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by

S. A. Brown-VanHoozer, R. C. Singleterry, Jr., R. W. King,
D. C. Crites and R. K. Magnuson

Argonne National Laboratory-West
P.O. Box 2528
Idaho Falls, ID 83403-2528

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S. A. Brown-VanHoozer*, R. C. Singleterry, Jr., R. W. King,
D. C. Crites, and R. K. Magnuson
Argonne National Lab.
P.O. Box 2528, MS6000
Idaho Falls, ID 83403
E-mail: alenka@anl.gov
208-533-7926

ABSTRACT

In the design and operation of nuclear power plants, the visualization process inherent in virtual environments (VE) allows for abstract design concepts to be made concrete and simulated without using a physical mock-up. This helps reduce the time and effort required to design and understand the system, thus providing the design team with a less complicated arrangement. Also, the outcome of human interactions with the components and system can be minimized through various testing of scenarios in real-time without the threat of injury to the user or damage to the equipment. If implemented, this will lead to a minimal total design and construction effort for nuclear power plants (NPP).

INTRODUCTION

Using VEs to design and construct a NPP allows a system designer to generate and examine different variations of NPP control room layouts, human-computer interface design, human-system interaction, and process control and operation without continuous relocation or rewiring of a physical mock-up, or through strictly quantitative graphical analysis. Since VE models are visually easier to interpret than two dimensional (2D) or even some three dimensional (3D) models, the potential for more extensive design reviews and hardware and process analysis is greatly enhanced, especially for the non-technical reviewer. Rendering techniques, such as high quality, photo-realistic VE, would provide less obscure views in a NPP design than that of a 3D model, and allow viewers to analyze and find deformities that could not be seen in wireframe models, e.g. AutoCAD™. The VE will also allow the reviewer to experience the design in situations that the user will experience.

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This type of design environment permits designers and users to update conceptual ideas in "real-time;" providing a more efficient method in the design process and the output of calculations that can be visualized in 3D detail. For the design and construction of NPPs, VEs have the capacity to provide improvement in design, mock-up, testing, equipment installation, training, and maintenance, thereby limiting cost overruns, downtime and delays. As an example, training of reactor personnel using all three primary senses (sight, sound and touch) would be enhanced for processes that lack direct visualization or that are hazardous in nature. Argonne has developed such virtual environments ranging from the low end multimedia environment, to the high end of a virtual reality CAVE™ environment. What follows are descriptions of the these VEs and their uses.

VIRTUAL ENVIRONMENTS

A. Background

A VE is a tool that combines hardware and software in the construction of spatially and temporally authentic physical environments which include objects that can be seen, heard or touched. Virtual reality (VR) technology can be thought of as the next level on the continuum of model building that allows one to add the impression of physical characteristics to the object(s) being created such as texture and weight in order to convey a sense of realism by making abstract data seem more real.

Virtual environments typically require artistic renderings of real or imagined spaces that are modeled on a computer in 3D space. The systems generally use high-end, graphics workstations with high resolution monitors, are generally not very portable, and range in cost from 10 thousand (personal computers) to 2 million dollars (super computers).

Four basic categories define VEs: (1) static - where there is no movement within the environment, e.g. AutoCAD programs, (2) dynamic - where there is some type of motion control on objects within the environment, e.g., CAVE™, (3) behavioral control - where objects detect and respond to circumstances within the environment based on a variety of preselected codes, and (4) "true" Artificial Intelligence (AI) on objects. Unfortunately, this area is in its infancy stage and has a long way to go before it is realized. Currently, Argonne National Laboratory is planning on using human factors studies involving neuro-linguistic programming (NLP) to link AI and the Cognitive Science of VEs and VRs. The University of Leuven in Belgium is currently studying linking NLP to AI and Cognitive Science.

B. Demonstrated Virtual Environments

1. Photographic Multimedia Virtual Environment. Photo-realistic panoramic scenes, audio movies, and objects of the Fuel Manufacturing Facility (FMF) were constructed to create an innovative computer-based multimedia training tool which Argonne-West calls InSight. InSight is an Argonne developed software application where scenes are viewed from outside the environment, and related information is linked to the environment, e.g., 3D objects, video clips, graphics, narrations, and text in multiple languages. It runs on a PC class computer and provides many of the features and attributes of a VE, such as the ability to interact with and explore a spatial environment, yet it does not require the prohibitive hardware and software costs of a high end VE. The underlying technology developed by Apple Computer, Inc. is called QuickTime VR™ which is a psuedo-VR model unlike the CAVE models (to be explained later in this paper). This application layer relies on a system extension called QuickTime™ that is used in generating and displaying VEs.

