Virtual Reality Visualization of Dose Rate Fields for Dose and Decommissioning Planning Using ADEPT-PSIM - 22257
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ABSTRACT

The decommissioning of nuclear systems can often involve complicated and dose intensive activities, especially in legacy facilities where construction did not anticipate decommissioning requirements. The following paper is a collaboration between Kinectrics and Cavendish Nuclear which describes the development of a process using Virtual Reality (VR) to model calculated and measured dose rate fields in “real world” scenarios. This will aide in the planning of decommissioning activities, reducing the dose accrual of personnel by allowing for the simulation of different decommissioning scenarios away from the elevated dose rate fields.

Kinectrics is the developer of the Advanced Dose Exposure Planning Tool (ADEPT) software which generates a 3D visualization of dose rate fields and isotopic activities using the latest VR technologies. The ADEPT software will be able to import data from multiple sources including dose rate and activity scans of facilities, laser scans or CAD models of geometries and data generated from a variety of nuclear codes including PSIM, Attila, MCNP and ORIGEN.

Cavendish Nuclear is the developer of the Particle Swarm Imaging (PSIM) software which is an innovative computational method that seeks to ‘image’ source terms using the information obtained from performing multiple measurements at different positions around a waste item or within a facility. At the heart of the PSIM analysis is the process of swarm ‘exploitation’ and ‘exploration’, inspired by the way swarming systems operate in nature. The source term is represented as a swarm of point sources of activity that iteratively ‘home-in’ on the true location of activity concentrations. The source terms imaged by PSIM provide the input into the ADEPT software which then propagates the 3D dose field around the item measured or within the facility.

This paper is intended to demonstrate the utility of the ADEPT-PSIM workflow for use in planning and optimizing activities and facility layouts where elevated dose rate fields will be expected. This will include the generation of a 3D model that can be used in commonly available VR software to visualize dose rate fields and dose accrual as the user is navigating through the model. This will be demonstrated specifically through a case study of a generic facility containing multiple source terms and shielding arrangements.

A generic facility will be designed in CAD and simulated source terms will be generated by the PSIM software. This data will be imported into the Attila software for meshing and radiation transport analysis. The Attila deterministic solver is a three-dimensional discrete ordnance (S_N) particle transport code that solves the Linear Boltzmann Transport Equation on an unstructured tetrahedral mesh. The results from Attila will be in the format of a mesh tally, which will be imported into the ADEPT software along with the CAD geometry to generate a user-navigable 3D VR model.

The VR models created by ADEPT will allow for easy visualization of the radiation fields within a facility that can assist in dose and decommissioning planning, operator training, shielding design, as well as the optimization of radioactive waste transportation routes and optimization of radioactive waste storage configurations within the facility.
INTRODUCTION

Kinectrics has been involved in performing outage activity transport monitoring surveys at nuclear stations for several years, which has led to the development of the Advanced Dose Exposure Planning Tool (ADEPT), [1]. ADEPT combines visualization and simulation of the radioactive environment at nuclear stations and includes reactor components like the reactor face, as well as vertical and horizontal feeder cabinets. The ADEPT interface allows users to walk through a virtual job plan and receive a live dose estimate for the planned work.

Kinectrics is currently working to further develop the ADEPT tool by incorporating the use of the radiation transport code Attila to create dose rate maps that can be loaded into ADEPT, as well as incorporating the use of Particle Swarm Imaging (PSIM) which has been developed by Cavendish Nuclear.

Cavendish Nuclear has been involved in providing radiometric measurement solutions for the entire nuclear life cycle. A recent development, called Particle Swarm Imaging (PSIM), provides an assay solution for specialist measurements of waste items, from small packages to large ISO-freight containers, and plant infrastructure. PSIM iteratively determines the location of activity concentrations using the information obtained as a result of performing multiple measurements at different positions around a waste item or within a facility. At the heart of the PSIM analysis is the process of swarm ‘exploitation’ and ‘exploration’, inspired by the way swarming systems operate in nature. The source term is represented as a swarm of point sources of activity that iteratively ‘home-in’ on the true location of activity concentrations. The source terms imaged by PSIM provide the input into the ADEPT software which then propagates the 3D dose field around the item measured or within the facility.

