Interactive Visual Intervention Planning
Interactive Visualization for Intervention Planning in Particle Accelerator Environments with Ionizing Radiation

Thomas Fabry[1], Christian Braesch[2] and Bruno Feral[1]
[1]*CERN, Geneva, Switzerland*
[2]*SYMME, Université de Savoie, Polytech Annecy-Chambéry, Chambéry, France*

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Abstract: Intervention planning is crucial for maintenance operations in particle accelerator environments with ionizing radiation, during which the radiation dose contracted by maintenance workers should be reduced to a minimum. In this context, we discuss the visualization aspects of a new software tool, which integrates interactive exploration of a scene depicting an accelerator facility augmented with residual radiation level simulations, with the visualization of intervention data such as the followed trajectory and maintenance tasks. The visualization of each of these aspects has its effect on the final predicted contracted radiation dose. In this context, we explore the possible benefits of a user study, with the goal of enhancing the visual conditions in which the intervention planner using the software tool is minimizing the radiation dose.

1 INTRODUCTION

Particle physics is a branch of modern physics that studies the smallest known constituents of matter. Particle physics research necessitates large and complex scientific instruments: particle accelerators and detectors (Wille, 2001; Myers, 2012). Accelerators boost beams of particles to high energies before they are made to collide with each other or with stationary targets. Detectors observe and record the results of these collisions. The circulation and collisions of high energy beams in the accelerators and detectors have an undesirable consequence, namely the radiological activation of some of the components of these facilities.

The complexity of particle accelerators and detectors lead to the frequent necessity of maintenance operations. To protect maintenance personnel from ionizing radiation during interventions in its particle accelerators and detectors, the so-called ALARP or ALARA approach (As Low As Reasonably Possible or Achievable (UKA, 2012; Grupen, 2010)) is mostly used, which consists of justifying, optimizing and limiting the dose received by all those who need to work on activated components.

A core issue during the planning of a maintenance intervention in a facility with ionizing radiation is the minimization of the equivalent dose contracted by the maintenance workers during the intervention. This optimization cannot easily be automated, since the practical feasibility of working conditions during the intervention tasks requires human assessment based on experience. The visual conditions in which the intervention planner can perform the optimization are important, and the several layers of data involved in the planning process, i.e. the facility geometry, the radiation levels and the intervention trajectory, therefore need to be appropriately visualized.

In this context, we develop a tool that brings state-of-the-art visualization techniques, similar to the ones found in medical imaging for example, to intervention planning to optimize human interventions in infrastructures in emitting ionizing radiation. We also submit the visualization method used in the developed tool to a user test to evaluate the effectiveness of the visualization and its perception by the user.

In the remainder of this article, first, we describe the important concepts of the planning of an intervention in an environment with ionizing radiation in section 2. Second, we discuss how visualization plays an important role in this application and what the requirements are for the application, and propose a software tool for this purpose in section 3. Next, we discuss and explore the benefits of a user test for the interactive visualization and intervention planning in section 4, and finally conclude the article in section 5.

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2 PLANNING OF AN INTERVENTION IN AN ENVIRONMENT WITH IONIZING RADIATION

2.1 Quantifying Ionizing Radiation

Ionizing radiation is radiation that has the power to liberate an electron from an atom or molecule, thus producing ions (atoms or molecules with an electric charge). Because ions are chemically reactive, they can cause biological damage when produced in living tissue. Ionizing radiation can result in e.g. radiation sickness and cancer, but also has practical uses in research, medicine, and other areas. Sources of ionizing radiation are ubiquitous, such as cosmic rays and naturally occurring radioactive materials, but ionizing radiation can also be created, with artificially created radioisotopes, X-ray tubes or particle accelerators, etc.

Ionizing radiation exists in various forms. The particles of which ionizing radiation consists must have a sufficiently high energy and interact with the atoms of a target. These particles can be photons (electromagnetic radiation), electrons, positrons, muons, protons, alpha particles, heavy atomic nuclei or neutrons.

Workers that perform maintenance in an environment with ionizing radiation contract a **radiation dose** D. The unit of radiation dose is the **gray** (Gy), which quantifies the amount of radiation energy absorbed by a kilogram of matter and is equivalent to J/kg.

Different types of radiation cause different levels of damage to living tissue. This issue is addressed by the **equivalent dose** H, which is calculated by multiplying the radiation dose D with a weighting factor Q that is defined based on the radiation type. The unit of equivalent dose is the **sievert** (Sv). The **effective dose equivalent** H_{eff} is the equivalent of H for partial body irradiation (Cossairt, 1999; Grupen, 2010).

