Virtual Environments in Training: NASA's Hubble Space Telescope Mission

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Abstract:

Virtual environment (VE) technology was used to construct a model of the Hubble Space Telescope (HST) and those elements that were replaced or serviced during the December, 1993 repair and maintenance mission conducted by the National Aeronautics and Space Administration (NASA). The VE also included the payload bay of the Space Shuttle and the fixtures used for transporting replacement systems into orbit. Beginning in September, 1993, approximately 100 members of the NASA HST flight team received over 200 hours of training using the VE. In addition to faithfully replicating the physical structure of the HST and the interrelationships of many of its elements, the VE also modeled the constraints associated with all maintenance and repair procedures. For the first time, a VE was integrated with a limited capability Intelligent Computer-Aided Training (ICAT) system. The ICAT component of the training provided identification of all relevant features of the HST, monitored procedures carried out by the trainees in real time, and intervened with assistance in response to procedural errors or requests for assistance. Data collected from trainees, after completion of the HST mission, demonstrated that, for most trainees, the VE training enhanced t he effectiveness of their job performance. The results of this project serve to define the future role of VEs in training within NASA and to provide evidence that VEs can successfully support training in the performance of complex procedural tasks.

Introduction

A rapidly maturing technology first proposed in the 1960s [Hall, 1963; Sutherland, 1968; Vickers, 1970] now offers a novel, unique avenue for the delivery of experiential training to personnel in many disciplines. Usually described as "virtual reality" (or virtual environments or synthetic environments or virtual worlds or artificial reality), this technology can provide both visual and auditory information of such fidelity that the observer can "suspend disbelief" and accept that he or she is actually somewhere else [Chung, 1989]. Further, the technology also permits perceptual and tactile interaction with the synthetic environment, enabling the user to transcend the role of passive observer and actively participate in shaping events [Minsky, 1990].

Extensive research and development in virtual reality technology has been stimulated by its application in areas such as engineering design [Orr, 1989], architecture [Brooks, 1987], data visualization [Brooks, 1988; Fuchs, 1989], and teleoperation [McGreevy, 1991]. Brooks and his coworkers at the University of North Carolina at Chapel Hill [Batter, 1972; Ouh-Young, 1988] have extensively explored the visualization and tactile/force feedback aspects of virtual reality for use by chemists and biochemists (in viewing, assembling, and manipulating molecules), but they have not addressed training or educational applications of the technology. Some education-related projects currently underway are typically directed at providing students with the tools needed to construct their own virtual world and the ability to explore that world [Merickel, 1990; McCormick, 1991; Byrne, 1992; McCluskey, 1992], rather than developing a reality whose implicit structure is based on pedagogical principles. The work reported here joins a small group of efforts that have specifically examined the training efficacy of virtual environments [Regian, 1992; Knerr, 1993; Kozak, 1993]. A closely-related project is also investigating the use of virtual environments in science education [Loftin, 1993].

NASA's virtual environment technology for training program

The NASA/JSC Software Technology Branch (STB) has been exploring the application of Virtual Environment Technology to Training since 1990. Simulations of elements of Space Station Freedom and Space Shuttle payloads (such as the IntellSat captured during STS-49) have been developed to test the technology's efficacy as a training tool and to identify specific research and development needs to improve training performance. During 1993 a major project, replicating all relevant repair and maintenance scenarios for the Hubble Space Telescope mission (STS-61), was completed. Over one hundred members of the flight control team were trained, beginning in September, 1993, with this system, providing an opportunity to demonstrate the potential of virtual environment technology in training. Related activities within the STB include:

1. an evaluation of tactile, force, and temperature feedback mechanisms to enhance training transfer;
2. the integration of virtual environments with Intelligent Computer-Aided Training (ICAT) technology;
3. the sharing of Virtual Environments over long distances for collective training and concurrent engineering (with NASA/Marshall Space Flight Center),
4. the development of software tools that support the rapid development and maintenance of virtual environments by training personnel; and
5. the development of a Virtual Physics Laboratory as an educational "spinoff" of this NASA activity.

