engines, head-mounted displays, and tracking sensors) can only reproduce the visual sensations associated with EVA. Present systems cannot provide the physical force sensations vital to realistic simulation of on-orbit replaceable unit manipulation. While exploring the effectiveness of AR&SD's virtual reality simulation in sessions with the Hubble Space Telescope crew, the AR&SD/McDonnell Douglas Aerospace (MDA) team developed a concept to simulate the inertia of payloads being manipulated in the virtual reality environment. The concept employed an intravehicular robot (Charlotte) developed by MDA for use inside the SpaceHab, Space Lab, and Space Station modules in a zero-g environment. Because Charlotte was designed to work alongside a Shuttle or Station crew, it is inherently safe, lightweight, low power, easy to set up, quiet, and reliable.

Charlotte was modified (Fig. 15) to incorporate force/torque sensors, EVA handholds, equations of motion, envelope checks, and safety checks but required few changes for safety concerns because of parallel efforts to certify the design to NASA-STD-3000 for flight operations with the crew. This new force feedback device was named Kinesthetic Application of Mechanical Force Reflection (KAMFR) and was incorporated as part of the virtual reality training simulation. The integration of KAMFR with the existing virtual reality system allowed for data transfer from a dynamic simulation to KAMFR and from KAMFR to the virtual reality simulation. In addition, data is transferred from the dynamic simulation to the virtual reality simulation, and hand controllers are used for RMS control. Using this architecture (Fig. 16), the virtual reality simulation environment will fully support combined RMS/EVA operations with a workstation for the RMS operator and a virtual environment for the EVA crew member. This will allow them to train for combined tasks in an environment that is not available in training facilities today. KAMFR has required minor hardware modifications (note the portable support frame shown in Fig. 15) for routine operations in the one-g environment, but in the future the simulation lab could be outfitted with hard mount points. KAMFR can be quickly reconfigured to optimize rotations and translations in various axes for a given training scenario.

As part of the validation of the KAMFR as a mass handling simulation, the virtual reality simulation application was configured to support crew training for the EDFT 01 (performed on STS-63 in February 1995). The simulation supported the RMS-based EVA tasks by integrating the RMS workstation with two virtual reality systems representing the two EVA crew members. The large on-orbit replaceable unit mass handling demonstration performed with the 2700 lb Spartan satellite, from both stationary foot restraints and RMS foot restraints, was used to validate the implementation of KAMFR as a dynamic mass handling simulation as part of the virtual reality system. The KAMFR robot to be used for the force feedback simulation was delivered in January 1995 and integrated into the virtual reality simulation in preparation for postflight evaluation by the STS-63 EVA crew members. This mass handling simulation has, to the satisfaction of the EVA crew members involved, successfully replicated the zero-g mass characteristics of the 2700 lb Spartan payload manually handled on STS-63.

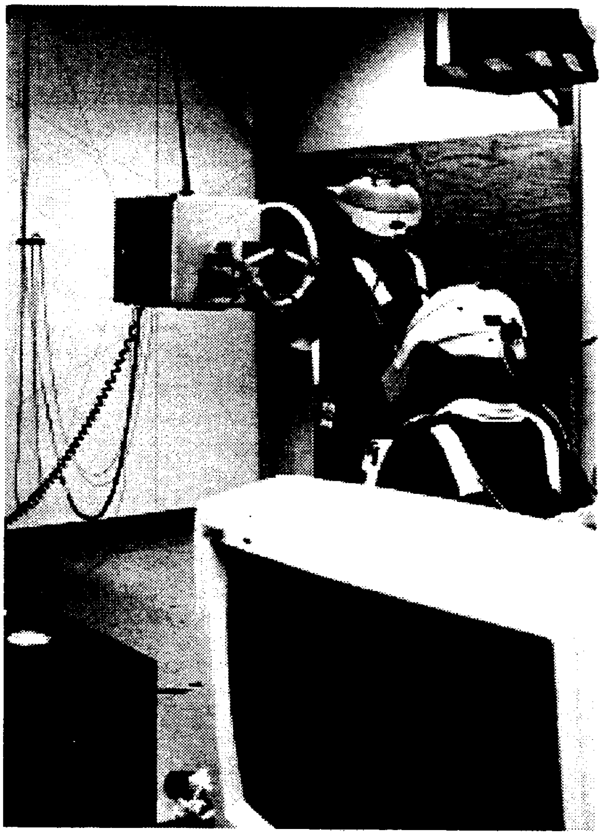

Figure 15. Force feedback robot KAMFR integrated with VR.

The STS-69 crew has also used this virtual reality simulation application in preparation for EDFT 02 (performed on the flight in September 1995). The portion of the detailed test objective which was simulated in virtual reality consisted of one EVA crew member on the end of the RMS evaluating space station-type fasteners, connectors, on-orbit replaceable unit interfaces, etc. at a task board located on the starboard side of the front of the Orbiter payload bay (bays 2 and 3). The RMS operations are complicated in this area and require a great deal of coordination between the RMS operator and both EVA crew members. The STS-69 simulation was also configured to support evaluation of contingency retrieval of the Wake Shield Facility using an EVA crew member on the end of the RMS. The simulation configuration is similar to that used by the STS-60 (February 1994) crew to evaluate the same contingency prior to their flight. Currently, the simulation is being used to perform engineering evaluations of proposed EVA handling devices for use with International Space Station on-orbit replaceable units. Development of a system of integrated robotic devices to allow more than one person to manipulate the same mass at the same time is now under development. With the addition of KAMFR(s) as a kinesthetic display device, the virtual reality environment will offer a complete RMS/EVA simulation capability.

