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A dose assessment method for arbitrary geometries with virtual reality in the nuclear facilities decommissioning

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ABSTRACT

During the decommissioning of nuclear facilities, a large number of cutting and demolition activities are performed, which results in a frequent change in the structure and produce many irregular objects. In order to assess dose rates during the cutting and demolition process, a flexible dose assessment method for arbitrary geometries and radiation sources was proposed based on virtual reality technology and Point-Kernel method. The initial geometry is designed with the three-dimensional computer-aided design tools. An approximate model is built automatically in the process of geometric modeling via three procedures namely: space division, rough modeling of the body and fine modeling of the surface, all in combination with collision detection of virtual reality technology. Then point kernels are generated by sampling within the approximate model, and when the material and radiometric attributes are inputted, dose rates can be calculated with the Point-Kernel method. To account for radiation scattering effects, buildup factors are calculated with the Geometric-Progression formula in the fitting function. The effectiveness and accuracy of the proposed method was verified by means of simulations using different geometries and the dose rate results were compared with that derived from CIDEC code, MCNP code and experimental measurements.

1. Introduction

The working environments during nuclear facility decommissioning are under high radiation and high risk, which makes it difficult to analyze the working process through practical experiments. In order to avoid this constraint, researchers such as Kim et al. (2006) and Jeong et al. (2014) use virtual reality (VR) techniques to simulate the decommissioning process, and perform dose assessment and safety analysis in virtual environments where the procedures can be carried out in a more feasible and safe way. In order to perform dose assessment and safety analysis during the cutting or demolition works, it is necessary to provide a flexible gamma dose rates calculation method for arbitrary geometries and gamma radiation sources to improve the efficiency and accuracy of simulations.

The Monte Carlo and the Point-Kernel methods are commonly used for calculating radiation shield effectiveness and dose rates. The Monte Carlo method is a high-precision probabilistic method that suffers from long computing time, for instance the Monte Carlo Neutron and Photo Transport Code (MCNP) (Breismeister, 2000). By contrast, the Point-Kernel method is an analytical method with less computing time but lacks rigor. When time is essential, the Point-Kernel method is usually used (Ohga, 2005).

The typical programs based on the Point-Kernel method are the QAD (Cain and QAD-CG, 1977), the PUTZ (Ingersoll, 1986), the Microshield, etc. These programs build the geometric space by manually combining geometry technology and modeling, which makes it difficult and inefficient to describe large-scale complex environments, especially dynamic environments such as the one obtainable in nuclear facilities. In order to solve the modeling problems of complex geometries, Vela et al. (2006) developed a code named CIDEC for calculating dose rates in scenarios with complex geometries and gamma radiation sources. The code uses the geometric modeling capabilities of computer-aided design (CAD) tools to construct the geometry, and then the geometry is exported to a DXF file format. In the second step, each volume is loaded with material and radiological attributes, and then the dose rates are calculated with the point kernel method. However, the code can't obtain the details of geometries, such as the volume, and has a limitation in the environment where structures and geometries change frequently.

To cope with both accuracy and time requirements, Caracena et al. (2013) presented an algorithm to calculate gamma dose rates for VR simulation applications in nuclear safeguards and security. The algorithm can generate a non-regular mesh model and computes the dose

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rate in real time. Moreover, Caracena et al. (2017) used the KD-tree based volume division method to improve the efficiency of the Point-Kernel method. However, geometrical source shapes are restricted to parallelepipeds.

Many researchers have studied the application of virtual reality in nuclear facilities decommissioning, such as the ALARA (as low as reasonably achievable) planning tool VISIPLAN (Vermeersch and Bosstraeten, 1998; Vermeersch, 2003), and the three-dimensional simulation tool VRdose Planner system (Sz˝oke and Johnsen, 2013). These programs also adopt the Point-Kernel method and can calculate dose rates in real time. However, the radiation sources need to be simplified with basic geometries.

Mól et al. (2009a, 2009b) used a game engine to support dose assessment and to optimize the operational routines in nuclear plants. The simulation platform collects dose rate data from radiation monitors installed in a real plant, then assess dose for personnel by interpolation, although it is only suitable in cases where the structures are constant.

During the decommissioning of nuclear facilities, a number of cutting and demolition operations are necessary, which makes the environments change frequently and lead to the production of various structures with arbitrary geometries and gamma radiation sources. The existing studies mainly approximate the radiation sources by combining the basic geometries (such as parallelepiped, cylinder, sphere, etc.) manually. Also, their need for much geometric modeling time for complex environments makes the dose assessment process inefficient.