Attila is a deterministic three-dimensional discrete ordinates (SN) particle transport code that solves the Linear Boltzmann Transport Equation on an unstructured tetrahedral mesh. To begin analysis on a radiation transport problem with the Attila suite, a CAD geometry of the problem is first imported into the Attila Graphical User Interface (GUI) where an unstructured mesh of the geometry is created. Attila can then be used to calculate the neutron and/or gamma flux throughout the meshed geometry, given defined source spectra and locations.

The overall ADEPT-PSIM workflow is shown below in Fig. 1. Geometry in the form of a CAD model is meshed in Attila and source term data from PSIM, ORIGEN, or other sources (e.g., radiometric scans) is used by Attila to calculate the neutron and gamma flux throughout the problem geometry. The ADEPT software then translates this data into a form that can be presented in a 3D virtual reality (VR) format. The work on ADEPT is ongoing and this paper presents an example of the proposed workflow.

Fig. 1. ADEPT-PSIM Workflow
PARTICLE SWARM IMAGING (PSIM)

Estimation of representative gamma and neutron ‘source terms’ for input into radiation transport codes such as Attila for generating dose fields within facilities is often challenging due to the complex geometries encountered as well as the levels of attenuation and scattering experienced between the source and detection device.

The source term can be difficult to estimate due to the fact that the distribution of signal generating material is often unknown and highly variable, ranging from uniformly dispersed sources (volume or surface) to the extreme case of single or multiple highly localized ‘hotspots’ of activity. Examples include, the non-uniform distribution of activity with a waste drum, dispersed source terms that may exist on a pond wall, plutonium hold-up within a facility etc.

Critically, the use of incorrect assumptions on the source term distribution within a scene can have a significant impact on the accuracy of the dose map modelled, an example of such a scenario is shown in Fig. 2.

Particle Swarm Imaging or PSIM [2, 3, 4] is an innovative computational method developed by Cavendish Nuclear that seeks to ‘image’ the source term using the information obtained from multiple measurements at different positions within a facility (the type of measurements performed range from gamma spectrometry, dose probes, gamma imagers, neutron measurement etc.).

The innovation that underpins PSIM is the treatment of the source term as a swarming system. The notion of a swarm is a familiar one, large groups of small insects, colonies of ants and bees, birds flocking, animals herding, bacterial growth, and fish schooling being just a few examples seen in the world around us. It is also well established that nature shows us that social creatures, when working together as unified swarming systems, can outperform the individual members when solving problems and making decisions. Swarming systems are therefore made up of a population of simple agents that interact locally with one another and with their environment. The agents follow simple commands, and although there are no specific rules stating how individual agents should behave, local and random interactions between agents can lead to the emergence of ‘intelligent’ behaviour, unknown to the individual agents. The swarm itself is most simply thought of as a group of simple components working together to achieve some end ‘goal’.

At the heart of the PSIM analysis is the process of swarm ‘exploitation’ and ‘exploration’, inspired by the way swarming systems operate in nature. The source term is represented as a swarm of point sources of activity that iteratively ‘home-in’ on the most likely location of activity concentrations, and unlike conventional analysis techniques only allow viable solutions, that is those that could actually give rise to the measured data, to be considered. The swarming process is repeated numerous times to build up a probability distribution of candidate solutions, with dense regions of the solution (i.e. those areas in the scene where the swarm ‘prefers’ to be) used to ‘pseudo’ image the source term present.
ADEPT – PSIM Workflow: Source Term Simulation & PSIM Image Reconstruction

A generic facility was designed in CAD and simulated source terms generated by the PSIM software. The 3D CAD model and the two source terms included for the purposes of simulation are shown in Fig. 3.

Fig. 3. ADEPT-PSIM generic facility 3D geometry model. The scene contains two source terms; a source term located within a series of pipes and a second ‘point source’ located within a drum.

