

USING VIRTUAL REALITY TECHNOLOGY TO INCLUDE FIELD OPERATORS IN SIMULATION AND TRAINING

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ABSTRACT

By using virtual reality technology, field operators can be included in simulator training. A study has been performed where field operators could perform their activities in a virtual plant and communicate with a control room operator who was placed in a physical control room simulator. This paper describes the use of VR technology in the study and how the operators experienced interacting with the virtual plant.

1. INTRODUCTION

1.1 Background

Simulator training is important to nuclear power plant (NPP) operation for establishing and maintaining a broad level of operator skills and to practice handling of situations that occur infrequently. There is a trend in simulator training towards a greater emphasis on “soft skills” like teamwork, communication and decision making (International Atomic Energy Agency, 2004). The quality of teamwork and communication within a shift team influences the team's ability to operate the plant. The different members of the shift team need to communicate with each other to successfully reach operating and safety goals. For instance, control room operators need to communicate with each other to coordinate activities and keep each other updated on the plant state, and they need to request actions to be performed by field operators. Field operators need to communicate with the control room operators to obtain information about the process state and to inform about the status of their own activities. It would be favourable to include the entire shift crew in this kind of training as this would ensure that all job positions have the possibility to practice these skills. By introducing virtual reality (VR) technology in the simulator training, it is possible to include both control room staff and staff external to the control room in training sessions.

1.2 Use of virtual reality technology in simulator training

VR technology can be used to create realistic, three-dimensional graphical simulations of a work environment. Such simulated environments are called virtual environments (VEs). VR technology includes a display for presenting the graphical simulated environment, and input devices for interacting with the VE. A user can view the environment as if from within, change the viewpoint to create the illusion of walking around in the environment, and interact with objects.

VR technology can thus be applied to create a simulation of a plant (virtual plant) where field operators can perform activities during the training session. This may offer a more realistic simulation of the cooperation between control room and field operators. It can provide more

detailed interactions where field operators are involved, and it can better match the realistic time needed for field operator activities, compared to if the tasks were role-played by an instructor. Role-playing does not typically take into account activities like moving to the correct location in the plant and operating the equipment.

The use of VR further implies that the field operators become more involved in the training. They can participate in various types of malfunction or emergency scenarios, and have the opportunity to practice procedures, communication and teamwork related to such situations.

1.3 Issues related to use of virtual reality technology

Several issues may have implications for the quality and efficiency of virtual reality systems e.g. the fidelity of the simulation, the degree to which the user feels present in the VE, and the options provided for navigating in the VE and interacting with objects in the VE. Some of these issues are discussed below.

1.3.1 Simulation fidelity

The fidelity of a simulation refers to the extent to which the simulation is similar to the real-world system that is simulated. Simulation fidelity is often described as a construct consisting of three dimensions: physical fidelity, functional fidelity, and psychological fidelity (Andrews and Bell, 2000). The term *physical fidelity* describes the physical similarity of the simulation to the real world. A simulation with high physical fidelity consists of parts that have the same physical characteristics as the object that are simulated, i.e. they have the same layout, look and feel the same, move in the same way and produce the same sounds. *Functional fidelity* is the extent to which actions performed on the simulator give realistic outcomes, or whether the simulator behaves the same way as the real system when the user interacts with it. *Psychological fidelity* can refer to the extent to which the user of the simulator feels that the simulation is similar to the real system (Andrews and Bell), or the extent to which the user's behaviour (including thoughts and emotions) is the same in the simulation as in the real world (Patrick, 1992). Simulation fidelity can influence how effective the simulation is for training and for transferring learned skills to the real situation.