The Hubble space telescope repair and maintenance mission

The Hubble Space Telescope

When Lyman Spitzer first proposed a great, earth-orbiting telescope in 1946, the nuclear source of stars had been known for just six years. External galaxies and the expanding universe were about twenty years of age in the human consciousness. Pluto was seventeen and the Seyfert galaxies were three. Quasars, black holes, gravitational lenses, and detection of the Big Bang were still in the future-together with much of what constitutes our current understanding of the solar system and the cosmos beyond it. [Brown, 1991]

Shortly after the launching of the Hubble Space Telescope (HST), in April, 1990, astronomers became aware that its optical system was flawed. A commission, chaired by Robert Brown and Holland Ford, was convened to investigate the problem and propose a solution. The report of this commission [Brown, 1991] became the blueprint for the HST repair and maintenance mission. The preparation and crew training for that mission became a major focus of NASA for over three years.

Mission Training in a Virtual Environment

The Hubble Space Telescope repair and maintenance mission (STS-61) was successfully completed in December, 1993. As a part of the training employed for that mission, over 100 flight controllers actively experienced immersive virtual environments, simulating the extravehicular activities (EVA) that were planned for the mission. This effort was apparently the first large-scale implementation of virtual environment (VE) technology for training personnel for a "real" mission. It was the result of a cooperative effort between the NASA Johnson Space Center's Software Technology Branch (PT4), the Space Flight Training Division, and the Flight Director Office. The primary training goal was to familiarize flight controllers, engineers, and technicians-all of whom were members of the mission's ground-based support team-with the location, appearance, and operability of the different components on the HST, as well as the related maintenance components in the Space Shuttle payload bay. Hence, the overall strategy of this project was to utilize VE for training while exploring the potential of VE training applications for space-related activities.

Training large numbers of flight controllers for any given Space Shuttle mission can be difficult due to the limited availability of training facilities and personnel. Important elements of hands-on training are conducted in heavily-scheduled facilities that are expensive to operate. Training time allocated for the primary flight control team is at a premium. First priority to the training facilities and simulations is usually given to this team and the crew. Much less time is available for the support and planning teams to train.

Crew training largely centered around the Weightless Environment Training Facility (WETF) in which astronauts can manipulate replicas of hardware components in neutral buoyancy. This training facility is expensive to operate and requires lengthy periods for training even one crew member. Thus, the WETF is generally unavailable for training non-astronaut members of a mission flight team. Other facilities, such as the Shuttle Mission Simulator, the air-bearing floor, and various engineering an part-task simulators are also generally unavailable for extensive use by ground-based support personnel.

With the complexity and importance of the Hubble Space Telescope repair and maintenance mission in December of 1993, other options for training flight support personnel needed to be considered. It was hypothesized that personnel involved with flight control, payload operations, and EVA planning could benefit from training in the HST and Space Shuttle cargo bay hardware configurations, equipment operation, and astronaut EVA procedures to more effectively support this mission. In particular, this mission contained more EVA operations than any previous mission and required extensive interaction between the flight crew and ground-based personnel. John Muratore, one of the three mission Flight Directors, suggested that a VE be developed to allow flight team members to gain an accurate knowledge of the HST geometry and the procedural steps to be followed in accomplishing the planned repairs and maintenance.

Development Software and Approach

Characteristics of the scenarios (e.g., models, environment layout, behaviors, feedback) were created using two NASA-developed software tools, an ANSI C compiler, and a computer-based audio application. The Solid Surface Modeler (SSM) program was used to develop the individual environment models, or objects. SSM is a 3-dimensional (3D) graphics development application for solid-shaded and wireframe geometric modeling. This software tool was originally created at the NASA Johnson Space Center specifically for building detailed 3D objects for animations and conceptual simulations. As such, it is well-suited for virtual environment model creation and was used extensively in this project. Beginning with elementary shapes (i.e., primitives), the complexity of objects was increased by combining these or altering them with geometric manipulations. Object surfaces were defined as flat or smooth with SSM, as were the color of objects using an 8-bit color palette.

