The virtual simulation system of nuclear radiation dose field based on virtual reality technology

line 1: Li Dan
line 2: *Sate Key Laboratory of Nuclear Power Safety Monitoring Technology and Equipment*
line 3: *China Nuclear Power Engineering Co., Ltd*
line 4: Shenzhen, China
line 5: dan.li@cgnpc.com.com

line 1: Zhang Jiawan
line 2: College of Intelligence and Computing
line 3: Tianjin University
line 4: Tianjin, China
line 5:jwzhang@tju.edu.cn

line 1: Zhang Yi
line 2: *Sate Key Laboratory of Nuclear Power Safety Monitoring Technology and Equipment*
line 3: *China Nuclear Power Engineering Co., Ltd*
line 4: Shenzhen, China
line 5:zhang-y@cgnpc.com.cn

***Abstract*— The virtual reality technology has been widely used in various industries such as nuclear power industry. The issue of nuclear radiation protection is a matter of great concern to nuclear power safety. Virtual reality technology can simulate the virtual nuclear power plant radiation environment realistically. Volume rendering is able to visualize radiation dose values and reflect the magnitude of the radiation data through different colors and opacity. The combination of the two technologies provides a system that simulates the process of maintenance in a virtual radiation environment. The system helps nuclear power maintenance person to view the radiation dose distribution in the room and analyze the dose that the person receives when servicing the equipment. Finally, strategies are provided to reduce the radiation of the person being exposed.**

Key words: nuclear radiation dose, virtual reality, volume rendering

I. RESEARCH BACKGROUND

Nuclear power is a clean energy source. At present, the power generated by nuclear power plants has accounted for 16% of the world's total power generation. The protection of nuclear radiation is a matter of concern in the development of nuclear technology and energy. As a computer simulation system that can create virtual worlds, virtual reality technology has been widely used in radiation protection at home and abroad.

The research department of GM has developed an augmented reality remote operating system [1] for performing tasks such as inspection, replenishment and maintenance of underwater nuclear power reactors. The Brazilian Institute of Nuclear Engineering [2] uses the game engine Unreal to simulate the 3D scene of the radiation field. VR technology is used to carry out all-round simulation training for the operators in control room of a nuclear power plant to reduce the cost and physical space usage. The nuclear power plant dose assessment and the optimization of the radiation area operation path are realized based on the radiation field dose data. Antônio [6] and others have developed simulation tools for radiation dose exposure assessment of nuclear power plant person. It supports training for nuclear power plant person, optimizing work tasks, and minimizing accepted doses. The virtual simulation of the 3D radiation dose field is important for personnel operation simulation and personnel training, but there are still some problems. The interaction and the fidelity of the system pose a great challenge in the virtual simulation system of the training of the staff. The dose and actual operation process of the staff in the virtual world are often unable to be calculated simultaneously, reducing the practicality of the system [3].

The main research content of this article is to render the volume data superimposed with the 3D geometric models to construct a 3D virtual radiation dose field. At the same time, virtual reality technology is used to perform virtual simulation and personnel training in the radiation environment.

II. KEY TECHNOLOGY

Volume rendering technology is mainly used for the visualization of 3D volume data. A 3D data field can be described by a 3D array of values called voxels. Medical image is a typical three-dimensional data field. For example, a series of medical image slice data is obtained by CT (computed tomography) or MRI (nuclear magnetic resonance) scanning. The slice data is regularized according to the position and angle information to form a regular data field composed of a uniform mesh in a three-dimensional space. Each cell on the grid describes attribute information such as the density of the object. The small cube surrounded by the corresponding eight cells between adjacent layers is called a voxel. Volume rendering uses this voxel as the basic unit of operation to calculate the effect of each voxel on the displayed image. The biggest advantage of volume rendering technology is that it can explore the internal structure of an object. It can display the comprehensive distribution of multiple substances in one image, and perform isosurface by controlling opacity. The current mainstream volume rendering algorithms include Ray-Casting [9], Splatting [10], Cell Projection [11], and Shear-Warp [12].