Conclusions

The use of virtual reality to support ground-based preparation for EVA assembly and maintenance of the International Space Station has been demonstrated to be a viable and productive application of the existing technology. In addition, the applications and system hardware/software architectures currently under development provide the cornerstone for a virtual reality training/familiarization system on board the International Space Station.

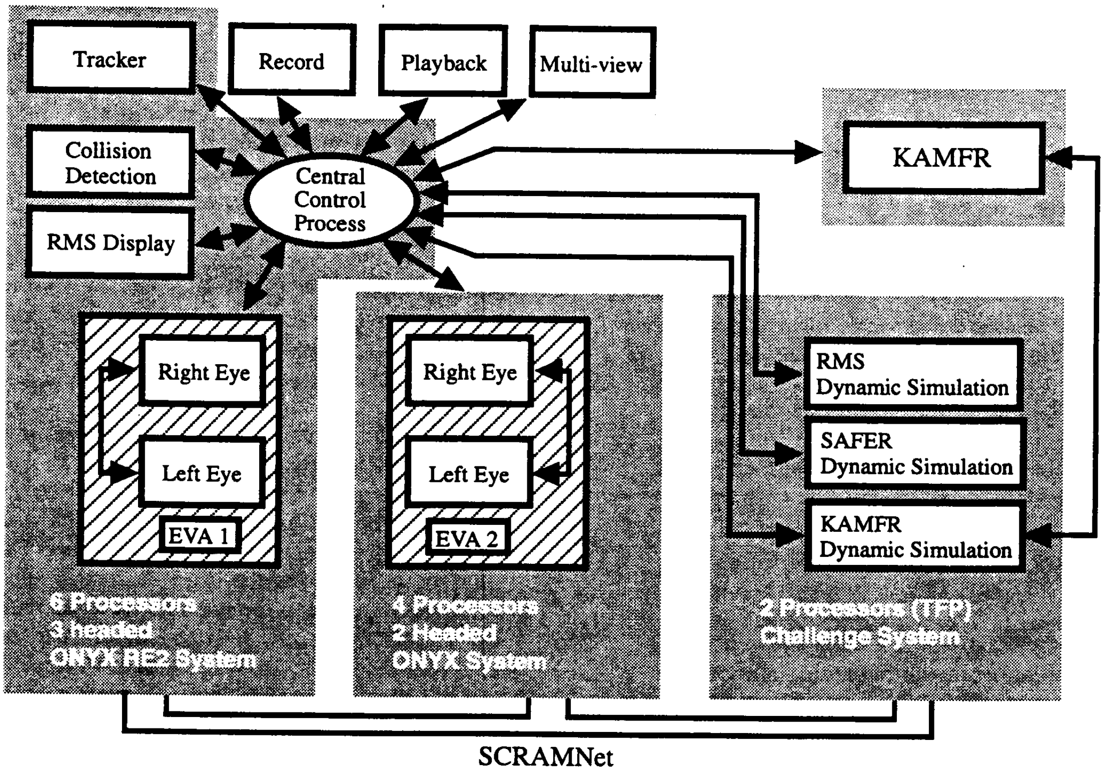

Figure 16. Current VR training simulation architecture.

There are five major technical areas of importance to virtual reality simulation.

- Computer graphics or display rendering
- Helmet-mounted display capability
- Tracking/sensor technology
- Kinesthetic display or force feedback capability
- System architecture and application development

The first three areas are being driven by powerful "outside" forces such as the entertainment industry and the home and business computer market—the requirements of which meet or exceed NASA's requirement to support virtual reality simulation capability development for the foreseeable future. The appropriate strategy becomes one of being prepared to use the technology when it becomes available as opposed to driving the technology to meet an application.

Kinesthetic display and force feedback will be most effective and cost efficient if developed for specific applications or families of similar applications, in lieu of a generic "one system does all" approach. Currently large-mass handling by two crew members is the focus of the effort in this area.

The final item, system architecture and application development, affords the largest return on NASA's investment in virtual reality. The virtual reality software architecture is being developed to support advancements in hardware technology as well as being tailored to accommodate the evolving requirements for integrated/interactive EVA simulation capability.

The development approach being taken to support today's EVA/RMS training requirements for virtual reality simulation lays the groundwork for understanding and applying the lessons learned to the areas of telepresence and teleoperation of robotic devices. These lessons learned include not only the technology but also the human interaction with that technology.

References

Homan, D., "Virtual Reality and the Hubble Space Telescope," AIAA Space Programs and Technologies Conference, Huntsville, Alabama, AIAA 94-4558, 1994.

Testa, B., "Virtually Walking in Space," *Virtual Reality Special Report*, (Winter 1994), pp. 67-74.