The Tree Display Manager (TDM) is a real-time graphics visualization tool used to create a hierarchical representation (i.e., a relationship tree) of the 3D models created with SSM. This tool allows developers to give structure and organization to the virtual HST scenarios, and to control users' viewing perspectives. It was also used to define the mobility and constraints of objects in a given environment as well as characteristics such as light sources, multiple views, and "trails" of an object's motion. The TDM tool was also developed at the NASA Johnson Space Center.

A Silicon Graphics, Inc. proprietary software graphics library (GL) was used to render the virtual environments. Likewise, the device controller and six scenario applications were developed in ANSI C to interrogate the input devices' data and to code behaviors, characteristics, and interactions between objects and the user within the virtual environment.

To accommodate the use of audio feedback in the training, the SoundTool utility provided on Sun/ Sparc workstations was used. This software has the capability of recording sound and storing the data as digital audio files, and playing these files over internal or external speaker systems. All of the sounds associated with the six HST scenarios (i.e., object identification and status messages) were recorded with SoundTool. A database of sound message codes and sound file names was created for rapid, real-time identification. A conventional external speaker was used for sound projection so that both active and passive participants could hear the feedback.

The full HST servicing and repair mission virtual environment training system included graphical representations, or models, of the HST, the Space Shuttle cargo bay, and maintenance/replacement hardware necessary for the user to complete the major procedural steps associated with the planned EVA servicing activities. There were six EVA scenarios developed, comprising two virtual environment training modules. These scenarios coincided with the six primary EVAs scheduled for the actual mission and included:

1. Solar Array change-outs
2. Rate Sensor Unit (RSU) change-outs
3. Corrective Optics Space Telescope Axial Replacement (COSTAR)
4. Wide Field/Planetary Camera (WF/PC II) change-out
5. Solar Array Drive Adapter Electronics (SADE) replacement and
6. Magnetic Sensing System (MSS) - Magnetometer installation over original Magnetometers

The specific procedural steps associated with each of the EVA tasks were determined from the Extravehicular Activity Annex for the HST First Servicing Mission (NSTS 14009, Annex 11, Revision B) and from extensive reviews of video recordings of astronauts undergoing training in the WETF. By developing the environment objects and hardware in accordance with engineering drawings, accurate and realistic models of the real objects were provided. The actual detail and fidelity of these environment models was ultimately dictated by the intricacy of the corresponding procedures. The behaviors and operations of these objects were also accurately portrayed in the virtual environment as necessary for completion of the stated goals. Figure 1 is a typical scene from one of the scenarios.

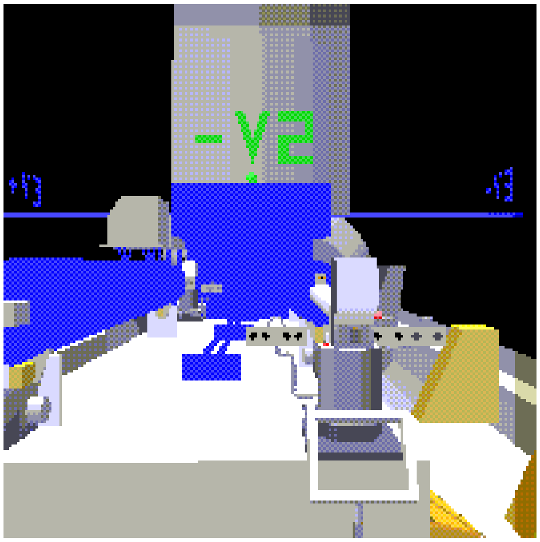

Figure 1 A view of the HST from the forward payload bay area. The axes and identifying letters show were used for reference and orientation purposes.