III. APPLICATION IMPLEMENTATION

The implementation of the entire application is mainly divided into two parts.

The first is the construction and rendering of the scene, including the radiation field data processing, radiation field rendering and scene fusion. Simulating the internal structure of the nuclear radiation dose field as accurately as possible gives the user a sense of realism.

The second is the interaction between the user and the scene. The users have an immersive experience due to the interaction and the real time of the system.

A. Scene construction

The geometric model scene is built in CAD, 3DMAX and other softwares. It is imported into Unity3D for subsequent development. After reading the radiation field data, the volume rendering calculation is performed. The dose rate in the radiation field is represented by different colors. Finally, the two scenes are accurately placed in one scene according to the their coordinates.

B. Data processing

The radiation field is continuous distributed in reality. The 3D radiation field data used in the project is generally a set of discrete spatial data points obtained through calculation or actual measurement (See Table 1). This method is called sampling. In order to make the radiation field in the scene display evenly, the data needs to be resampled. The data field is reconstructed through data filtering and interpolation.

Table 1 Radiation field data.

x /cm	y /cm	z/cm	dose /mSv·h-1	error/mSv·h-1
2.2016E+002	-1.2576E+003	3.9916E+002	1.11015E-001	0.1490
2.2016E+002	-1.2576E+003	4.0148E+002	1.20046E-001	0.1432
2.2016E+002	-1.2576E+003	4.0380E+002	1.49952E-001	0.1392
2.2016E+002	-1.2576E+003	4.0612E+002	1.35964E-001	0.1485
2.2016E+002	-1.2576E+003	4.0844E+002	1.46378E-001	0.1390
2.2016E+002	-1.2576E+003	4.1076E+002	1.66317E-001	0.1293

The steps to implement data reconstruction [4] are as follows:

1） Selcet a suitable reconstructed kernel function, and then perform a 3D convolution operation on the discrete 3D data field. Finally reconstruct a continuous three-dimensional data field.
2） Perform a geometric transformation of continuous 3D data fields according to a given viewing direction.
3） Use the low-pass filter function to remove the frequency components above the limit according to the Nyquist sampling theorem.
4） Resample the filtered function.

When the amount of sampled data is larger than the data required for actual visualization, the reconstruction of the three-dimensional radiation field is completed by eliminating redundant data points. When the sampled data points are less than the points required for actual visualization, the data field is reconstructed by interpolation. The principle of three-dimensional volume data interpolation [5] is shown in Figure 1.

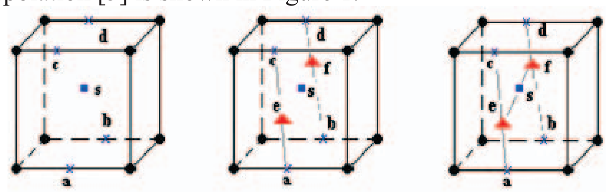

Figure 1 Principle of 3D volume data interpolation.

The point that needs to be visualized is assumed to be s. The eight vertices (voxels) closest to the s in the space are obtained, so that they constitute the smallest cube unit. The radiation dose rate at point s is obtained by interpolation of 8 voxels around it. Firstly, one-dimensional interpolation is performed along the x-axis voxel data to obtain four interpolation points a, b, c, and d. Then, one-dimensional interpolation is performed along the y-axis to calculate interpolation points e and f according to the data values of a, b, c, and d. Finally, the resampled data value of the s point is calculated by interpolating along the z-axis according to the dose values of e and f. In order to ensure the speed and accuracy of scene rendering, this paper chooses linear interpolation as the

After the data processing, the acquired data is in the format of a 3D data field, stored in the form of a three-dimensional array. The data is read according to the sampling precision. Calculating each sampling point to obtain color and opacity. The fusion calculation is performed to obtain the color of each pixel. Volume rendering pipeline is shown in Figure 2.