"Multimedia mirrors the way in which the human mind thinks, learns and remembers by moving easily from words to images to sound, stopping along the way for interpretation, analysis and in-depth exploration," (Oblinger 1992).[1] Panoramic scenes and related media provide an effective training experience, and which was experienced with Argonne's facility-specific training of staff and technicians that included: security, nuclear materials control and accountability, and emergency procedures. The effective use of the primary representational systems (visual, auditory and kinesthetic) enhanced the users interest in the training material since the user was engaged interactively with the facility rather than simply a spectator in a classroom or laboratory. An in depth human factors study would determine the true effectiveness of this particular system (the FMF model), nevertheless, advantages and disadvantages of multimedia based training are well documented.

Manipulation of the FMF VE (viewing left or right, up or down, and moving from one location to another) is controlled through an ordinary mouse device. Zooming in and out provides the illusional depth perception which is achieved via two separate control keys. Through such manipulation, a 360° view of the VE scene is permitted. This is accomplished by photographing 12 orientations (30° viewing angle for each orientation) at each node or location in the VE model to capture the full 360° panorama with some overlap between the orientations. The photographs are then scanned into the computer and electronically stitched together to provide a seamless transition between views at a particular location in the VE. With multiple nodes, the views are linked to provide the appropriate view directions and zoom level. Hot spots are defined and navigable objects or other media are linked to each spot. Hot spots allow the user to click on designated areas of the scene and launch various types of media to augment the training. The software supports an unlimited number of nodes to describe a VE, 21 nodes were used for the FMF VE. Additionally each node can have 256 hot spots, but no more than 10 per node were used for FMF.

An object in InSight is a significant type of media accessed through the panoramic scene which enhances the VE experience. Objects in the scenes are activated through the hot spots and "grabbed" with the mouse device for manipulation (turned around or tipped on end). An object is made of multiple photos that when linked together can be observed from different fields of view (fov) and angles while remaining in visual perspective. The act of grabbing the object and moving it causes the software to update the new orientation from an internal database and rapidly display the new orientation of the object selected. The outcome is an impression of the object in a 3D image.

Ultimately, the user becomes part of the VE activity rather than simply being an observer as with most traditional training settings.

2. The Three Dimensional Graphical Environment. A 3D graphical model was constructed of the Sodium Process Facility (SPF) control room and the Sodium Carbonate (SC) addition to the facility using 3-D Studio™. This graphics package, created by Autodesk™, allows for the creation of photo-realistic renderings and animation using a high end desktop computer such as the Pentium™. A lower end desktop computer could be used such as an i486™; however, rendering time would take anywhere from 8 to 20 minutes instead of one to two minutes for the Pentium system. 3-D Studio offers several embedded programs to

create various 3D geometric shapes, surface colors, scripts and variables for data-driven animations, and textures which can be applied to objects to provide a photo-realistic image, e.g., an object textured with "wood" characteristics will look similar to a piece of real wood. Designers create their own surfaces with a built-in Material Editor, animate images with the Keyframer program, and provide the capability for user input.

The SPF and SC models were generated from AutoCAD files and blueprints. The objective was to determine whether this type virtual environment would be feasible for engineers in design of new systems and facilities where they could actually visualize what was drawn on paper or in a wireframe format. It was the intent of this project to have the engineers become more aware of the type of capabilities this type of 3D VE would provide in discovering flaws or inaccuracies in design calculations or in the maintenance and location of equipment. Like the InSight model, this model is viewed from the outside-in with the ability to create animations and human models. The human model in the design allows for human reliability work flow analysis to be performed with the potential for spotting logistical and/or health hazards. Also, the placement of objects, such as surveillance cameras and lighting, for best effects can be investigated. 3-D Studio is compatible with AutoCAD so that existing drawings can quickly be rendered for modifications and/or building of new facilities, equipment or processes.

The models were presented to the SPF and SC design engineers for comments. Being able to visualize the existing and new facility, the designers realized that they could use this VE for identifying mistakes or conflicts throughout the design phases. As the control console progressed on paper, the components could be incorporated onto the console in the VE thereby allowing the designers to see the physical arrangement. Animation of the processes could be integrated with a human model to monitor work flow analysis of the tasks to be performed and the types of problems that would arise in the event of an accident. This VE is an ideal system for engineers to develop new concepts while sitting at their desk; however, to determine the long term physiological effect of such a system on the designer, a human factors based study is still required for the use of 3D VE systems.

3. The CAVE Environment[2]. An AutoCAD model of Argonne National Laboratory --- West's (ANL-W) Experimental Breeder Reactor-II, and it's fuel-handling sequence, were selected to be modeled in a high end VE known as the CAVE. The objective was to determine whether a virtual environment of this nature would be feasible in the areas of human factors research and application in nuclear systems, system calculations of nuclear modeling, control room design for operations and simulations, and training. The research project was two fold: construction of the virtual reality (VR) model in the CAVE VE, and implementation of a human factor study.