Virtual environment training approach

Training Objectives

Since the terminal goals of this system were to transfer knowledge of the HST hardware and EVA procedures, the intended approach to the training addressed both cognitive and psychomotor skills. Before a learner entered the virtual HST environment, he/she already had some basic knowledge of the hardware components and task procedures from previous experiences and document study. The virtual environment therefore provided learners with a three dimensional view of what they had previously seen only in two dimensional drawings or photographs. It was believed the users' cognitive skills associated with task procedures would be improved because of the learner's ability to visualize a particular hardware component or astronaut's orientation in space, and because the learner was expected to recall the correct procedural steps in the correct sequence to accomplish a particular task. Levels of guided learning were used with respect to the "selectability" of an object out of the proper procedural sequence and with the instructional aids available to the user. These components of the training system were based on limited Intelligent Computer-Aided Training capability that was integrated with the virtual environment [Loftin, 1991, 1994]. An important consideration in executing a particular procedural step has to do with an astronaut's orientation to the hardware component. In these virtual training environments, the learner could maneuver with six degrees of freedom and experience this orientation first-hand to gain a better understanding of the psychomotor and visualization skills required of astronauts.

Description of Training Process

In completing the virtual tasks associated with the mission's EVA procedures, it was anticipated the training system users would have several prerequisite skills and basic knowledge. In particular, this included:

1. knowing the correct sequence of EVA activities;
2. awareness of the position and orientation of the HST, fixtures, components, and astronauts;
3. identifying hardware components; and
4. specific tasks associated with the repair/maintenance of individual components (e.g., bolts to be removed in sequence).

Description of Subjects

Users of the training system were 105 flight controllers who were actively immersed in the virtual environment using a head-mounted display system. Other members of the flight support team were able to observe using a monitor located near the subject. The trainees had varying levels of familiarity with the HST repair mission documented procedures and hardware components. All were highly motivated to learn the material and capable of mastering the user actions necessary for interaction in the virtual environment. It was assumed that the target group for this training had moderate to high learning and achievement capabilities, and excellent problem-solving skills.

Post-Flight Subject Survey

From the beginning of September, 1993 until the first week of the space shuttle HST repair mission in December of 1993, 105 flight controllers were trained with the VE EVA scenarios. Several of these trainees were involved in more than one training session. After this VE training and the HST mission were completed, a questionnaire was developed and sent to all trainees to survey their impressions and comments on the HST VE training scenarios. The purposes of this questionnaire were threefold:

1. to study the effectiveness of this training in enhancing the flight controllers' performance during the HST mission,
2. to evaluate the training potential of VE technology, and
3. to assess some of the human factors issues and user-to-environment interface methodologies afforded by the training system.

The survey feedback will be used to improve future VE training applications and to evolve virtual technology as an effective training medium by improving the content of virtual environments (i.e., graphics and instruction), and users' interactions within them. In developing these survey questions, both instructional issues and technical aspects of the HST training scenarios were addressed. A copy of the questionnaire, as well as the high, low, and average of responses to each question can be obtained through the senior author (RBL).

The survey contained four sections:

1. Personal Data,
2. Session Data,
3. Physical Data, and
4. Improvements and Suggestions.

Within these sections, there were four types, or formats, of questions asked. The most frequently used was a ranking scale called a "Likert" scale. This type of scale was deemed to be the most appropriate in most cases as the purpose of this questionnaire was to assess more subjective concepts such as perceptions, attitudes, and self-evaluations. Numerical values corresponding to various adjectives describing users' experiences served to evaluate the sample and recommendations. The second most frequent type of question was a simple checklist, which was primarily used to collect data on the specific virtual environment hardware used and the training scenarios experienced. A third format was also a checklist type, but incorporated a ranking scale. Questions with this format pertained to the respondents' physical side-effects and severity. Finally, the fourth type of question gathered optional written responses and comments. These solicited rationale for responses to many of the individual questions and suggestions for improvement of virtual reality training applications.