1.3.2 Sense of presence

Witmer & Singer (1998) defined *sense of presence* as "the subjective experience of being in one place, even when one is physically situated in another", or as "experiencing the computer-generated environment rather than the actual physical locale". A sense of presence in the VE is achieved by making an environment that causes the user to suspend disbelief and accept the computer-generated experience as "real" (Louka, 1999). Sense of presence is thus related to psychological fidelity. In the literature on sense of presence, the following factors are mentioned as important for producing presence: the ability to interact with the VE; the transparency of the user interface; the extent and quality of sensory information; reduction of distracting elements in the physical environment; realism and meaningfulness of the VE; field of view; and the user's tendency to feel presence (Steuer, 1992; Wilson, Foreman & Tlauka, 1997; Hoffman, Prothero, Wells & Groen, 1998; Stanney et al., 1998; Witmer & Singer, 1998).

1.3.3 Navigation and interaction

An important part of VR is the ability to navigate in the VE and interact with it. Navigation consists of activities performed to move from one location to another, including orientation, wayfinding, and travelling (Sebok, Helgar & Nystad, 2002). Navigation should be as easy and intuitive as possible. Some challenges facing navigation in VR are the *tunnel effect*, where the VR display technology tends to provide a limited field of view that makes it difficult to orient and keep one's sense of direction in the VE, and the lack of, or low quality of, cues like shadows and textures that reduce the user's ability to judge distance, motion, and direction (Sebok, Helgar and Nystad). Challenges related to interaction with objects in the VE are to make natural mappings from interaction devices (e.g. mouse movements) to actions in the VE, and how to integrate a variety of interaction controls to manage navigation and interaction in three dimensions (Steed and Tromp, 1998).

2. A STUDY USING VR TO INCLUDE FIELD OPERATORS IN NPP SIMULATION

A study performed at the Halden Reactor Project (HRP) investigated teamwork in a hypothetical future NPP operational concept, with higher automation levels, changed operator roles and new technology (see Skjerve, Strand, Skraaning & Nihlwing, 2005a; Skjerve et al. 2005b). VR was used in the study as a representation of a real plant to make it possible to include field operators in the study. The physical plant was depicted for the field operators as a VE where the field operators performed their activities. The field operators could navigate in the virtual plant and perform actions to operate the virtual equipment. The operators' experiences in the virtual plant were assessed by use of questionnaires, interviews and observations. The following sections of this paper will describe the use of the VR technology in the study and how the operators experienced interacting with the virtual plant. The results will be discussed in terms of the simulation fidelity, usability and effectiveness of the virtual plant.

2.1 Participants and procedure

The study used 18 participants from the Forsmark 3 (F3) and Oskarshamn 3 (O3) NPPs in Sweden divided into 6 crews. Each crew consisted of three operators, who in the home plant had the roles of shift supervisor (SS), reactor operator (RO), and field operator (FO). In the study, the SS or RO had the role of control room operator, while the other two had the roles of field operators. The average age of the operators was 44 years. The average experience as operator in the home plant was 17 years.

After an initial introduction, the operators were introduced to the plant simulator and the VR model in a one-day training session. Then the operators participated in 12 scenario sessions distributed over three days. Each scenario lasted approximately 40 minutes. The operators filled out questionnaires after each scenario. At the end of the study, a semi-structured interview was conducted.

2.2 Test Facility: the MTO Lab

The HRP's MTO lab (Man-Technology-Organisation lab) consists of the Halden Man-Machine Laboratory (HAMMLAB) and the VR lab, which are located together, separated by a movable wall. HAMMLAB is a flexible and adaptable control centre simulator whose

equipment and functions can be manipulated to produce different experimental conditions. The VR lab also offers great flexibility to be suited for different studies. The MTO lab also has multiple facilities for collecting data during experiments, including audio and video recordings and computer logs. An observers' gallery gives the experimental staff an overview of both HAMMLAB and the VR lab.

As this study incorporated cooperation between a control-room operator and field operators, both the control room environment and the physical environment needed to be simulated. For this reason, both HAMMLAB and the VR lab were for the first time concurrently utilized in a large-scale exploratory study (HAMMLAB represented the control room environment, and the VR lab represented the physical plant in the form of a VE). The control-room operator was located in HAMMLAB, and the two field operators were located in the adjacent VR lab.

The study was performed using the HAMlab BOiling water (HAMBO) Simulator, which is a near full-scope simulator based on the Swedish nuclear power plant Forsmark unit 3 (see Karlson et al., 2001 for a more detailed description of the simulator).