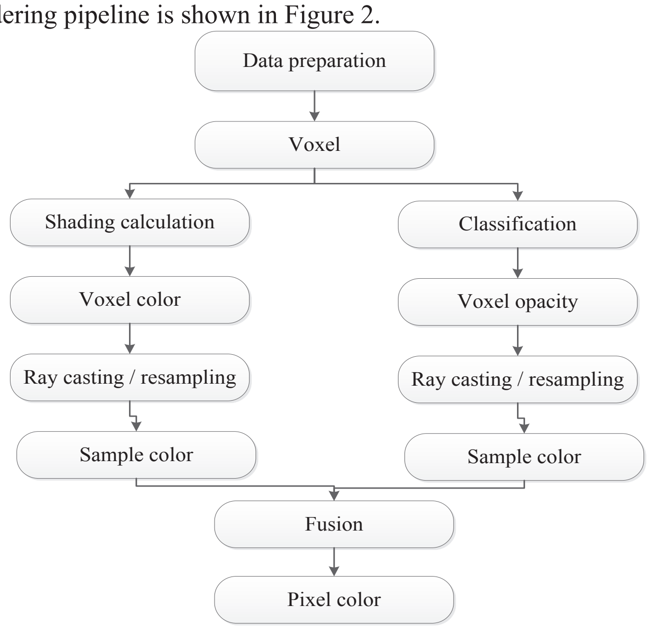

Figure 2 Volume rendering pipeline

One of the methods of implementing volume rendering in Unity3D is the ray casting [8], which is a direct volume rendering algorithm based on image sequences. One light is emitted from a fixed direction (usually the line of sight) for each pixel of the image. The Light traverses the entire sequence of images. And during the process, the sequence of images is sampled to obtain color information. The values of color are accumulated according to the light absorption model till the light traverses the entire image sequence. The latest value of color is the color of the rendered image.

A key problem is to show the mapping between the dose rate in the radiation dose field and the color of the radiation carrier. As the dose rate gradually increasing, the color changes from green to red. Setting transparency for the radiation field is also needed, which can enhance the sense of reality of the worker when he moving in the radiation field. Two problems can be solved by transfer function in the volume rendering algorithm. First, the transfer function converts the sampled values of the volume data into the values of color and opacity. Besides, the volume rendering algorithm converts the volume data into the form of an image. The transfer function can be defined as [7]:

$$T: x \mapsto \{c, a\}, x \in \mathbb{R}^n$$

$\{c, a\}$ is usually a two-tuple of color and opacity, x is the attribute value of the volume data, and the dimension n of x is the number of attributes. The space formed by x is called the feature space. The transfer function can be seen as a classification of volume data. Voxels with different characteristics are mapped to different visual features. The different levels of volume data values are mapped to the corresponding colors. This process is a trial-and-error process. Finally, the mapping from data to optical features is obtained (See Figure 3).

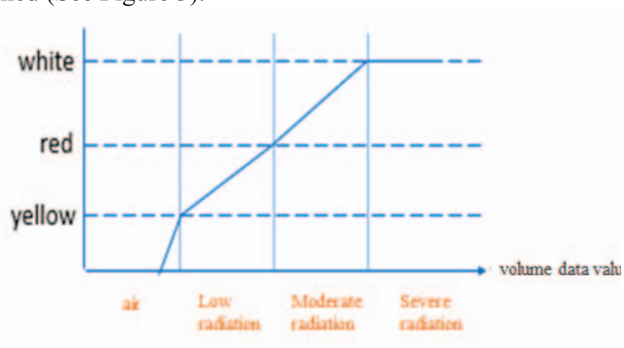

Figure 3 Transfer function settings

Gourand Shading is an indispensable operation for realistic graphics rendering. Introducing shadow calculation into volume rendering can improve the quality of the rendered image and provide more information to the user. In Unity3D, the gourand shading is done by shader. Shader is part of the computer graphics rendering pipeline. It is an applets that tells the computer how to render and color objects in the scene. This process involves calculating the color and lighting values and attaching them to the object so that the object could be displayed on the screen. Unity3D provides three shaders to be programmed. Surface shader that consumes the least resources but still supports rich effects is chosen. The shader is programmed by adding additional required variables for texture coordinates and surface functions in the user-defined structure Input.

