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A NEW MODULAR VOXEL-BASED METHODOLOGY FOR RADIATION TRANSPORT SIMULATIONS USING CAD MODELS WITH NEREIDA

Osiris Núñez-Chongo[1,5], Mauricio Suárez-Durán[2], Hernán Asorey[3], Iván Sidelnik[4], Roberto Méndez[1],
Manuel Carretero[5] and Rafael Mayo-García[1],

[1]Dept. of Technology, Centre for Energy, Environmental and Technological Res., Madrid, SPAIN
[2]Dept. de Ciencias Naturales y Exactas, Universidad de la Costa, Barranquilla, COLOMBIA
[3]piensas.xyz, Las Rozas Innova, Las Rozas de Madrid, SPAIN
[4]Dept. Física de Neutrones, CNEA, Centro Atómico Bariloche, San Carlos de Bariloche, ARGENTINA
[5]Dept. of Mathematics, Gregorio Millán Institute for Fluid Dynamics, Nanoscience and Industrial Mathematics, Universidad Carlos III de Madrid, Leganés, SPAIN

ABSTRACT

This work introduces a voxel-based methodology integrated into the NEREIDA framework to improve radiation transport modeling in complex geometries. The approach automates CAD import, material assignment, and adaptive voxelization, enabling accurate and reproducible GEANT4 simulations. Structural and virtual voxelization are combined to preserve geometric detail while allowing precise analysis of neutron flux, dose, and shielding performance. Validation with a digital twin of the Laboratorio de Patrones Neutrónicos using ^{252}Cf and ^{241}AmBe sources reproduced experimental conditions. Results show over one order of magnitude improvement in spatial resolution and a substantial reduction in computation time with multithreading. This integration strengthens NEREIDA's capabilities for CAD-based neutron transport, providing a scalable and efficient tool for radiation protection, nuclear metrology, and safety analysis.

1 INTRODUCTION

Accurate modeling of radiation transport in complex environments, such as nuclear facilities, requires not only a detailed geometric description, but also the ability to efficiently solve local dosimetric quantities. Some traditional simulation systems using GEANT4 are often based on manual construction of the geometry within the software and require laborious material assignment. These limitations restrict the scalability, reproducibility, and flexibility of the models. The main objective of this work is to present a new modular voxel-based methodology to improve the efficiency of radiation transport simulations, which is integrated into NEREIDA. This includes automatic CAD geometry imports, robust integration with GEANT4, adaptive voxel representation of geometries for high-fidelity neutron transport, automatic material assignment, and voxel-based scoring. The proposed integration has the potential to improve the accuracy, reproducibility, and scalability of neutron dosimetry studies, offering tangible benefits for both experimental design and regulatory licensing.

2 NEW METHODOLOGY INTEGRATED INTO NEREIDA AND PREVIOUS RESULTS

This new methodology combines advanced geometric processing with flexible scoring strategies, which is the core innovation of the framework. The workflow begins with the import of a STEP file generated in AutoCAD or equivalent software. These files are processed with Python scripts in FreeCAD, where the geometry is hierarchically decomposed and tessellated with a resolution adapted to the smallest CAD features. The tessellated structure is then exported as a GDML logical volume, preserving spatial consistency and allowing seamless integration into the GEANT4 environment. At this stage, materials can be assigned directly during preprocessing using Python scripts or voxelized adaptively using GEANT4's nested parameterization.

This option captures material heterogeneity, crucial for anthropomorphic phantoms. In addition, NEREIDA introduces virtual voxelization, in which a user-defined scoring mesh is superimposed on regions of interest, regardless of the underlying geometry. This is achieved using GEANT4's `G4VScoringMesh` system, in which a virtual mesh is superimposed on a selected region to collect spatially resolved data such as energy deposition, neutron flux, and absorbed dose.

Together, structural and virtual voxelization provide a flexible methodology that preserves the accuracy of complex geometries while enabling detailed localized analysis. This dual approach facilitates the study of shielding efficiency, hot spots, and safety-critical regions without altering the physical model, and lays the foundation for reproducible and standardized simulation practices. Figure 1 illustrates this process: starting from the original CAD model (first) and the geometry imported using nested parameterization (second). To validate the framework, a simplified 3D digital twin of the *Laboratorio de Patrones Neutrónicos* (LPN-CIEMAT) was constructed, including reinforced concrete shielding, operational areas and physical properties of Madrid's soil. Simulations with ^{252}Cf and ^{241}AmBe sources reproduced operational conditions and provided dose and flux values at multiple detector positions. Figure 1 also shows an example of voxel-based scoring in the digital twin (third) and the visualization of neutron tracks emitted by the ^{252}Cf source (fourth). Voxel-based scoring improved spatial resolution by more than one order of magnitude compared with standard GEANT4 mesh tallies, enabling finer discrimination of local neutron flux and dose gradients.

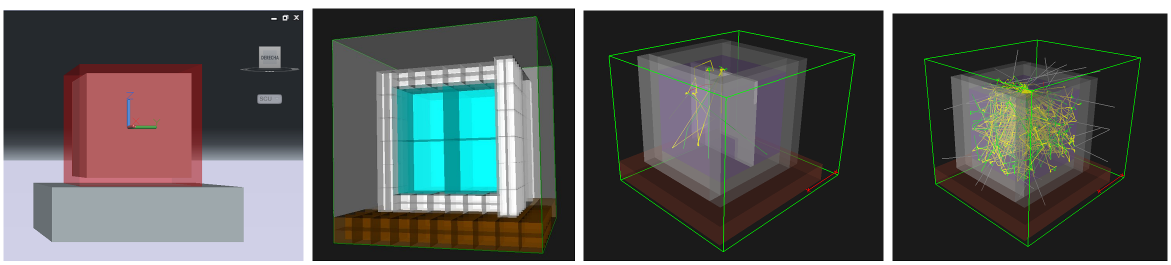

Figure 1: Visualization of the NEREIDA simulation workflow: Original CAD model (first), geometry imported into GEANT4 using nested parameterization (second), example of voxel-based scoring in the digital twin of the LPN-CIEMAT (third), visualization of neutron tracks emitted by the ^{252}Cf source (fourth).

Performance tests with GEANT4 multithreading confirmed that execution time decreases significantly with parallelization: simulations completed in less than one-third of the time when 16 threads were used compared to single-threaded runs, with increased scalability as the number of threads increased. However, for small geometries, scalability is limited by GEANT4 event-level parallelism. This indicates that while simple cases quickly reach saturation, complex CAD-based geometries with millions of particles are precisely where HPC resources yield the greatest benefits.

3 CONCLUSION

The proposed voxel-based approach significantly extends NEREIDA's capabilities for CAD-driven radiation transport simulations. By integrating automated geometry processing, dual voxelization, and parallel execution, the framework achieves substantial improvements in spatial resolution and computational speed. NEREIDA proves to be a robust, scalable, and HPC-ready platform that effectively links engineering design with advanced Monte Carlo simulation, providing a practical tool for nuclear metrology, radiation protection, and licensing analyses.

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