TRAINING SOFTWARE USING VIRTUAL-REALITY TECHNOLOGY AND PRE-CALCULATED EFFECTIVE DOSE DATA

Aiping Ding,*† Di Zhang,* and X. George Xu*

Abstract—**This paper describes the development of a software package, called VR Dose Simulator, which aims to provide interactive radiation safety and ALARA training to radiation workers using virtual-reality (VR) simulations. Combined with a pre-calculated effective dose equivalent (EDE) database, a virtual radiation environment was constructed in VR authoring software, EON Studio, using 3-D models of a real nuclear power plant building. Models of avatars representing two workers were adopted with arms and legs of the avatar being controlled in the software to simulate walking and other postures. Collision detection algorithms were developed for various parts of the 3-D power plant building and avatars to confine the avatars to certain regions of the virtual environment. Ten different camera viewpoints were assigned to conveniently cover the entire virtual scenery in different viewing angles. A user can control the avatar to carry out radiological engineering tasks using two modes of avatar navigation. A user can also specify two types of radiation source: ^{137}Cs and ^{60}Co. The location of the avatar inside the virtual environment during the course of the avatar's movement is linked to the EDE database. The accumulative dose is calculated and displayed on the screen in real-time. Based on the final accumulated dose and the completion status of all virtual tasks, a score is given to evaluate the performance of the user. The paper concludes that VR-based simulation technologies are interactive and engaging, thus potentially useful in improving the quality of radiation safety training. The paper also summarizes several challenges: more streamlined data conversion, realistic avatar movement and posture, more intuitive implementation of the data communication between EON Studio and VB.NET, and more versatile utilization of EDE data such as a source near the body, etc., all of which needs to be addressed in future efforts to develop this type of software.**
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Key words: as low as reasonably achievable (ALARA); dose assessment; dose equivalent, effective; effective dose

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INTRODUCTION

TRAINING OF workers about the radiation safety principle of as low as reasonably achievable (ALARA) is an important part of any operational health physics program (Cember 1996; ICRP 1977). Daily and emergency procedures involving complex radiation environments, such as those found during the refueling in nuclear power plants, can benefit from effective training (EPRI 2004). Many nuclear weapon research laboratories have been in various phases of decommissioning and would frequently require the exercise of ALARA in the handling of intractable radioactive contamination and waste issues (U.S. DOE 1980, 1997). Radiological assessment of shielding and potential personnel exposures for proposed new power plants is part of the challenging licensing process. And user-friendly software that can realistically simulate potential exposure scenarios with meaningful radiation protection dose quantities will be very useful (EPRI 2004). Recently, recognizing a growing need for interactive visualization technologies, the nuclear power industry has sponsored a number of projects involving the latest computer and virtual reality (VR) simulation technologies for ALARA training, job optimization, security inspection, and evaluation of new reactor design (Knight et al. 1997; Lee et al. 2001; Vitanza 2001; Whisker et al. 2003; EPRI 2004; Iguchi et al. 2004; Ohga et al. 2005; Zhang and Xu 2007). One of those projects was the Halden Reactor Project, an international cooperation project to modernize the control room design, train the refueling specialists and evaluate the radiation exposure in the decommissioning process (Vitanza 2001).

VR refers to a computer technology that allows a user to interact with or navigate through a computer-created 3-dimensional (3-D) environment. It provides an artificial world in which the user has an illusion of being involved or even immersed in that environment with an ability to interactively manipulate building objects and avatars (Burdea and Coiffet 2003). Modern VR technologies can be classified into 3 modes: (1) the 2.5-D non-immersive mode that simply presents the image on an affordable 2-D display device such as a PC and creates a 3-D illusion that is responsive to simple user input through the keyboard; (2) the 3-D semi-immersive mode that involves a mathematical model of the virtual world, together with specific user-input devices such as shutter eyeglasses or hand-held controller from which the computer uses the model or data to create a real feel for the virtual environment; (3) the 3-D immersive mode is the 3-D semi-immersive mode plus some additional features that can create a much more realistic illusion of being immersed in a virtual world, such as those created by the professional CAVE system (Burdea and Coiffet 2003; EPRI 2004). The main advantage of the first mode is the relatively low cost in hardware. Most existing PC games are usually designed using this 2.5-D non-immersive mode, coupled with increasingly sophisticated VR software and powerful visual displays.