In the VR lab, each of the two field operators was placed in front of a large screen on which was presented a 3D model of the plant. One of the screens was a 493x187 cm front-projected screen. The other was a 366x142 cm back-projected large screen. A separate computer was running the VR model for each display (Dual 3 Ghz Intel Xeon 2, 2 Gb RAM). See Figure 1 for an illustration of the VR-lab set-up ("P" is short for "projector").

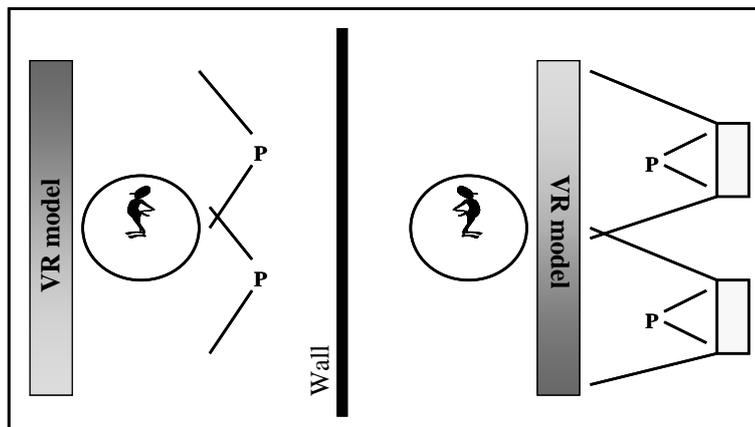


Figure 1. The VR-lab set-up.

2.3 The virtual plant

The VR model of the plant included a subset of rooms that the operators had to access in order to perform the given tasks. The field operators were able to enter the part of the plant they wanted by selecting the appropriate building, floor and room from an overview map. When a room was selected, the time used to walk to the room was simulated.

Once the selected room appeared on the display, the operator could navigate in the room using a set of navigation functions. These functions allowed the operator to move horizontally and vertically in the room and to look around. There were also functions to automatically go back to the starting position in the room, to straighten the view horizontally, or to automatically navigate to a selected object. To prevent confusing the operators, navigation was limited to within the walls of a room. Thus, it was not possible to go through the external

walls of the room. To interact with the virtual objects that were connected to the simulator, the operator could click on the object with a mouse, and select an action from a pop-up menu. Example actions were to open and close valves, or activate and deactivate buttons.

All significant objects for performing the scenario tasks were included in the room models. The VR models had a level of detail and realism that made it possible for the operators to recognize the surroundings and to perform manual activities. The selection of objects was also based on what was needed for the operators in each scenario. The geometry of the rooms themselves were made to accurately mimic the real rooms. All rooms were located in their original layout in the plant, and this provided the foundation for calculating the distance and the time it took to navigate between the rooms in the model. See Figure 2 for an example view of a room in the virtual plant.

All the rooms were modelled in Multigen Creator. The objects in, or the contents of, the rooms, were modelled in Multigen Creator and inserted into the rooms using the HVRC CREATE software tool developed by IFE. The simple user interface of the HVRC CREATE software makes it possible for users without modelling experience, and only basic computer skills, to construct the layout of the virtual rooms. Thus, e.g. operators can be included in the modelling process to check that the VR models are correct and that they include the objects needed for performing the scenarios.

If the operator requested to enter a room that was not modelled, an empty room appeared on the large screen display. When entering such a room, the operators had to contact the experimental staff to tell them what operations the operator wanted to perform. The purpose of including the empty room was to avoid having to model all the rooms in the plant, but still make the entire plant available to the operators.



Figure 2. Operator in front of the VR model of the plant.

2.3.1 The coupling between simulator and VR models

Objects in the VR model were connected to the simulator's communication system to let the field operators interact with the HAMBO simulator through the VE. In this way, actions that the operators performed in the virtual plant affected the simulator state. For instance, when a field operator opened a valve in the plant, this was registered in the simulator. The communication between the simulator and the virtual plant was two-way. The simulator updated the VR model in order to maintain consistency, which means that e.g. an analogue indicator value in VR dynamically changed when the corresponding value in the simulator changed.