As described earlier, PSIM seeks to ‘image’ the source term using the information obtained as a result of performing multiple measurements at different positions around each of the source terms. Fig. 4 shows the source term geometries and the multiple measurement positions selected. The data points in the right hand figures show the locations of the measurement positions, the signals from which were used by PSIM to reconstruct the source terms for input into the Attila dose mapping software.

Fig. 4(a) represents the ‘Drum’ source term simulating a waste drum containing radioactive material. The 24 measurement locations shown in Error! Reference source not found. (b) simulate the signals (dose rates, photopeak count rates etc.) obtained from measurements at a distance of 30 cm from the drums outer surface, and at the three different heights shown.

Fig. 4(c) represents the ‘Pipes’ source term simulating the hold-up of material within 14 metallic pipes of differing heights. The 140 measurement locations shown in Fig. 4(d) simulate the signals (for example dose rates) obtained from measurements at a distance of 40 cm from the pipe outer surfaces.

PSIM reconstructs the source term image from the input signals (i.e. measured photopeak count rates, dose rates etc.) by seeking only those swarm solutions that could actually give rise to the signals measured (the methodology describing how this is achieved is given in [4]). The image PSIM creates represents the set of candidate solutions that fulfill this criteria, consisting of many thousands of data points, each representing a particles location in the (x, y, z) space of the measurement geometry and its emission strength (activity). Using this information, the total activity of the imaged source term can be directly calculated. However, the purpose of the PSIM analysis is not only to provide a visual image of the source term and its total activity, but also provide a suitable input into the dose mapping software Attila for the calculation of the dose rate field.
Fig. 4. ADEPT-PSIM source term geometries and measurement positions used in the PSIM source term reconstructions.

Fig. 5 and Fig. 6 show the actual source terms used in the simulation as well as the PSIM reconstructed source term in each case. The left hand figures show the actual source term simulated and the right hand figures show the PSIM image of the source term reconstructed from the signals simulated at each measurement position.

Fig. 5. ‘Pipes’ actual source term (left) and the PSIM reconstructed source term (right).
Fig. 6. The left hand figures (a), (b) and (c) show the actual source term used in the “Drum” scenario in the \((x - y)\), \((x - z)\) and \((y - z)\) planes respectively. The right hand figures in each case show the PSIM reconstructed source term.

PSIM is able to reduce the overall size of the source term from the many thousands that make up the reconstructed image to a more manageable size for the dose field calculation (in Fig. 5 and Fig. 6 the reduced source term is represented by the superimposed dataset shown in red). These reduced source terms typically consist of between ten to a hundred points (dependent on the complexity and uniformity of the source term) and can be reduced to a single point as shown in Fig. 6 for the ‘Drum’ scenario.

The example reconstructions presented in this section demonstrate how PSIM can reconstruct representative source terms from measurements performed in close proximity to the source term requiring characterisation. The nature of the measurements can range from gamma photopeak spectrometry, total spectrum counting, dose rates etc., as long as a model can be realized that relates the quantity in question (such as activity, mass etc.) to the signal measured (photopeak count rate, total count rate, dose rate etc.).

The application of PSIM not only allows the total source term strength to be evaluated and an image of its distribution to be visualized within the scene but generates an accurate representation of the source term for input into the Attila dose mapping software. This methodology avoids the need for assumptions as to the activity distribution to be made, mitigating the risk of calculating dose maps that are in fact poor representations of the real situation, as was seen in the example provided in Fig. 2.
GENERATING DOSE RATE DATA FOR VR

In order to utilize the data from PSIM or other sources in the VR software, it must be converted into a compatible format. One of the primary purposes of the ADEPT software is to act as a translator between the various input sources including geometries (e.g., CAD, laser scanning), source terms (e.g. PSIM, ORIGEN, MCNP, radiometric scans), simulation software (e.g. MCNP, Attila) and the VR suite. This part of the workflow is currently in development and is being designed in a modular format to allow for the streamlined integration of additional data sources over time.