Most of the VR-based software applications developed for the nuclear industry, however, have focused mostly on technologies involving immersive VR interfaces and computer visions (EPRI 2004). As such, these software tools did not consider proper radiation protection dose quantities. We believe that, in order for the VR technology to be useful in ALARA related radiation protection planning, such simulation software should be based on realistic dose data such as the effective dose equivalent (EDE) required by the U.S. Nuclear Regulatory Commission (NRC) for radiation protection purposes (ICRP 1977; U.S. NRC 1992). In particular, the Electric Power Research Institute (EPRI) has previously sponsored a number of projects that resulted in a large amount of EDE data and various personnel monitoring methodologies that have gained acceptance in the nuclear power plants (Reece et al. 1994; Reece and Xu 1997; Xu et al. 2006a, 2006b). Although these earlier EPRI-sponsored projects have produced valuable EDE data, the radiation environment had been necessarily simplified as parallel beams or point radiation sources and the workers were also assumed to be stationary with respect to the radiation sources. Furthermore, there is no tool to use this EDE data directly in a 3-D radiation environment.

To address these needs stated above, a project has been carried out to demonstrate the feasibility of VR-based training software, called VR Dose Simulator, that simulates a realistic nuclear power plant environment in 3-D and displays EDE data in real-time using an interactive software graphic user interface (GUI). This software is designed with the 2.5-D non-immersive mode that is feasible to implement for most radiation protection programs. This paper describes the methods used for developing this VR software, various tools for implementing 3-D building geometries and avatars, and associated software functionalities including dose reporting and performance scoring.

MATERIALS AND METHODS

The VR Dose Simulator is designed in a similar way as an interactive computer game. It contains a VR core software platform and GUI controls with the following four software modules: 1) a 3-D model of the nuclear power plant defined originally by a Computer Aided Design (CAD) data set; 2) two avatars, representing one male worker and one female worker, in 3DS format designed with "jointed parts;" 3) a pre-calculated EDE database, used for the dose calculation; and 4) a scoring system; the Visual Basic.NET (http://msdn.microsoft.com/vstudio) is used as the major programming tool to develop object-oriented modules according to the architecture.

The VR core software platform is based on the EON Studio (http://www.eonreality.com/), a VR authoring software that allows users to customize the interactive realistic real-time visual environment and has been used by many PC game designers. The 3-D CAD model was originally designed in SolidWorks (http://www.solidworks.com/) for a real nuclear power plant including functional parts such as the reactor vessel, circular wall, pressurizer, steam generator, and various piping. Although commercial CAD software packages have slightly different data formats, the effort to adopt such a CAD model into the VR core software platform is manageable. To simulate workers performing radiological engineering tasks, two avatar models representing a male and a female were bought from 3-D Special Corp (http://www.3-d-models.com/).

The 3-D models of the nuclear power plant and avatars were imported into the VR software to construct the VR environment that is supported by necessary interactive data communications within the virtual system. Dose calculation, scoring system and software GUIs were designed using Visual Basic NETwork (VB.NET). The whole software design process is illustrated in Fig. 1.

3-D models of the nuclear power plant environment and workers

In this software, two types of models were designed: 1) the 3-D nuclear power plant building model, which is shown in Fig. 2; and 2) the 3-D avatar model, which is shown in Fig. 3.

The 3-D model of the nuclear power plant building was originally defined in SolidWorks as a solid-geometry model. To make this model easy to control and compatible with the collision detection in VR software, the solid geometry was converted to the surface model in the STL (stereolithography) format. The model was also simplified by eliminating unnecessary internal parts in the original CAD data.

