The visualization of 3D radiation dose field in virtual environment

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Abstract. Avoiding the harm caused by nuclear radiation is an important topic in the field of nuclear physics. For nuclear radiation protection, it is necessary to show the distribution of radiation dose in the power plants. In this paper, we propose the methods combining ray-casting volume rendering and geometry model fusion to visualize the 3D nuclear radiation dose field. We implement a nuclear radiation dose field virtual simulation system based on Unity3D, combined with virtual reality to help workers conduct nuclear radiation operations and training. Moreover, we plan the maintenance path of the workers based on the NEAT algorithm, thus providing necessary radiation protection measures. The experimental results and evaluation show the efficiency of our virtual radiation dose visualization and simulation system.

1. Introduction
The increasing depletion of fossil fuels and the increasing environmental pollution have resulted in the vigorous development of new sustainable energy sources such as nuclear power, wind power, and solar power. Among them, nuclear energy, as a clean and economical energy source, has received the attention of many countries. Due to the rapid development of nuclear energy and the widespread use of nuclear technology, nuclear safety and radiation protection have become the focus of social attention. How to effectively reduce the radiation exposure of workers in the radiation environment is one of the main contents of radiation protection and one of the main goals of the safe operation of nuclear facilities.

According to the different mechanisms of the biological effects of ionizing radiation on the human body, it can be divided into deterministic effects and random effects. The goals of radiation protection can be divided into two points: preventing the occurrence of deterministic effects and reducing the probability of random effects. Therefore, due to the large amount of radioactive materials, radiation protection must be strictly considered during the operation, maintenance and decommissioning of nuclear facilities. The principle of as low as reasonably achievable should be considered to ensure that the exposure of workers does not exceed the limitation under any circumstances.

With the development of computer hardware and related technologies, visualization and virtual reality technologies have developed rapidly and have also been applied to the field of radiation protection. Virtual reality technology utilizes computer to simulate the complex radiation environment of nuclear facilities, and uses computer graphics technology to graphically display the dose rate distribution in the virtual scene, which can evaluate the dose received by virtual personnel in advance. The radiation field visualization technology combines radiation protection and virtual simulation, and simulates real complex scenes through computer calculations and graphic display methods, so as to perform virtual experimental operations and data acquisition. When formulating nuclear facility maintenance and decommissioning strategies, we can optimize the maintenance and decommissioning plan and the path of the staff during the decommissioning operation by understanding the three-
dimensional space dose distribution of nuclear facilities, thus reducing the radiation damage to the staff. Meanwhile, virtual reality can solve the imperceptible problem of radiation field through displaying the distribution of the dose, so that the staff can avoid high-dose areas to reduce the radiation exposure.

Volume rendering is limited to visualize the radiation dose field[1]. It cannot effectively integrate the geometric model and volume data. Surface rendering such as marching cubes cannot display the internal details of dose distribution[2], which makes it hard to show the difference of the radiation dose in different areas. Furthermore, the fusion between geometry model and volume leads to the occlusion problems, which can be solved by the depth peeling method[3]. Virtual simulation of 3D radiation dose field is significant for personnel operation simulation and training. In recent years, the development of virtual reality brings a variety of methods to protect the nuclear radiation[4]. However, there are still some problems that need to be solved in the future. When the virtual simulation system is used to train staff in maintenance or dose assessment, there are extremely high requirements for the interactivity and fidelity of the system, which not only allows users to have an immersive experience, but also helps users be familiar with the working environment accurately.

In this paper, we propose methods combining volume rendering and virtual reality. We implement a virtual nuclear radiation simulation and visualization system which provides the view of radiation dose of virtual person and plans a proper path for workers to check and maintain the devices in virtual nuclear power plants. Due to the imperceptibility of radiation field, we can better present the calculated dose rate distribution of radiation field with the help of virtual reality technology. Thus, it can enhance the effect of virtual simulation and staff training in the radiation environment.

The main contributions of this paper are as follows:

1. We combine the ray-casting volume rendering and geometry model fusion to show the detail distribution of the nuclear radiation dose, which is significant to radiation protection.
2. We propose to plan a proper path based on NEAT algorithm for workers to work in the nuclear facilities, which can reduce the radiation exposure of workers.
3. We implement a virtual nuclear radiation dose simulation and visualization system which can provide insight view of radiation dose field and give suggestions to design radiation protection programs.