Results

Survey Returns

Of the 105 surveys mailed to trainees, 38 completed forms were returned. Whereas completion rates on mail questionnaires are typically low-with figures of 40 or 50 percent considered good-the 38-questionnaire response on this mailing was typical of voluntary return rates. As nearly all surveys returned were completed in their entirety, the results should form a solid basis for assessing and improving virtual reality training applications. On occasion, some questions were not answered. Therefore, the compiled results referenced in this paper are based on the number of answers received for each question. Similarly, written comments to questions were somewhat sporadic, with some questions receiving many far-ranging remarks while others had none.

Survey Results

An important finding concerned the overall effectiveness rating of training. Users graded overall effectiveness at "slightly over effective" or 4.08 (out of a range of 0 - 5). Figure 2 shows the lowest, highest, and average rating for the overall case as well as that for each of the six scenarios. Comments showed that users found that visualizing activities enhanced understanding. Comments from subjects also noted that efficiency in training delivery was also increased, corresponding to the ability to compress of EVA (Extravehicular Activity) time from hours into minutes. For example, a five hour EVA would take thirty-five minutes in HST/VR.

At an average of 3.75 (out of a range of 0 - 5), users reported "just below significant" knowledge gains from the HST/VR training experience. The ability to visualize tasks (and positions of various items in the shuttle cargo bay and on the HST) had a positive impact on user's comprehension of activities and objects. Apparently, the user's prior knowledge influenced ratings somewhat negatively where experts reported not learning as much as novices. However, this should not be mistaken as a negative outcome.

The audio and instructional aids (i.e., audio messages and visual cues) of HST/VR received high marks of 4.2 (out of a range of 0 - 5) for their enhancement of the "immersiveness" of the experience. The majority of comments corresponding to this question were all very positive and ranged from just "Fun!" to being ". . . the neatest training tool . . ." that individual had ever used. Respondents reported that VR training or replication of EVA procedures would have been beneficial early on in the flight planning activities. Also, the HST/VR system could have been used as a prototyping tool for task reconfiguration or troubleshooting.

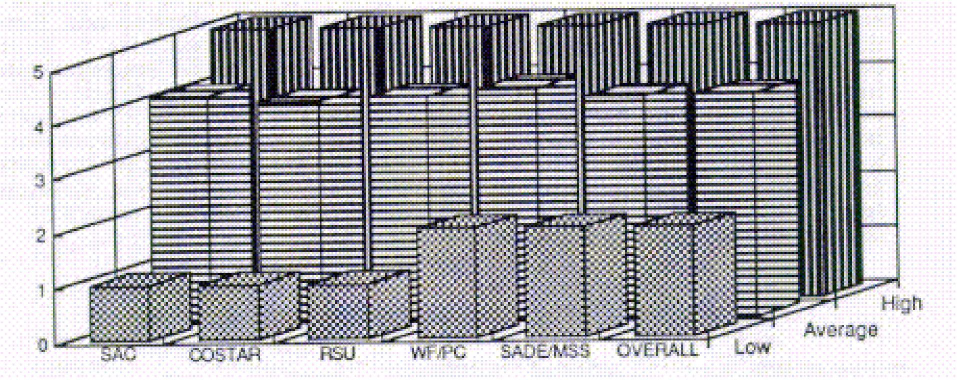

Figure 2 Subject ratings of performence enhancement due to the use of the HST Virtual Environment Training System. High and Low ratings, in addition to the average rat6ing are shown for five senarios and for the overall training experience.

An interesting trend from the questionnaire dealt with physical side-effects such as nausea, oculomotor problems, and disorientation resulting in mild cases of simulator-sickness. Apparently, compared with current and past simulator sickness studies, HST/VR trainees reported relatively lower rates of the various side-effects elaborated in the survey. Figure 3 shows the rate of occurrence of these side-effects by type.