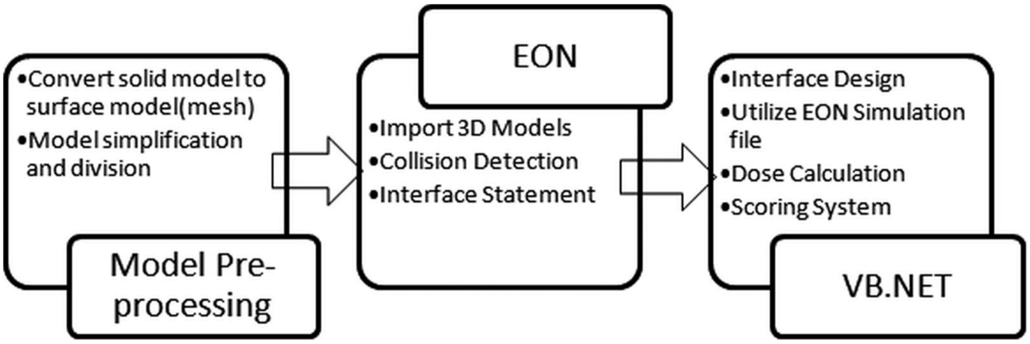

Fig. 1. The flowchart of the whole VR process: first, model pre-processing; then, import the 3-D model into EON to create the virtual environment; VB.NET is a programming tool to implement the whole system integration.

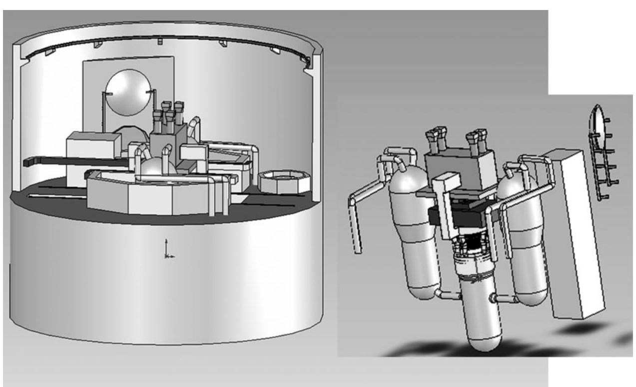

Fig. 2. The original 3-D model of the nuclear power plant in SolidWorks, including reactor vessel, circular wall, pressurizer, steam generator, other pipes, etc.

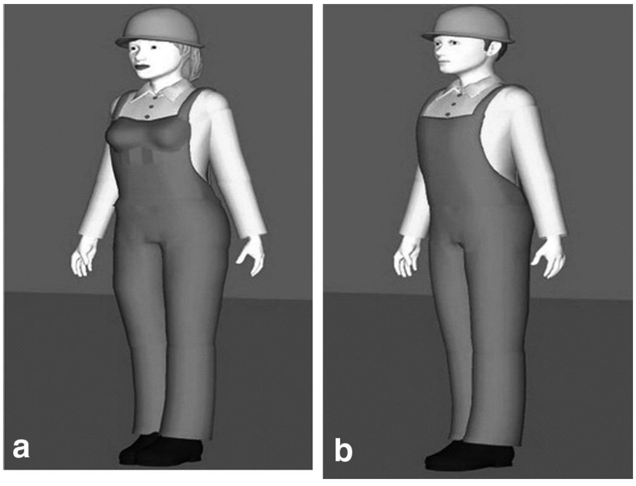

Fig. 3. 3-D avatar models, in 3DS format with "jointed parts," were adopted: a) a female worker, Jane; and b) a male worker, John.

To ensure that the avatars would walk in the virtual environment without entering into a solid object such as the walls, a collision detection algorithm needs to be established. To this end, different solid objects were specified into special groups in the EON environment and assigned unique physical properties of collision. Certain objects of the original model, such as the circular wall, had to be divided into multiple pieces with well-defined boundaries.

In the VR Dose Simulator software, an avatar acts as a virtual worker who would accomplish virtual radiological engineering jobs in the virtual nuclear power plant controlled by a user through the mouse, keyboard, or joystick. The locations of the avatar are computationally related to the pre-calculated EDE data, thus the movement of the avatar allows the EDE to be accumulated throughout a job in real-time. A user is engaged in the radiation safety training because the VR environment generates a high degree of interactivity and, as a feedback to the user, a score is displayed during the training to evaluate the user performance.