Due to time constraints, it was not possible to connect all the objects in the rooms to the simulator. On the basis of the likely progression of the scenarios, a selection of objects was made. Operations on these objects intervened directly with the process simulator. If the operator attempted to perform actions on objects that were not connected to the simulator (static objects), a message asked the operator to contact the experimental staff for execution of the requested operations.

Examples of the process objects that were modelled and connected to the simulator are shown in Figure 3.

The VR Framework was developed using the software development kits Java and Java 3D. Java is a general purpose cross-platform programming language developed by Sun Microsystems Inc. Java 3D is a high level 3D application programming interface for constructing 3D applications using the Java programming language. The communication interface of the HAMBO Simulator is built upon the SoftwareBus Library (<http://www.ife.no/swbus>) developed by IFE. Software Bus is an object-oriented, Transmission Control Protocol (TCP)/Internet Protocol (IP) based, data communication system particularly aimed at simulator systems and process surveillance and control systems.

The system is highly configurable and component-based, which makes it possible for non-programmers to expand the VE by adding configurable process objects which automatically connects to the HAMBO simulator.

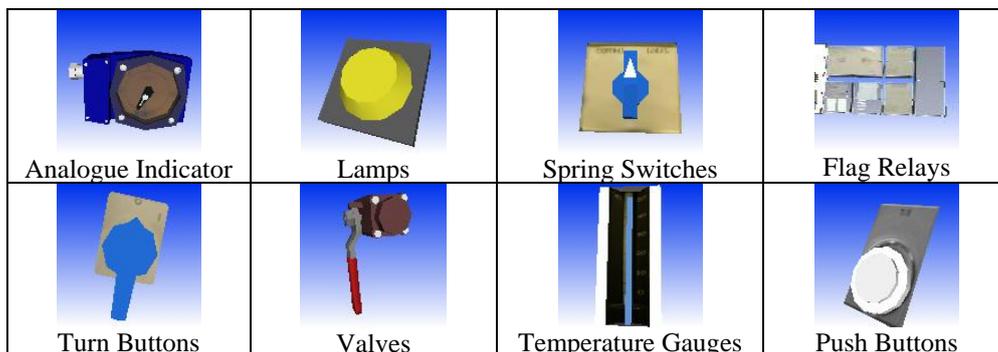


Figure 3: Modelled VR-objects connected to the simulator.

2.4 Data Collection Techniques

Data were collected during the study in the form of questionnaires, interviews and observations.

2.4.1 Questionnaires

Before working through the scenarios, the operators completed a questionnaire that provided background data, including age, education, occupational experience, and experience with computers and computer games.

Slater, Usoh and Steed (1995) have developed a questionnaire to assess the users feeling of spatial presence in a VE. The questionnaire consists of 6 questions and was answered by the two field operators. It gives an indication of how real the VE felt for the user, how involved the user was, and how engrossed he/she was by it.

A questionnaire was used to measure the quality of navigation in the virtual environment. This consisted of four items from the navigation questionnaire used in Sebok, Helgar and Nystad (2002) that ask about the participants' general impression of the navigation quality, their ability to move in the VE, and the navigation speed. This questionnaire was presented to the field operators.

2.4.2 Interviews

An interview of the operators was conducted after completion of all scenarios. The topic of the interview included the operators' experience of using the virtual plant, and usability issues related to interaction with the VE.

2.4.3 Video recordings and observation

Video recordings were made of each scenario, including a recording of each of the field operators and the large screen display they were looking at. The operators were also observed from the experimenters' gallery during the scenarios. Problems and other interesting occurrences during the scenarios were noted.

3. RESULTS AND DISCUSSION

3.1 Analysis approach

The participants' individual experience with the advanced technology and the virtual plant was quantitatively assessed by examining questionnaire responses, and qualitatively by analysing interviews and observations. Statistical analyses were made to investigate the questionnaire data.