The remainder of this paper is organized as follows: Section 2 discusses the related work. Section 3 introduces the virtual radiation field simulation. In Section 4, we provide a overview of the virtual retirement work simulation. Section 5 presents the virtual simulation system. Finally, we show the evaluation from the domain scientists and summarize the conclusions in Section 6.

2. Related Work
With the continuous development of nuclear technology, people pay more and more attention to the safety of nuclear radiation field. The maturity of scientific visualization has also contributed to the development of the field of nuclear radiation protection. At present, extensive researches have been carried out in the field of radiation protection all over the world.

Li et al. utilized virtual simulation technology as an auxiliary tool for radiation protection and dose assessment[5]. They proposed a simple method for virtual human voxel model. Based on voxel model, a dose assessment and visualization method for virtual human body in radiation environment is proposed. Their validation tests showed that these methods could expose workers to radiation doses in a virtual simulation plan. Li and Shang et al. developed an accurate human dose assessment method based on the inhomogeneity of radiation field and the difference of radiation-sensitive organs[6]. The results showed that compared with the traditional methods, the voxel-based organ dose assessment method can reach the precise organ level dose. This approach has also been integrated into the RVIS, which is a nuclear radiation safety simulation system. Tang et al. focused on the research of the superconducting Tokamak (EAST) device[7]. They developed a virtual radiation simulation (RVIS) system that utilize virtual reality to dosimetry to improve maintenance efficiency and reduce radiation exposure for maintenance personnel. RVIS can be used to assess workload in radiation environments, optimize maintenance plans, and visualize three-dimensional dose rate distributions. Wagner et al. studied the interactive teaching method of radiation protection and improved the shortcomings of the traditional text-based, picture-
based and video methods[8]. They proposed a new software module that simulates and visualizes radiation distribution and resulting dose values in a matter of seconds.

There are a variety of excellent research results on rendering and visualization of radiation dose field. Cao et al. proposed a visualization method which aimed at solving the problems that traditional volume rendering are difficult to adapt to the visual analysis of large-scale numerical reactor data for numerical reactors oriented to physical characteristics[9]. The experimental results showed that this method was used to process the data of large-scale reactor, and to show the structure of reactor and the interface of key medium with high quality. In addition, Cao et al. carried out efficient visualization of the high-resolution virtual reactor which enabled scientists to simulate and analyse all aspects of existing nuclear reactor design in unprecedented detail[10]. Johnson et al. proposed a new lighting model to enhance the rendering effect of volume rendering[11]. This new technology generated more realistic images, thus making it possible to depict anatomical details more accurately. Englert et al. proposed a streaming framework to optimize large-scale 3D applications and allowed real-time interaction independent of network bandwidth or rendering units[12].

With the help of virtual reality technology, the staffs immerse themselves in the virtual environment for homework exercises and training, which can provide practical advice and safety guarantee for them to work in the real environment. Wang et al. proposed a 3D rendering method in remote presentation system based on the latest virtual reality technology[13]. Two CAVE systems in different locations were connected online. The head position of the local user was tracked and sent to a remote server to reconstruct the 3D model of the remote user and present the 3D image, which was sent back to the local graphics workstation and presented on the billboard with the 3D environment. As early as 1995, Corby and Nafis of the general research and development centre developed an augmented reality remote operating system to perform anticipated inspection, resupply, and repair of storage and transportation losses of underwater nuclear power reactors[14]. Hitachi group developed a radiation field dose calculation and visualization system for nuclear power plant maintenance support. The Brazilian Institute of Nuclear Engineering used the game engine Unreal to simulate the three-dimensional scene of the radiation field, and used the three-dimensional virtual reality technology to conduct comprehensive simulation training for the operators in the control room of a nuclear power plant to reduce costs and use of physical space[15]. They implemented the nuclear power plant dose assessment and the optimization of the radiation area operation path based on the measured radiation dose data.