In the EON Studio, once the modified 3-D nuclear power plant and avatar models had been imported, an interactive controlling function was added by creating the "Events" for the arms and legs of the avatar in the EON Studio GUI. Realistic walking movement allows a user to use a PC device to control the avatar in negotiating various regions of the virtual power plant building. The collision detection module makes sure that an avatar only walks on the surface of the floors within certain regions of the CAD drawing and does not run into solid objects in the 3-D building. In order to view the whole virtual environment from different viewing angles, ten different camera viewpoints were assigned in the EON Studio to cover every corner of the building. A user is allowed to switch between the camera viewpoints by choosing the number keys of the PC keyboard.

Design of the interactive GUI

The Microsoft Visual Studio 2005 (http://msdn.microsoft.com/en-us/library/ms950416.aspx) is an efficient and advanced object-oriented development tool. As part of the Visual Studio 2005, VB.NET was used as the major programming language in the development of the GUIs.

The data communication between the EON virtual environment and VB.NET is critical for the dose calculation and scoring system module. Through the so-called "out-events" that are defined in the proper "nodes" and the script-programming interface available in EON Studio, it is convenient for VB.NET to access the information defined in the EON.

As to be explained in the next section on "EDE Calculations," the coordinates of an avatar are used in both the "dose map" mode and the "fixed source" mode to accumulate the EDE. First, an "Instance" (i.e., an object in computer's memory) in VB.NET is generated to represent an EON file, and then the avatar's coordinates are transmitted through out-events of this instance. The coordinate information displayed in the screen is refreshed in real-time and the EDE is calculated and displayed in every second.

The "scoring system" is a feedback designed to evaluate the performance of a user. The user receives 20 points for arriving at each way point—a location in the nuclear power plant that work is required to cover for a certain task. Meanwhile, the score is also based on the final accumulated total EDE and the completion of all related virtual jobs. A minimum dose is defined in advance as the accumulated dose an ideal worker would receive. On the other hand, a user is penalized for carelessly entering a high radiation area or for wasting time in transitioning from one way point to the next.

EDE calculations

In the United States, all nuclear power plants are required by the U.S. NRC to assess the EDE that was originally recommended by the International Commission on Radiological Protection (ICRP 1977; U.S. NRC 1992). Mathematically, EDE, denoted as H_E, is calculated as a weighted sum of organs/tissues dose equivalents (H_i):

$$H_E = \sum_i W_i H_i, \tag{1}$$

where W_i is the tissue weighting factor explicitly defined by the U.S. NRC (1992). EDE values have been calculated using whole-body human phantoms and Monte Carlo simulations for exposure scenarios typical to the nuclear power plants (Reece et al. 1994; Reece and Xu 1997; Xu et al. 2006a, 2006b). These previously calculated EDE values were adopted for the VR Dose Simulator which offers two source terms: a "dose map" mode that represents typical radiation surveys performed by a hand-held instrument and a "fixed source" mode that represents a gamma source producing a "parallel beam" exposure to workers.

For the "dose map" mode, the whole floor is divided into a 10 × 10 grid. The dose map, which defines the exposure rate at the center of each square area, is specified by an instructor of the training course. This feature allows the instructor to adjust the exposure condition according the trainee's experience and progress. The software converts the exposure rate to EDE according to the time a user spends at each location.

Under the fixed source mode, a gamma-ray emitter and its radioactivity are specified by the user in the software GUI. A point source geometry is used to calculate photon fluence at the location of the worker because the previously calculated EDE values were normalized by the photon fluence. Several unidirectional exposure geometries were used, including anterior-posterior (AP), posterior-anterior (AP), left lateral (LLAT), and right lateral (RLAT). As a worker walks around on the floor, the accumulated EDE can be calculated.