The final step is fusion computing, also known as image compositing. The values of color and opacity of each sample point in the volume data field of the ray are calculated as the order of from-front-to-back or from-back-to-front ,along a ray which starts from the pixel point and passes through the volume data field. According to the calculated result, the pixel color of the light which is finally displayed on the screen is obtained. The color values of each pixel on the screen are calculated in the same way to form the final rendered image. This project selects the from-front-to-back as fusion calculation. Its formula is as follows:

$$\text{B under A} \equiv C_{outB} = (1 - \alpha_{outA})C_B + C_{outA}$$
$$\alpha_{outB} = (1 - \alpha_{outA})\alpha_B + \alpha_{outA}$$

C. Scene fusion

The most important thing of this project is the fusion of 3D geometric model and volume data in the scene. It involves not only the volume data processing the occlusion by the 3D geometric model, but also Real-time calculation of the influence on the radiation dose rate distribution by increase ,decrease and movement of the 3D geometric models.

Depth peeling technology can solve the problem of occlusion processing and depth overlay . Depth peeling is a technique for sorting depth values. The principle is straightforward. The standard depth detection outputs the point on the screen with the smallest Z value in the scene, which is the closest vertex to us. While there is also a vertex existing that is the second or the third closest to us. It should be rendered multiple times to display them. At the first rendering, it is processed in the normal way so that the z value of each vertex on the surface closest to us is obtained. At the second rendering, the current depth value of each vertex is compared with the former. Any value less than or equal to the Z value obtained at the first pass should be peel off. The following process can be analogized. In Unity3D, the depth buffer is enabled by default. The correct order of rendering for opaque objects is from-front-to back and from-back-to-front for semitransparent objects. Except for semitransparent objects, most objects will be rendered according to the actual conditions, showing the correct occlusion relationship. The final effect is shown in Figure 4.

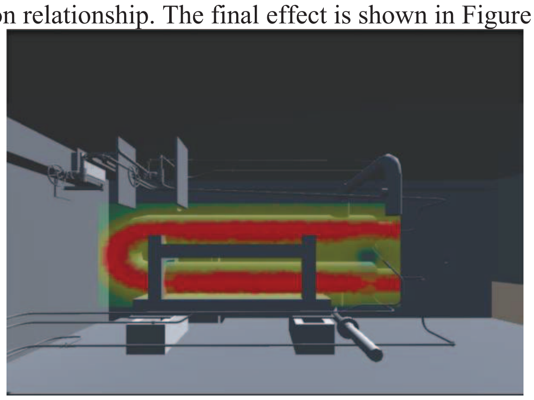

Figure 4 Implementation of scene fusion in Unity

D. Interaction

1) system structure

The virtual reality system established in this paper is developed based on the Unity3D platform. In order to enhance the operator's immersive experience, better training and emergency drills, the nuclear facility virtual scene is deployed in HTC VIVE and HoloLens to meet the different needs of operators. The system architecture is shown in Figure 5.

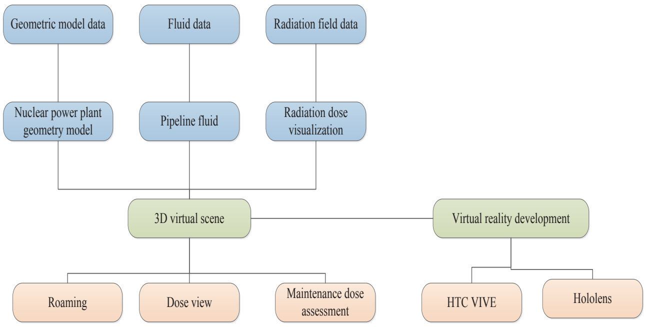

Figure 5 Architecture of virtual reality simulation system

2) Roaming

There are two types of roaming in a three-dimensional virtual radiation scene in this study: one is to use the HTC VIVE device (see Figure 6-(a)). The other is to use Hololens (see Figure 6-(b)).