2.2 Intervention Planning Concepts

An **intervention** I is a set of **tasks** T_k that need to be completed by the maintenance worker, each with a specific description and an estimated duration τ_k:

$$I = \{T_k; \quad k = 0, 1, \ldots, K\}. \qquad (1)$$

Task T_0 corresponds to the entrance of the facility by the worker; task T_K corresponds to the exit of the facility.

A **trajectory** $\mathcal{T}$ consists of a series of **locations** m_i, with $i = 0, 1, \ldots, N$. At each location m_i, a maintenance worker will spend an amount of time denoted by t_i. The **path** between two consecutive locations m_i and m_{i+1} is denoted by S_i, with $i = 0, 1, \ldots, N-1$. Each path S_i is taken by the maintenance worker at a velocity v_i.

The planner of an intervention will decide on a trajectory $\mathcal{T}$ with an intervention I in mind, thus constructing a map between I and $\mathcal{T}$. As a result:

$$\forall\, T_k \in I: \quad T_k \text{ is assigned to a location } m_i \text{ and } t_i = \tau_k,$$
$$\forall\, m_i \in \mathcal{T} \text{ and } \nexists\, T_k \text{ assigned to location } m_i: \quad t_i = 0,$$

with $K \leq N$.

The equivalent dose H contracted by the maintenance worker performing an intervention I mapped on a trajectory $\mathcal{T}$ is calculated as the sum of the radiation received at the locations m_i and the radiation received over the paths S_i between the locations:

$$H(I, \mathcal{T}) = \sum_{i=0}^{N} t_i \dot{H}(m_i) + \sum_{i=0}^{N-1} \int_{m_i}^{m_{i+1}} v_i^{-1} \dot{H}(s)\,\mathrm{d}s, \quad (2)$$

where s is a point on the path S_i. The radiation rates $\dot{H}$ are available from simulations of the activation of the facility equipment or from manual measurements performed previously in the irradiated facility.

A trajectory is optimal when the equivalent dose H is minimal, respecting the constraints that all tasks require a minimal execution time and that the velocities v_i have to stay within the abilities of the maintenance worker. Some aspects of the trajectory optimization could be automated: the locations m_i can be placed such that the total amount of received radiation is minimized. However, other aspects require human assessment based on experience, such as practical considerations on the location from where a task is executed, or the velocity with which a specific part of the trajectory can be taken.

3 VISUALIZATION FOR INTERACTIVE INTERVENTION PLANNING

3.1 Approach

To make sure that the optimization of the radiation dose coming with the human intervention in infrastructures emitting ionizing radiation can be performed in the best possible conditions, the visualization of the particle accelerator and detector facilities, the radiation levels and the intervention data plays an important role.

Radiation level simulations are a tool that are much used to assess the radiological conditions of accelerator facilities where maintenance interventions will be necessary. The FLUKA package is a tool that can be used for the simulation of radiation levels and other radiological quantities after operation of accelerator and detector infrastructure (FLU, 2012; Battistoni et al., 2007; Fassò et al., 2005). The results of these simulations are most often visualized using the FLUKA Advanced Interface (FLAIR) (Vlachoudis, 2009) in a 2D way (see figure 1 for an example of a FLAIR visualization of a radiation level simulation), and this is also what is typically used for communication between Radiation Protection experts and other persons involved in maintenance operation planning at accelerator facilities (Vollaire and Widorski, 2011). Other software programs have been developed to allow visualization of FLUKA simulation results, such as SimpleGeo (Theis, 2012; Theis et al., 2006). SimpleGeo is an interactive solid modeler, which is made for implementing geometries for particle transport problems based on Constructive Solid Geometry (CSG). Together with the DaVis3D plugin (DaV, 2012), SimpleGeo allows interactive visualization of two-dimensional cuts of FLUKA voxel geometries.

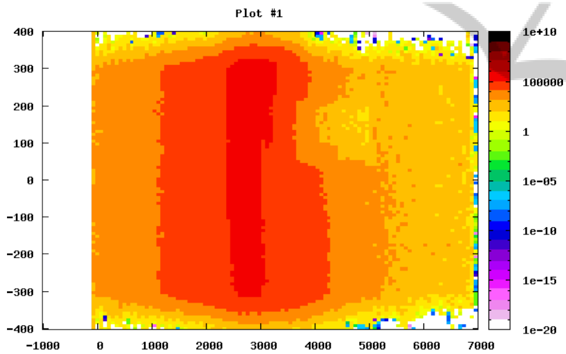


Figure 1: A typical FLAIR visualization of radiation levels.