The CAVE, developed at the Electronic Visualization Laboratory (EVL) at the University of Illinois-Chicago (UIC), is a 10ft x 10ft x 9ft room whose walls and floor display computer-generated video images. "The field of view of the CAVE display achieves a full 360^{o} for the entire display, and produces an inside-out effect where the viewer is inside the model looking out. The CAVE shows all views from a fixed location simultaneously," (Cruz-Neira et al 1992)[3].

Images are projected from behind the translucent vinyl walls of the CAVE, and the floor's image is reflected from above. The images are integrated across walls and floor and give the user the illusion of being immersed in a seamless world. The computer-generated scene is projected from the point of view of the user, who wears a magnetically-tracked pair of stereo glasses. The user interacts with the virtual scene via a magnetically-tracked 3D mouse called a "wand." This device can be used to manipulate objects in the environment and navigate through the virtual scene. The computer that drives the CAVE is the Silicon Graphics, Inc. (SGI) ONYX™ graphics super computer. A separate ONYX graphics engine supplies the image for each CAVE display surface. Magnetic tracking is currently provided by Ascension Technologies Flock of Birds'™ system.

Though not easily transportable, the CAVE is a human-computer interface technology which allows for an immersion of the user into the interface, unlike the photo media or 3D VE such as a SGI monitor with stereoscopic capabilities. This is an interface in which the individual has presence because the 3D interface space can be mapped directly to the person's 3D physical space. Users can interact with their computer data similar to the way they can with objects in the physical world since the data is part of the interface.

The users presence in this virtual world, where the person's data model resides, is established by having the computer track the individual's location and orientation in the scene. This tracking data is used to render the scene at all times from the user's point of view. The individual's interaction with this model is made possible by tracking and reading input from an input device usually held in the individual's hand. The results are: (1) as the user walks around, the user always sees the scene as part of the real world, and (2) with the input device, the user can manipulate objects in the scene.

The initial EBR-II model started as paper blueprints which were converted to an AutoCAD model in DXF format at ANL-W. The DXF files were then converted to the CAVE environment at UIC and Argonne National Laboratory-East (ANL-E) where fifteen reactor components, (the fuel handling process equipment, the primary tank, the reactor vessel, and the fuel subassembly files) were broken down into hierarchical layers for ease of processing by the multiple graphics engines. These were then massaged and converted into SGI's proprietary Inventor™ format so that the model could be displayed in the CAVE environment. Each reactor segment was modeled in great enough detail for spatial realism, but in little enough detail for temporal realism (real-time interaction). A CAVE application program called VEBR, written in the C language, was used for exploration and manipulation of the EBR-II VR model. This enabled the user to manipulate the model's components, navigate through the virtual scene, and simulate the fuel-handling sequence.

Texture and surface lighting effects were incorporated into the model giving an effective illusion of 3D, metallic gray piping, and shadows. A low "humming" sound was implemented to enhance the effect of immersion within the liquid sodium chamber, and the "realism" of the model was augmented by rendering certain walls transparent. Dynamic operation included the transfer of a subassembly, the lowering and raising of the storage basket, the hold down mechanism, the gripper and the reactor vessel cover.

Two reactor operators were able to compare the CAVE model to a 3D VE model of EBR-II on a SGI 25 inch monitor. They were able to reach out to "life-like" components such as, the transfer arm, the subassembly, etc., in the CAVE environment using the stereoscopic devices, but were only able to perceive a false depth to the 3D model of EBR-II projected on the SGI monitor. The operators remarked how much more comprehensive the CAVE type of model would be in explaining to new operators and engineers how the system operated. This they felt was due to the size of the model and the inside-out effect. The operators found the CAVE VE to be an excellent tool for training in developing accurate user mental models. The operators considered the CAVE model the better VE tool for troubleshooting areas which have restricted human access or can not be seen by direct visual examination, and for training. They considered the VE at the SGI monitor level the better system for using in Operations. Both participants felt that the learning curve would be greatly enhanced through either type of VEs. However, the visual feature of the CAVE provided the capability of generating the model in a truer 360^{o} fov in comparison to the fov of the SGI monitor.

General observations of the operators' physiological responses to the system were noted. After four hours of continuous involvement with the CAVE interface, the operators displayed no signs of discomfort, only slight eye fatigue. The operators were less comfortable using the stereoscopic devices with the SGI monitor, because they felt more enclosed in the VE scene. Further study would be required for a more accurate account of their physiological responses to the system.