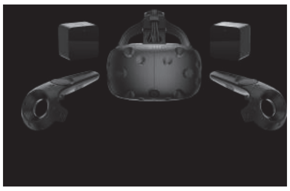
Figure 6-(a) HTC VIVE


Figure 6-(b) Hololens

Figure 6 Virtual reality device

Applications deployed on HTC VIVE are developed in Unity3D via the VRTK plugin. The user wears a head-mounted display and enters the virtual environment. And they roams in the scene as if walking in a real environment. Turning the head switches the angle of view. Users can also use the HTC VIVE handle to select the area in the scene that they want to reach and complete the move by "transfer". The handle is also a primary medium for user interaction.

Applications deployed on HoloLens are developed in Unity3D via the HoloToolkit plugin. After the user wears it, HoloLens automatically scans the space in which the current user is and meshes the space. It generates virtual scenes that are superimposed with the real environment. The user walks in real world to complete the movement, turning the head to switch the angle of view. User interaction is mainly done by gaze and gestures.

3) Radiation field dose view

In the virtual environment, the dose rate of the device can be calculated by considering the wrapping of the geometric model after the geometric model of the nuclear reaction equipment is aligned with the three-dimensional radiation field. The user can select the specified device, and the space coordinate information of the device will be obtained. Since the radiation dose rate value exists in the form of spatial coordinate points, the voxel which is also called the three-dimensional grid corresponding to the spatial position occupied by the device can be calculated. And the radiation dose rate corresponding to the grid can be easily obtained. By the way, the sum of the dose rates in this spatial range is the dose rate of the device. The space occupied by the nuclear reaction equipment is assumed as V (Xi-j, Yp-q, Zm-n). Equipment dose rate is D. The minimum cube dose rate from i to j along the x-axis, from p to q along the Y-axis, and from m to n along the Z-axis is Dx, y, z. The dose rate of the device is as follow.

$$D=\sum_{x=i}^{x=j}\sum_{y=p}^{y=q}\sum_{z=m}^{z=n} D_{x,y,z}$$

Finally, the device dose rate is displayed on the UI for the user to view in real time.

4) Maintenance dose assessment

When a worker walks in a radiation environment, the radiation dose he receives is related to the location attribute and duration in which he is located. The radiation dose rate value of the virtual person at the current position can be obtained through the location attribute information. Duration reflects the accumulation of radiation received by a virtual person under given radiation conditions.

The radiation dose rate values of different parts of the human body model are different in the virtual simulation environment. If the human body model is triangulated and discrete into multiple triangular mesh units, the radiation dose rate of each point in the radiation field can be calculated. Then the average is taken to get the radiation dose rate of the virtual person at the current position. This method is too computationally intensive affecting the efficiency of data processing. Considering the simplicity and feasibility, this paper studies the radiation dose rate of the human body model which approximately equal to the radiation dose rate of the human body weight in the spatial position.

The position coordinate information extracted to the center of gravity of the human body model is compared with coordinate information of the dose rate value. When it is matched, the radiation dose rate of the point is extracted as the radiation dose rate of the human body model at the current position. When it is not, the radiation dose rate at the nearest point from the point is extracted as which of the human body model at the current position. Multiplying the extracted radiation dose rate by the duration, the radiation dose received by the virtual person who completed the single action is calculated. The total radiation dose received by the maintenance personnel during the maintenance process is obtained through accumulating the radiation doses received by all the human body actions.

IV. Conclusion

This paper describes the application of a virtual simulation of radiation dose based on virtual reality device. Visualization of the radiation field visually shows the distribution of the intensity of the dose in front of the staff and personnel. The staff can avoid the area with high radiation intensity and select the area with small radiation when determining the working path during the decommissioning operation process. It helps reduce the radiation dose received by maintenance personnel. The calculation of human body model radiation dose simulation can understand the degree of damage to the human body so that it is helpful to provide the necessary radiation protection measures for the maintenance personnel. At the same time, because the radiation field is imperceptible, virtual reality technology can better represent distribution of the calculated radiation field dose rate. It enhances the effectiveness of staff training in radiation environments.

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