3.2 Spatial presence

The average spatial presence rating was 3.7. The spatial presence scale ranged from 1 to 7, so these rating indicate that the operators did not feel totally present in the VE, but they were also not totally in the real world. The spatial presence ratings of the operators who had more experience with the plant were slightly higher than the ratings of less experienced operators (4.1 and 3.3, respectively). Previous VR research has found similar results, namely that users who are more familiar with the environment represented in VR experience higher levels of spatial presence than users who are less familiar with the environment (Hoffman et al., 1998; Nystad & Sebok, 2004). The reason for this is probably that the virtual representation of the environment triggers additional details from memory, which helps to "fill in" aspects missing

from the VE and thereby increase the realism. This may imply that if the user is familiar with the real environment, the physical fidelity of the VE does not have to be very high for the user to feel as if it is real. Of course, the physical fidelity must still be good enough to ensure proper transfer of training to the real environment. It is however unclear whether spatial presence is related to training efficiency and transfer of training.

3.3 Navigation and interaction

The operators rated the navigation quality on average 3.6 on a scale from 1 to 5. This means the operators found navigating in the virtual plant neither very easy nor very difficult. The rated navigation quality increased slightly across the course of the study.

Some operators reported that it was difficult to find the way in the virtual plant because they were not very familiar with the plant. The operators who were field operators in their home plants, and therefore had fresh experience from the actual plant, did not report the same problems. This shows that wayfinding ability in the virtual plant was not related to the detail of the VR models, but rather to the knowledge the operators had of the real plant. The operators with fresh plant experience rated navigation quality slightly higher than the less experienced operators (4.0 versus 3.1).

There were some reported problems with navigation in the VE. Some of the operators had problems navigating in narrow spaces and navigating around corners. Others had problems with keeping level with the floor because they rotated both in the horizontal and vertical direction. It was probably because of these problems that many operators preferred the automatic navigation functions, i.e. the aim function to navigate to a selected location, and the function to go to the starting point in the room. When users are fairly unfamiliar with the navigation functions, such automated navigation can be useful.

3.4 Simulation fidelity

When designing the VE, it was not a goal that the real and virtual plants should be as visually similar as possible. A selection of objects were modelled to make it possible for the operators to recognize the rooms and to find their way around. The objects that were modelled were also made at a relatively high level of detail. One discrepancy in the models compared to the real plant was that some labels were missing from the panels. This was seen as a problem because it made it more difficult to find the correct objects, like meters, switches and buttons on the panels. Since the operators use labels to identify these objects in the real plant, they should also be present in the VR model.

The operators who had most experience with the plant generally had no problems finding their way in the virtual plant or finding the correct objects to operate. This indicates that the physical fidelity of the virtual plant was good. The physical fidelity of the virtual plant can be increased further by including additional cues in the model. Sounds and leakages were not included in the VE used in the study, but this can provide information about equipment failure and can be useful for diagnosis. In this respect, they can give important information to the operators, and should be a part of the simulation. Adding such cues increases the degree of similarity to the real plant, and may also increase the psychological fidelity because it provides additional realistic ways for the operators to relate to the simulation.

The behaviour of the virtual plant was in some parts similar to the real plant, but in other parts it differed. The number of functions that were possible to perform by the field operators in the

virtual plant was quite large because the operators could contact the experimental staff to perform actions on objects that were not connected to the simulator. The process of operating static objects through the experimental staff worked quite well once the operators got used to it.

The way the user interacts with the simulation is likely to influence the psychological fidelity. Fidelity may be reduced if the tasks in the simulator are difficult to perform (i.e. poor usability), or if the tasks are performed differently from the way they are performed in reality. Interaction problems can take the focus away from the task, and thereby reduce the psychological fidelity or spatial presence. Support for this can be found in the high positive correlation between perceived navigation quality and spatial presence found in this study, which means that difficulties in navigation were associated with low spatial presence. But this relationship may also be influenced by a third factor like e.g. age or computer experience. In some incidents during the scenario runs, the operators experienced difficulties in performing the tasks they wanted to do, e.g. not managing to navigate to the right place, getting stuck within virtual cabinets, and difficulties in operating equipment in the virtual plant. Such problems were particularly detrimental for psychological fidelity when the operators were not able to solve the problems on their own and needed help from external staff. When the operators used a long time to solve usability problems, the time used to perform the simulated tasks increased. This may also have influenced the perceived realism of the simulation. The lesson learned from this is that the better the usability of the virtual plant, the easier it is for the user to act as if the simulation is real.