Fig. 4 illustrates how the position of the avatar is used to calculate the EDE. (X_0, Y_0) is the coordinate of the point source, while (X, Y) is the coordinate of the worker. So $\vec{a}$ is the vector pointing from the source to the worker. $\vec{b}$ is the vector pointing to the direction towards which the worker is walking. In Cartesian coordinate as dashed line shown in Fig. 4, α is the angle of vector $\vec{a}$, and

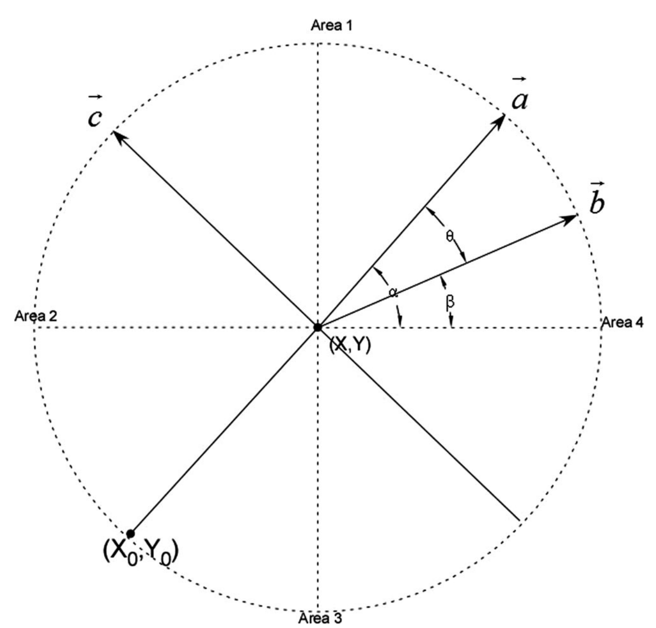

Fig. 4. Illustration of the worker's geometry in terms of the point source mode. The whole virtual environment was divided into 4 areas. Worker's geometry is as follows: in area 1, PA + LLAT; in area 2, LLAT + AP; in area 3, RLAT + AP; in area 4, RLAT + PA.

β is the angle of vector $\vec{b}$. Geometry for dose calculation is related to the relationship between vector $\vec{a}$ and vector $\vec{b}$. In the coordination, based on vector $\vec{a}$ and vector $\vec{c}$, which is perpendicular to vector $\vec{a}$, if vector $\vec{b}$ is in area 1, the geometry is a combination of the PA and LLAT exposures; if vector $\vec{b}$ is in area 2, the geometry is a combination of the LLAT and AP exposures; if vector $\vec{b}$ is in area 3, the geometry is a combination of the AP and RLAT exposures; and if vector $\vec{b}$ is in area 4, the geometry is a combination of the RLAT and PA. Under each circumstance θ, the difference of $\vec{a}$ and $\vec{b}$ was used to interpolate between two different geometries.

RESULTS AND DISCUSSION

Using the methods described earlier, a virtual 3-D nuclear power plant was constructed in the EON Studio and the software package was designed by integrating the EON Studio file and the VB.Net code. Table 1 summarizes the most important software functions defined in the EON Studio and VB.Net.

Two avatars were imported into the virtual background in EON Studio and assigned an interactive controlling function in jointed parts of arms and legs for a user to simulate the virtual training procedure. Collision detection was defined for grouped CAD objects and the avatars so that the avatars can move within certain regions of the virtual environment, such as the floor surface without crossing the wall. Ten different camera viewpoints were also assigned to cover the whole virtual scenery and it was very convenient for the user to switch the viewpoint through the keyboard. The constructed virtual power plant building with the avatar is shown as Fig. 5.

Fig. 6 shows the GUI in the VR Dose Simulator where a user can choose from two navigation modes for the virtual task: automatic navigation and interactive navigation. In the automatic navigation mode, the avatar walks along a route defined by a user at the beginning of the training. This navigation is similar to an animated movie and the user does not interactively control the navigation. This navigation mode can be used to demonstrate an ideal way to cover some specific way points during the job planning and then the software carries out this route automatically. In an interface illustrated in Fig. 6, the locations for the avatar to finish these virtual jobs, or “way points,” are defined using the X and Y coordinates. For each pre-defined way point, a user can specify the time for an avatar to stay at each location. The time ranges from 10 s to several hours. When the avatar arrives at one way point, there will be a prompt displayed on the screen to notify the user. In the interactive navigation mode, on the other hand, the user can actively control how and where the avatar moves in the nuclear power plant by using the computer keyboard. A number of keys on the keyboard are defined for this interactive navigation mode: “Up ↑” and “Down ↓” keys control the avatar moving forward and backward, while “Left←” and “Right→” keys control the avatar turning to left and right. Some of the way points can be used to simulate a worker who stops at a station to change clothes and shoes, wear a radiation badge, or check out tools. There is a way point that simulates a worker who fixes a valve. Yet another way point simulates where a nuclear waste container needs to be removed. At each of these way points, if the avatar stays there over 10 s, the dose calculation will use the time specified in the initial interface to calculate the dose. Otherwise, the actual staying time will be used. The shorter time the worker spends in finishing these jobs, the less dose he or she would receive.