In this paper we present a demonstration of the proposed workflow utilizing simulated PSIM source data, CAD geometry and Attila to create the models and dose rate data for inclusion in a VR simulation.

Processing PSIM Data in Attila

The CAD geometry of the generic facility (see Fig. 3) used in the PSIM simulation was converted into the Parasolid format required by Attila using CAD software. In order to generate the dose rate maps for use in the VR suite, an Attila calculation was generated and run. The CAD geometry was imported into Attila and converted into an unstructured, tetrahedral mesh (see Fig. 7).

The FENDL 3.1d cross-section libraries supplied with Attila were used and the same material compositions used in the PSIM calculations were assigned to the various bodies in the geometry. As the ADEPT software is currently in development, conversion of the PSIM point cloud source terms into a format suitable for Attila is not yet possible, however the source terms generated by PSIM were used to create representative volume sources in the drum and pipe geometries.

The simulation was run using the Attila deterministic solver with a scattering degree (P_N order) of 3 and the Triangular Chebychev Legendre quadrature with an S_N order of 22. These settings were sufficient to remove any discontinuities in the results and ensure convergence. A dose rate map based on the PSIM
reconstructed source terms is shown in Fig.5 and Fig. 6, through a plane 1 m above the floor is presented in Fig. 8. The dose rates maps were generated using the Tecplot analysis tool, which was also used to export the dose rates and gamma flux at each node of the mesh into a CSV file, suitable for use in the VR suite.

Fig. 8. Attila dose rate map generated from the “Drum” and “Pipe” source terms.

**CREATION OF VIRTUAL REALITY (VR) MODEL USING ADEPT SOFTWARE AND UNITY ENGINE**

Unity will be used as the physics engine to simulate radiation accumulation and user VR interactions. The 3D CAD model used in Atilla to calculate the particle transport will be imported into Unity as an object (.obj) file. Separately, the dose rate output from the Atilla particle transport solver is mapped in Tecplot and exported as a text file. The text file is then parsed through a custom parser to generate a CSV file that is readable in Unity. The dose rate data is then imported into Unity and a 3D heat map generated from the data points. By overlaying both the 3D CAD model and heat map, it is possible to determine the user dose accumulation based on their positions in a live simulation.

**Importing CAD Model into Unity**

The 3D CAD modeled in Atilla was imported into Unity and the scale of the model was reduced to match the Unity coordinate system. The orientation of the model is then adjusted to ensure it is aligned with the dose rate map. Fig. 9 shows the exterior view of the 3D model imported into Unity from Atilla. The air component of the 3D model was removed in Fig. 10 to reveal the actual facility structure. Each component on the 3D models (floor, walls, ceiling, etc.) has basic prototyping textures applied to them.
The above plot (Fig. 10) shows the interior view of the 3D model imported into Unity from Atilla. For the interior view, the pillars have the same prototyping texture as the wall, floor, and ceiling. The pipes and drum have different textures applied to them to show the areas of interest in the facility.

A basic VR rig was placed in the center interior (indicated by the green box outlined). The VR setup allows for basic user navigation and first-person viewing of the 3D environment.

**Importing Atilla Dose Rate Data into Unity**

The dose rate data generated from Atilla is exported as a text file and parsed through a custom parser to provide a Unity readable CSV file. Only the dose rate for the air zone was extracted through the parser since it is the only zone that the user can physically navigate. This is to both save computational power and reduce visual noise. The CSV file is then imported into Unity and a heat map is generated based on the data points. Each data point is represented by a small cube object in Unity that is generated during start-up. The red, yellow, and green standard texture was applied to the cube based on the dose rate associated with the data point.

Fig. 11 shows the visualization of the dose rate data exported from Atilla in Unity. The red zone indicates a high dose rate, yellow indicates moderate values and green indicates a low dose rate. The different color zones will be transparent / invisible in the actual simulation to reduce rendering load and visual clutter. However, the collider associated with the heat map will be present to enable dose rate detection and calculation through the Body Dose Accumulation framework described later.
Fig. 1. Point cloud data and heat map of the radiation field visualized with Unity

Overlaying Heat Map and 3D Model

The code that generates the 3D heat map is then imported into the development environment along with the associated CSV data and the heatmap is set to be generated during startup. Fig. 12 shows the exterior view of the heatmap and 3D model overlaid on each other. As shown in the image, the alignment fits perfectly with only minor adjustments needed to the scale and rotation of the 3D model.