If an operator wanted to perform an action on an object that was not connected to the simulator, he or she had to contact the process expert on the experimenters' gallery to execute the action. The way these actions were performed thus differ from the way they are performed in the real plant. Other actions that differed from the real plant were the way the operators navigated in the virtual rooms. It was possible to move both horizontally and vertically, so the operators could fly through the room. There was no collision avoidance within the rooms, so they could move through objects that were supposed to be solid. It was possible to perform actions on objects that were far away, not only those within arm's reach. All of these discrepancies between the virtual and the real plant may have made the operators more aware that the simulation was just a simulation. This may have reduced the level of psychological fidelity. However, the operators sometimes behaved in the virtual plant as they would in the real world, even when they did not have to. Some operators were observed to navigate around objects in the virtual rooms instead of moving through them. This could be an indication that the operators were able to suspend disbelief and treat the virtual plant as real.

The inclusion of the VE in the study made it possible to add a new dimension to the simulation by letting field operators participate in the scenarios. This meant that the control room operator could relate to the real field operators instead of to a member of the experimental staff playing this role. Most of the crews participating in the study were also working together in the same crew in the home plant, so they were familiar with each other and had a predefined way of working together. The communication with the control room operator would probably not have been the same in a role-playing situation with a member of the experimental staff. Inclusion of field operators in the simulation is likely to have increased the psychological fidelity for the control room operator compared to studies where field operators are not included. The control room operator could communicate with the field operators in the same way as in the home plant. From observations made during the scenario runs, it seemed that the operators were able to behave quite naturally in their interactions with

each other. In other words, the operators could act as if the field operators were in the real plant.

3.5 Implications for use of VR in simulation and training

The physical fidelity of the VE must be good enough to make it possible to perform the required tasks. If information in the environment is needed to fulfil the task (e.g. labelling), then this information should be included in the VR models. Task analysis techniques can be applied to determine which parts of the environment need to be simulated, i.e. what information is needed in the VE. To increase the physical fidelity, cues like sound or leakages may be added.

For training and simulation purposes, the interaction with the VE should be similar to the real world. Navigation should be constrained to the floor, and if vertical movement is to be performed, then it should be required to climb ladders or stairs. Collision avoidance can be used to avoid movement through objects. The interaction can be made more realistic if it is necessary to be close to the object in order to operate it, e.g. valves and switches. Interaction should also be easy to perform (after some initial training and adaptation) so that the user can concentrate on the tasks to be performed instead of on how to interact with the environment.

For inexperienced users, navigation in the VE can be cumbersome. It can be useful to automate the process of navigation in the virtual plant. Functions like automatic transportation to a selected object, automatic navigation to a selected landmark, and automatic climbing of stairs and ladders can be included.

Inclusion of field operators seemed to support psychological fidelity, because the control room operator could relate to the field operators as he/she would in the home plant. The level of psychological fidelity experienced by the field operators in the virtual plant was moderate (based on spatial presence ratings). When the user is familiar with the real environment, the physical fidelity may not have to be very high in order to reach a moderate level of psychological fidelity.

The virtual plant can be modelled in a simple way using the tools described in this paper. A simple user interface makes it possible for operators to take part in building the contents of the virtual rooms and to make dynamic connections between the process objects and the plant simulator.

The most important implication from this study is that VR can successfully be used to include field operators in simulator studies or simulator training. Field operators could interact with the control room in much the same way as in the real plant. This makes it possible to extend the traditional way of performing simulator training, as it allows field operators and other external staff to take a much more active part in the training experience.

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