Fig. 7 shows the software GUI where a user can choose from two radiation source terms: dose map and fixed source. The “dose map” is based on a dose rate file, which records the exposure rate in each small square of

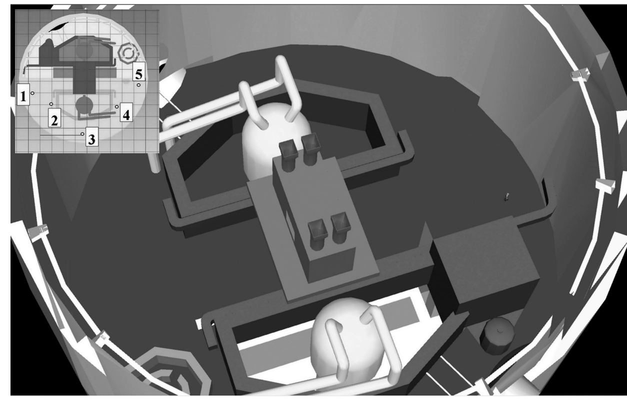

Fig. 5. A 3-D nuclear power plant model adopted in the VR environment. The avatar can be controlled by a user to cover 5 “way points” on the floor to finish various virtual jobs.

Table 1. Major functions defined in the EON and VB.Net. The data communication between EON and VB.Net was implemented by the EON script node.

Functions defined in EON	Functions defined in VB.Net
1. Automatic navigation	1. Avatar selection
2. Interactive navigation	2. Virtual job planning
3. Avatar posture and movement	3. Radiation source information
4. Camera viewpoints	4. Visualization of way points
5. Interactive controlling function	5. Avatars position, accumulated dose and scoring
6. Collision detection	
7. Script node	

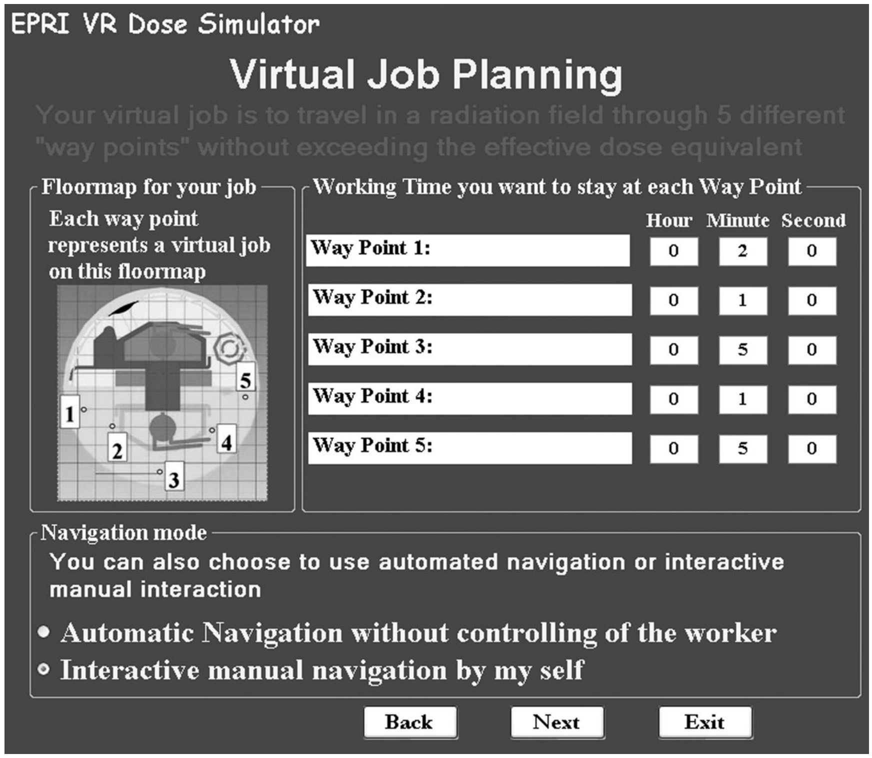

Fig. 6. Virtual job planning interface. A user can define the working time at each way point and choose the navigation mode between the "Automatic Navigation" and "Interactive Navigation."