3. Virtual radiation field simulation and visualization

The text of your paper should be formatted as follows: In this section, we implement the virtual reality system based on the Unity3D platform. In order to increase the immersive experience of operator and better conduct training and emergency drills, we propose to deploy the nuclear facility virtual scene in HTC VIVE and HoloLens to meet the different needs of operators.

Through this multi-repetitive simulation roaming, the operators can familiarize themselves with the nuclear facility. The virtual reality system visualizes the radiation field distribution and makes the pipeline fluid real. The simulation allows the operator to intuitively feel the radiation intensity and distribution in the working environment. When the operator roams in the virtual radiation scene of the nuclear facility, the virtual person can be assessed for personal exposure dose, which optimizes the path of the nuclear facility decommissioning project.
The operator can view the radiation dose rate of any of the smallest cubes in the radiation field. The three-dimensional radiation data field applied in this paper is uniform grid structured data. When the operator chooses to view any of the smallest cubes in the scene, it means looking at the 3D mesh in the space. For each grid, the dose rate and error are fixed. We determine the dose rate mapped by this grid by taking the spatial coordinates of the current grid and display it on the UI for the user to view, as shown in figure 1.

The cutting operation of the radiation field essentially separates the spatial grid. The result is shown in figure 2. There are two main cases: one is along the coordinate axis and the other is diagonally cutting. When cutting along the coordinate axis, the section can be thought as a very thin slice that passes vertically through the entire radiation field in the x, y, and z directions to form a two-dimensional grid. The radiation dose rate is determined by the three-dimensional grid to which the grid belongs. Assuming that $D_{x,y,z}$ is the three-dimensional grid dose rate, $S$ is the unit two-dimensional grid area, the average dose of the section is $D$. The dose rate of the entire section can be regarded as the average of the sum of the dose rates of the grids. Take the cut along $x=p$ as an example, the expression is as follows:

$$D_{x=p} = \sum_{y_0}^{y_n} \sum_{z_0}^{z_n} D_{p,i,j} \cdot S_{i,j} / (y_n - y_0) \cdot (z_n - z_0)$$ (1)
4. Virtual retirement work simulation

4.1. Maintenance work steps

The maintenance work carried out by the staff in the reactor is based on certain maintenance steps rather than random walk test. The personnel dose calculation is based on the maintenance procedure as well. Therefore, the radiation dose of the human body is the sum of the radiation doses received for each human body action, that is, space walking and maintenance work. When performing simulation calculations in the virtual environment, the radiation does that a virtual person receives for a single human motion is approximately equal to the radiation dose rate at the current location multiplied by the time of a single human motion.

When the staff performs maintenance in a radiation environment, the operation is mainly divided into the following steps:

1. From point A, enter the work area and arrive at the maintenance area B.
2. Maintenance work at B.
3. After the maintenance is completed, leave B, reach safe area C, and leave the radiation environment.

$D$ is the total radiation dose received by the staff during maintenance, $D_{x-y}$ is the average dose from $x$ to $y$ maintenance personnel, $t_{x-y}$ is the time taken by maintenance personnel from $x$ to $y$, and $D_z$ is the maintenance personnel at $z$. The dose, $t_z$, is the time taken by the maintenance personnel at $z$, and the dose received by the staff during the entire maintenance process is:

$$D = D_{A-B} \cdot t_{A-B} + D_B \cdot t_B + D_{B-C} \cdot t_{B-C}$$

When multiple equipment needs to be repaired in one operation, the total dose is the sum that moving during each maintenance process and within the radiation field.

4.2. Path planning based on NEAT algorithm

The NEAT algorithm is Evolving Neural Networks through Augmenting Topologies [16]. The algorithm is different from the traditional neural network as we discussed before. It not only trains and modifies the weight of the network, but also modifies the topology of the network, including add nodes and delete nodes.

In a virtual environment, the ground exists in the form of a grid, and the path travelled by the worker in the dose field can be abstracted into a set of topological grid connections. Under the premise that the area is allowed to travel, we can get the information of the starting point, operating position and end point of the worker. It is clear that the ultimate goal is to find the grid connection combination with the smallest total dose. In the actual calculation, we choose to use the equivalent cuboid instead of the staff's
volume. Due to the uncertainty of topology, after considering the advantages and disadvantages of various algorithms, we propose to solve the path planning problem by using NEAT algorithm. The neural network is used to train the virtual human path selection. Based on the genetic algorithm, the neural network is evolved through operations such as crossover and mutation to obtain an optimal path. The result is shown in figure 4.