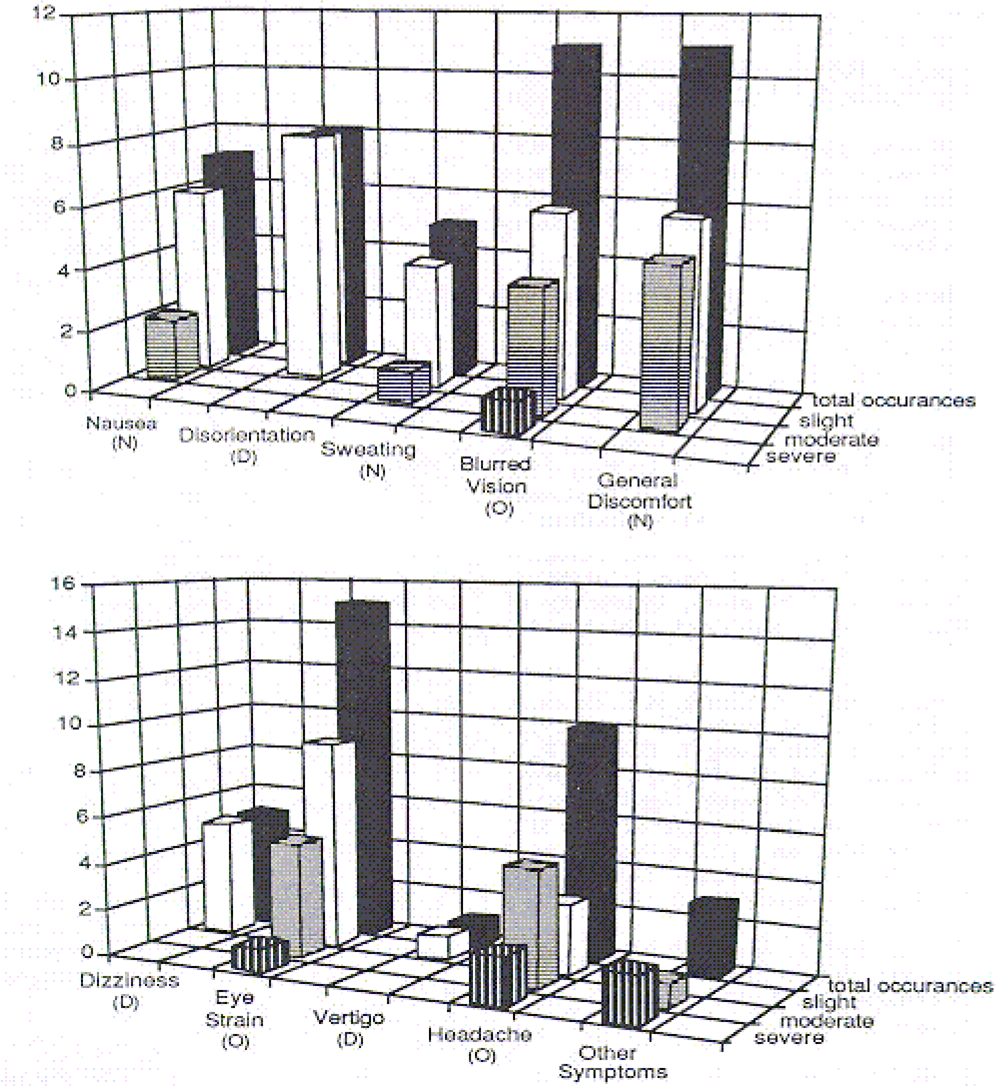

Figure 3: These two charts display the occurence of simulator sickness syptoms among the subjects. Syptoms are classified as nausea (N), diorientation (D), and oculomotor (O) after Kennedy, 1992.