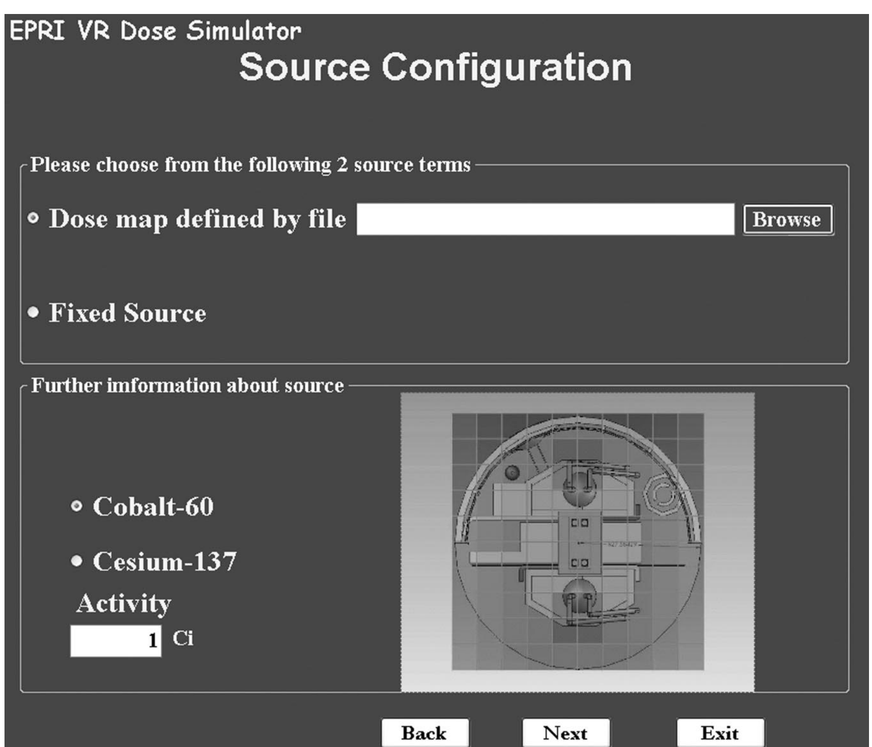

Fig. 7. Source configuration user interface for a user to choose from two radiation modes: dose map and fixed source.