(a) Global view                                                     (b) User view

Figure 4. The result of automatic planning path.

5. Virtual reality simulation and visualization system

Based on the above methods, we render a realistic nuclear radiation scene. We obtain the radiation dose data from the China General Nuclear Power Group. The data consists of two parts, one is the geometric model data of the nuclear radiation pipeline, and the other is the volume data of the nuclear radiation dose. The size of volume data is 100×200×100, the spacing between the data is 2.31, 2.8, and 2.32 in the X-Y-Z direction, and the centre of the data is located at (220.16, -1257.6, 399.16).

We design different transfer functions for the volume rendering of the nuclear radiation dose field. We map the dose from small to large varying from green to red, and yellow is a interim. It can be seen that the dose near the exchanger area is higher than other areas. We implement a real-time and interactive rendering, which allows to view internal features by rotating and scaling the window.

The virtual reality system in this paper is based on the Unity3D platform. In order to increase the immersive experience and conduct training and emergency drills better, we propose to deploy the nuclear facility virtual scene in HTC VIVE and HoloLens to meet different demands.

In order to ensure the effective application of virtual reality in nuclear power plant radiation protection, we manage the scene well after establishing the virtual nuclear power plant model, put the structure and content of each scene in the same inheritance system, and effectively combined their contents. If the resource takes a long time to load, a synchronous approach can lead to the problem of jamming. Our solution utilizes multi-threading or use the engine's own asynchronous loading method.
Through this multi-repetitive simulation roaming, operator can be familiar with the nuclear facility and understand the walking routine in advance. We visualize the radiation field distribution in the virtual reality system, and the pipeline fluid is simulated realistically, allowing the operator to intuitively feel the radiation intensity and distribution in the working environment. When the operator roams in the virtual radiation environment of the nuclear facility, the virtual person can be assessed for personal exposure dose, providing technical support for the optimal path and work plan of the nuclear facility decommissioning project.

6. Evaluation and Conclusion

In order to evaluate the effectiveness of our system, we invite 10 nuclear experts from China General Nuclear Power Group to conduct user survey and feedback. These experts have rich experience in the field of nuclear radiation, which bring representative opinions. We list some questions for investigation. For each question, experts are required to score, from 1-5 points to represent the improvement of satisfaction, and experts are also required to provide feedback. After briefly introducing the background and functions of our system, we conduct a demonstration of the use of the system, and then let experts experience and evaluate them in turn. We mainly set up two questions:

1. Compared with displaying on an ordinary computer, can a virtual reality system provide a more realistic and immersive experience?
2. Can you clearly view the radiation dose distribution in the system and whether the setting of the walking route is reasonable?

By summarizing the ratings and opinions of the experts, we summarize the following evaluation and conclusions: for the first question, all the experts believe that the virtual reality system can indeed provide good immersive experience. The system does not need to enter the real nuclear power plant to check the operation of the equipment and the surrounding radiation distribution. For question 2, all experts believe that the distribution of doses can be viewed intuitively through the system and can be viewed from different angles. For the maintenance path of employees, they believe that the NEAT algorithm can give an optimal solution. However, it is possible that under dynamic radiation leakage scenarios, the setting of this path will be more complicated, which is a key research direction for us in the future.

In summary, the simulation and visualization of the nuclear radiation dose field is a very important topic. It belongs to the cross-disciplinary research of nuclear physics and computer science, involving important research issues such as nuclear safety, nuclear simulation and scientific visualization. In this paper, the nuclear radiation dose field is rendered through the ray-casting volume rendering. We combine the virtual reality to implement a virtual system which provides immersive and interactive experience for users. We will design and implement more functions of the virtual simulation of radiation dose field in the future work, and study the effect of the flow of liquid in the nuclear radiation pipeline on the radiation dose, which involves issues related to the visualization of the flow field.

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