Consequently, this paper proposes a flexible gamma dose rate calculation method based on virtual reality and Point-Kernel method. The VR-based method (VRBM) proposed in this research can model for structures with arbitrary geometries and radiation sources automatically and has the ability to deal with the scenario where the structure changes frequently. The initial geometric model is designed by computer-aided design (CAD) tools, such as SolidWorks, 3dMax or Unigraphics. After the initial geometric model is loaded, an approximate model is built automatically by space division and collision detection, and then a set of point kernels are distributed within the approximate model by sampling. Then inputs such as the initial materials and radiological attributes are specified and the dose rates are calculated with the Point-Kernel method. When the cutting procedure is performed, the reconstructed model is updated automatically. The method makes it possible to assess dose rates for arbitrary geometries and radiation sources efficiently during the nuclear facilities decommissioning.

The paper is organized as follows: Section 2 briefly describes the Point-Kernel method and the CIDEC code's method. Section 3 focuses on the implementation of the proposed method. Section 4 is allotted to describe the experiments and results. Section 5 analyzes the results of experiments. Section 6 presents the concluding remarks.

2. Methods used for dose assessment

The two methods used in this paper are the Point-Kernel method and CIDEC code's method. The following section provides a brief description of Point-Kernel method and CIDEC code's method.

2.1. Point kernel method

The Point-Kernel method is an approximate but efficient approach for evaluating photon responses in shielding analyses. However, because the method lacks rigor, it has limitations in cases that need high precision. Nevertheless, the method is still successfully applied in design and safety analysis works. When the method is correctly applied, it can provide fairly good results for gamma radiation (Harima, 1993).

The main idea of Point-Kernel method is that the radiation source can be seen as consisting of a series of discrete elementary cells (point kernels), and the dose rate at the detecting point is composed of the contributions of all point kernels to the detecting point (Prokhorets, 2007). The total dose rate from a point kernel isotropic with energy E to the detecting point is given by:

$$D(r, E) = C(E)S(E)B(E, t(E))\frac{e^{-t(E)}}{4\pi r^2} \quad (1)$$

where r is the distance from the point kernel to the detecting point, C is gamma flux density to dose rate conversion factor, S is the strength of the point kernel, B is the buildup factor, which can be obtained from the ANSI/ANS-6.4.3 and the Geometric-Progression formula (ANSI/ANS-6.4.3, 1991). The mean free paths (mfp), t, between the point kernel and the detecting point can be calculated with the following equation

$$t(E) = \sum_{i=1}^{n} \mu_i(E) d_i \quad (2)$$

where i is the index of the space region, n is the number of regions, μ_i is the linear attenuation factor for i-th region, and d_i is the section of the line between the detecting point and the point kernel in the i-th region.

Therefore, the total dose rate at the detecting point can be calculated by integration of Eq. (1) over the source volume V and summation over the energies E of radiation spectrum

$$D = \int_0^{E_{max}} dE \iiint_V^v D(r, E) dr \quad (3)$$

2.2. CIDEC code's method

The CIDEC code can compute dose rate values in scenarios with a set of volumetric radioactive sources and shields (Vela et al., 2006). Before doing the calculations, the geometry of the scenario is generated using the CAD tools, and the file corresponding to the geometry is saved in DXF format. Once the geometry is loaded, material and radiometric attributes are imported for each volume. All volumes are considered to be homogeneous, both from isotopic and material composition points of view. Then a set of cell (source) points are assigned to each radioactive source. The method for generating cell points is shown in Fig. 1.

A parallelepiped volume containing the volume is obtained, and the coordinate of lower bound of the parallelepiped is (x_m, y_m, z_m). A point P_e external to the parallelepiped is defined with coordinates (x_m+d, y_m+d, z_m+d) where d is a constant. For each point P_i of the grid, the intersection points between the volume contour and the line $P_e \rightarrow P_i$ are calculated. The intersection point closer to P_i is defined as P_r. The normal that is pointing outward to the surface at P_r is defined as $\boldsymbol{v_n}$, and $\boldsymbol{v_{im}}$ is a vector from P_i to P_r. Therefore, P_i is inside the volume if the inner product $\boldsymbol{v_n} \cdot \boldsymbol{v_{im}} > 0$. Otherwise, P_i is outside the volume. In the next step, the cell points are randomly selected from the points inside the volume. Once the cell points are obtained, the specific activity for each cell point is calculated. Then, the Point-Kernel method is used for dose calculation in a uniform continuous media.

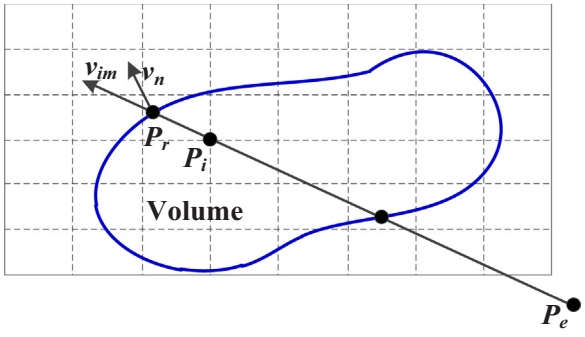

Fig. 1. Two-dimensional viewgraph showing the method for identifying cell points. A mesh grid is represented with dashed lines. P_i points are the intersections in the mesh grid. The volume contour is shown in blue. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)