Based on reports and comments received from flight controllers during the actual STS-61 HST mission operations, the HST/VR development team received compliments, during and after the mission, on its realistic modeling of the shuttle cargo bay and HST. Several flight controllers compared down-linked video data with what they had experienced in VR. The result seemed to be empathy and instant recognition of those objects associated with the HST/VR project scenario and the real mission.

Conclusions

As the results above demonstrate, members of the flight team judged, on the average, that the use of virtual environment for training had a positive effect on their job performance during the HST repair and maintenance mission. The discomfort experienced by many of the participants did not pose a serious problem with training transfer but should be studied further. A number of approaches that can reduce this discomfort or better manage it have been proposed and will be explored in future work [Kennedy, 1992]. The positive experiences reported here have broadened and deepened the interest of NASA in the use of Virtual Environment Technology as a training tool. Perhaps just as important is the ability that VEs afford for the training of personnel who currently receive little or no experiential preparation for their assigned task.

Future Work

One main activity that continued after the resoundingly successful completion of both the HST/VR training project and STS-61 mission was the completion of a third, albeit lower priority, training module. This will accommodate anticipated servicing and repair tasks for the future HST oriented missions. All HST/VR training scenarios that have been and will be developed can be technologically embellished with more intelligent training features.

More intelligent training functionality will be incorporated into future VR applications development. Such technologies as ICAT (Intelligent Computer-Aided Training), CBT (Computer Based Training), and others could be interfaced to create a more comprehensive VR training environment. Such issues as lesson planning and management could benefit delivery of such VR based training systems.

As VR hardware technologies improve, efficacy in training and simulation will result. The search for advanced Head Mounted Displays will provide improved resolution and field-of-views to enhance visualization and, therefore, immersion capabilities. Improved haptic (e.g., tactile) sensing capabilities will also expand functionality of training application to various tasks. Faster computing hardware by Silicon Graphics and others will also serve to improve the capacity for overall VR application development efforts like the HST/VR project.

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About the Authors

R. Bowen Loftin holds a B.S. in physics from Texas A&M University and an M.A. and a Ph.D. from Rice University, also in physics. He serves as NASA/Johnson Space Center's Principal Investigator for Advanced Training Technologies. In his "other" life, Dr. Loftin is Professor of Computer Science and Director of the Virtual Environment Technology Laboratory at the University of Houston and Professor of Physics at the University of Houston-Downtown. Since 1983, Dr. Loftin, his students, and coworkers have been exploring the application of advanced software technologies such as artificial intelligence and interactive computer graphics to the development of training systems. Much of this work has been done in cooperation with the Software Technology Branch of the National Aeronautics and Space Administration's Lyndon B. Johnson Space Center in Houston, Texas. Completed and on-going projects include intelligent computer-aided training systems for astronauts, flight controllers, test engineers, and computer operators; an intelligent tutoring system for high school and college physics students; and a virtual environment used in preparing the flight team for the Hubble Space Telescope maintenance mission. Dr. Loftin has been the recipient of numerous awards, including the American Association of Artificial Intelligence Award for an Innovative Application of Artificial Intelligence, NASA's Space Act Award, and the NASA Public Service Medal. He is the author of more than ninety technical presentations and publications.

Patrick J. Kenney graduated from the University of Wisconsin-Oshkosh in 1984 with a B.S. in Physics and from the University of Houston-Clear Lake in December, 1994 with a M.S. in Instructional Technology. He has supported NASA at the Johnson Space Center since 1984, first as a space shuttle navigation flight controller, then in shuttle cargo/payload integration and flight software verification. Since 1989, Mr. Kenney has supported the Client/Server System Branch (formerly the Software Technology Branch) of the NASA/JSC Information Systems Directorate in the areas of technology evaluation, expert systems and multimedia applications development, and virtual training environments. His work with virtual environments (VE) involves development and prototyping, incorporation of mission-specific procedures and training scenarios, and integration of existing simulations and intelligent computer-aided training technology with VEs. Mr. Kenney's masters thesis involved the instructional design and technical development of a VE for studying planetary motion.