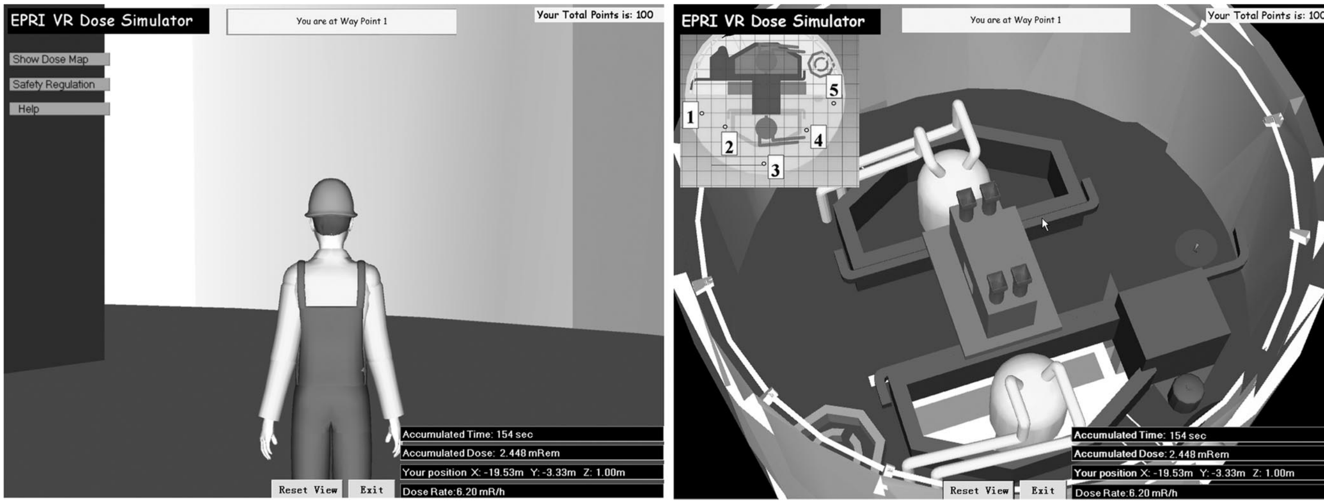

Fig. 8. User controlling interface with the accumulated time, the accumulated dose to the worker, the current position of the avatar and the current dose rate shown on the screen in the real time.

the plant region. These data are usually obtained using a radiation survey meter in a real nuclear power plant environment. In the "fixed source" scenario, the user can specify either the ^{137}Cs or the ^{60}Co, as well as the radioactivity. If the avatar stays at one way point for a period of time, the software will calculate the accumulated EDE. A score is displayed on the screen to reflect the number of virtual jobs that have been finished and the accumulated EDE to the worker. During the VR simulation process, the accumulated time, the accumulated dose to the worker, the current position of the avatar and the current dose rate are also displayed on the screen in real-time, as illustrated in Fig. 8. In a game-like 3-D interactive learning environment, a user is constantly reminded of ALARA and procedures that can improve the efficiency of the work.

CONCLUSION

This paper has described the methods used to develop a software package, VR Dose Simulator, that provides an interactive and engaging way of training workers about radiation safety and ALARA by requiring the trainee to make good decisions in a complex radiation environment. This software package is based on VR technology involving a VR authoring platform called EON Studio. The software has created a built-in dose reporting mechanism using a pre-calculated EDE database. A virtual radiation environment is constructed in EON Studio by directly importing 3-D geometries of a real nuclear power plant and two avatars representing workers. Interactive control functions allow the arms and legs of the avatar to simulate realistic walking and other postures such as turning a valve. To make sure the avatar would walk within certain regions of the virtual environment, a set of collision detection algorithms was developed to define the relationship between an avatar and various parts of the 3-D building structure. The physical location of the avatar in the virtual background, once selected by a trainee, is linked in real-time to the EDE database. The accumulative EDE is calculated with the avatar's movement, so the trainee can review the accumulative dose on the screen in real-time during the exercise. The software has provided two radiation source modes that a trainee can select: dose map and fixed source mode. Under the dose map mode, the input data is the distribution of exposure rate in a real nuclear power plant. This mode provides an accurate calculation of dose. In the fixed source mode, a ^{137}Cs or ^{60}Co point source will irradiate the worker who walks through different parts of the radiation field according to the hot-key operation of the trainee. Based on the final accumulated dose and the completion of all virtual tasks, a score is given to evaluate the performance of the user. To our knowledge, VR Dose Simulator is the only software package that is based on a real nuclear power plant 3-D drawing and EDE database.

This project has demonstrated that VR-based simulation technologies are interactive and engaging, thus potentially useful in improving the quality of radiation safety training. Also demonstrated is the feasibility to adopt a 3-D CAD drawing into the VR authoring software to construct a virtual radiation environment for a specific nuclear facility. Finally, this project has illustrated how the EDE data can be integrated into such VR software for realistic training and even for job planning involving high-exposure situations. This project also identified several challenges in developing this type of software: more streamlined conversion from a 3-D CAD drawing of the building to the VR environment, revision of the CAD data for collision detection, realistic avatar movement and posture, more intuitive implementation of the data communication between EON Studio and VB.NET, more versatile utilization of EDE data such as a source near the body, additional user-input device joysticks, sound effects, as well as the use of shielding as part of job planning.

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