Fig. 12. Exterior view of dose rate heatmap overlaid with the 3D model
Fig. 13 shows the interior of the facility with the heat map overlaid. The radiation fields around the pillars, pipe, and drums match with that of the 3D model. Fig. 14 shows a less cluttered version of the heat map with all green zones removed.

![Fig. 13. Interior view of the dose rate heatmap overlayed with the 3D model](image1)

![Fig. 14. Interior view of the dose rate heatmap (green zone excluded) overlayed with the 3D model](image2)

**Development of the Body Dose Accumulation Framework**

Implementation of the body dose accumulation framework in the VR model is currently in development. The 3D heat map provides radiation zones that can be used as a trigger to obtain the dose rate in a particular area in the virtual environment. A dose receptor will be developed to receive the dose rate once it enters a radiation zone. The zones are a set of colliders placed next to each other with predefined dose rates obtained from the heat map. Each time a dose receptor enters the zone, a trigger function will be called to obtain the dose rate associated with the zone and this will depict the dose rate that the dose receptor will receive. If the dose receptor overlaps multiple colliders, the average dose rate between the collider will be taken as the final dose rate. The dose rate is then calculated with respect to time to provide a total dose accumulation that the user receives during their time within the simulation. A pictorial representation of the dose accumulation framework is shown below in Fig. 15.
The dose receptors can be attached to any point on the body model to simulate dose accumulation received for different parts of the body. This will allow for comprehensive tracking of radiation exposure for each part of the body separately. Combining the framework with a VR setup will allow for accurate simulation of the user interactions and dose they receive while in the VR environment. Potential dose rate receptor locations on the body are shown in Fig. 16 below.

Fig. 15. Basic concept of the dose accumulation framework

Fig. 16. Potential dose receptor positions [5]
Implementing the Initial VR Test Environment

The methodology above was implemented in the VR environment for one dose receptor. In the current implementation of the test environment, the average dose rate from multiple overlapping colliders was not calculated. The dose rate will update based on the latest collider from the heat map that the dose receptor comes into contact with. The next implementation of the Test Environment will have this functionality enabled.

A simple user interface was developed to show the dose rate, total dose accumulated and dose rate graph as a function of time. Fig. 17 depicts the user interface display, showing the dose rate profile as the user walks past the group of radioactive pipes in the virtual environment.

![Fig. 17. Dose rate profile when the user walks past the “Pipes” source term in the test environment](image)

CONCLUSIONS

Kinectrics and Cavendish Nuclear are currently in the process of developing a ADEPT - PSIM workflow to create virtual reality (VR) simulations of radiological environments for a variety of situations including decommissioning operations, building/equipment layout optimization and training.

The key benefits of virtual reality simulations of radiological environments include:

- Virtual job-planning to assess options to reduce dose uptake to personnel during routine and non-routine operations
- Assess the effect of shielding on the potential dose uptake during operations
- Evaluate the impact of working in different plant configurations and scenarios
- Provide a training tool for new personnel and contractors

Examples and the benefits of using the PSIM analysis approach to generate accurate representations of the source terms for input into the Attila dose mapping software have been illustrated. The PSIM approach avoids the need for assumptions as to the distribution of the source term to be made, mitigating the risk of calculating dose maps that are poor representations of the real situation.
With this initial demonstration we have shown the feasibility of our approach based on the ADEPT-PSIM workflow shown in Fig. 1. Future developments of ADEPT-PSIM will include the automation of data import, modules for incorporating laser scanning of geometries, modelling radioactive decay of sources and the resultant changes in dose rate fields over time. In addition, it is planned that future versions will allow for the movement of equipment/shielding and incorporate the resultant changes in dose rate fields in real time.

REFERENCES