C. Concerns

Today's focus on VEs or VRs still remains centered on hardware implementation and software modeling, and continues to ignore the implication of VEs on the human using the system. A report of a study released by the National Research Council, in autumn of 1994, indicates that "...the importance of adequate hardware and human interaction, without which the VR [VE] field will never come close to realizing its potential, tends to be underplayed by the VR [VE] community," (W.Gibbs 1994).[4]

Virtual environments have a tendency to cause physiological repercussions, e.g., irritability, dizziness, inadequacies in performance, to the human associated with the VE interface. For example, a head mounted display that utilizes stereo optical devices creates a disorienting lag time between head movement and display update. Other drawbacks involve, (1) information processing preferences[5,6] between visual, auditor and kinesthetic oriented individuals,[5] (2) spatial consideration of the environment, (3) age and gender, (4) color blindness, (5) physical impairments, e.g. individuals that wear glasses, and so forth.

Virtual environment designers need to be aware that in using VEs, such as those mentioned in this paper, requires that they become more sensitive to the pros and cons associated with the human-interaction to these environments. These systems require careful consideration and evaluation before being installed in an operational or even a training environment for **frequent** use.

Long term effects on the optical and nervous system, behavioral indicators, and so forth are the underlining tasks of the human factor studies, and can only be accomplished if the engineer and human factor specialist work together.

D. Future Work Being Considered

Various lines of research can be pursued from the projects described so far. The most exciting is the potential of the CAVE environment. Various improvements to the systems are being contemplated. These will allow better resolution in the projected images, better control of the environment by the user, and faster model execution. Improvements to the existing models are also being researched.

A proposal to extend the EBR-II model to study human factor responses in the training environment has been proposed by ANL-W and the University of Idaho. This includes color coding and labeling of objects in the model. When a user would like to examine an object up close, that object is selected and highlighted. The object can then be moved independent of the model, brought to the foreground, and examined. During normal operation of the model, an object can be highlighted to enhance its visibility during movement. This model improvement does not need improvements to the CAVE environment itself.

The next step of model improvement is the addition of force feedback mechanisms to simulate physical barriers like walls, buttons, valves, etc.... This however, necessitates additions to the CAVE environment. Various research projects at various institutions are developing gloves, body suits, and the like to generate forces on the body that would be necessary to allow the user to perceive the grabbing of a valve handle and turning it. The research is slow and the computers are not fast enough to execute the current algorithms. So such applications as Real 3D™ are alternatives in implementing and studying a human model. Here the software allows for the user to program a human model to perform specific tasks in a virtual environment. Work flow and human reliability analysis can be determined as well as anthropometric and biomechanic feedback problems.

An intermediate step is to introduce real physical objects into the CAVE environment to give objects in the model some feedback force. This limits the CAVE operation to the 10ft by 10ft by 9ft volume imposed by the physical walls of the CAVE because the virtual objects would always need to appear on the physical object. Depending on the situation being simulated, the added sensation of force feedback will compensate for the loss of environmental movement. This tradeoff would be advantageous for the design of a control room model.

NPP control rooms do not move during normal and abnormal operation. Therefore, an ergonomically placed, transparent surface to project the control panel onto would serve as a suitable force feedback mechanism. To complete the model, a fingertip positional system would need to be added to the CAVE hardware. This control room model could then be connected to an enhanced EBR-II model. The controls would be connected to the components in the model and when a coolant pump is activated, the corresponding pump in the model would start along with the noise associated with that pump. Visual cues for shaft rotation and coolant movement would be necessary to fully simulate the startup and operation of the pump. Other components could be simulated to allow full operational procedures to be implemented in the VE.

For training purposes, an operator can be exposed to abnormal operational conditions. During the correction procedure, the operator can see, hear, and feel how the actions on the control panel affect the systems in the plant. This greatly enhances the operators connection with plant systems and their control.

Many other research projects and applications can be conceived and executed using these VE based systems. However, as different computer platforms are introduced for design applications innovative ideas for executing former (research) applications will need to be considered. This is because today's results may no longer be relevant for tomorrow's solutions.

CONCLUSION

In the realm of engineering development, VE has the potential to be an excellent tool for NPP design. It allows the user to take a step closer to virtual objects within the VE by enhancing the physical sensations from the immersion of the user in the model. In using a VE media, disruptions of facility operations can be eliminated or minimized, training is enhanced since the primary representational systems or modalities: visual, auditory and kinesthetic, are taken into account, costs in mock-up and testing are reduced, and the presentation of a conceptual design is better understood.

Problems that emerge with the use of these environments will take time to resolve, and will require the cooperation of both the design engineers and the human factor specialist.

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