There is however no tool that can enhance the intervention that is advanced enough to help intervention planners and, intuitive enough to be interesting for the maintenance workers, has 3D display possiblilities for both the models of the facilities and the FLUKA simulation data, offers the possibility to perform interactive visual inspection of the radiation levels, construct trajectories, and can calculate the resulting radiation dose contracted during a planned intervention.

We opted to develop intervention planning software in Python (pyt, 2012), and to use The Visualization Toolkit (Schroeder et al., 2006) for the visualization aspects of the intervention planning. For the development of the graphical user interface (GUI), we chose to make use of wxPython (Rappin and Dunn, 2006). Because major attention has to be paid to the requirement of an intuitive graphical user interface allowing fast and flexible visualization, trajectory creation, and reporting, the user interface (UI) is as much as possible decoupled from the back-end of the software.

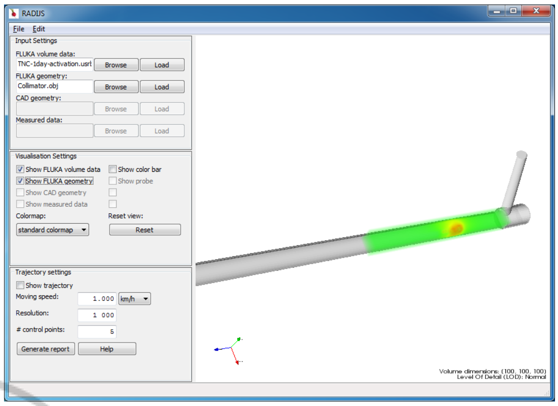


Figure 2: A screenshot of the software's Graphical User Interface, showing the volume rendering of a radiation dose simulation in the TNC tunnel at CERN. The geometry of the cavern is shown as well and is partly translucent to be able to have an overall view on the situation.

Figure 2 shows a screenshot of the GUI of the tool that was developed, illustrating the volume rendering of the example radiation dose rates in the TNC tunnel at CERN (Charitonidis et al., 2011).

In summary, the intervention planning software requires appropriate visualization of the facility geometry, the radiation levels and the trajectory information, as well as tools for interaction with them. In addition, the software has to provide an interface where the total radiation dose can be assessed and the resulting trajectory is summarized. We thus developed a new software tool to be in line with the needs that are detailed in the following subsections.

3.2 Interactive Visualization of the Facility Geometry and the Radiation Levels

The intervention planner software offers an interface for the user where he can select the file containing the geometry of the facility as well as the file containing the applicable radiation levels. To get a good insight into the work conditions in the facility, several tools are available to interact with the geometries and to assess the radiation levels at specific points.

Due to the nature of FLUKA simulation data, frequently used at CERN, and the requirement of a clear visualization of the working conditions, volume rendering is the natural choice to visualize the facility geometry and the radiation levels. We consider volume rendering to be a very intuitive volume visualization technique, compared to e.g. volume slicing. Volume rendering has been around for many years (Levoy, 1988; Drebin et al., 1988). Recently, the development and improvement of off-the-shelve GPUs has led to the proposition of several interactive advanced volumetric illumination models (Ritschel, 2007).

3.3 Interactive Visualization of the Trajectory Information

The trajectory is represented by a three-dimensional cardinal spline. Splines are an ideal mathematical representation of the trajectory, since they are piecewise defined and possess a high degree of smoothness at the points where their polynomial pieces connect, i.e. at the locations m_i. In addition, splines are very intuitive to work with and allow to design and control complex curves.

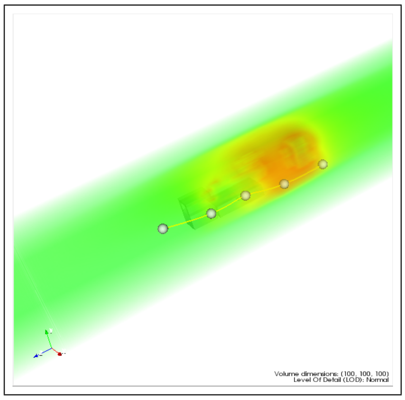
The number of locations is easily adjustable by the user through the GUI, and the locations can be displaced by the user to shape the spline into the trajectory that the maintenance worker will follow. To illustrate the importance of trajectory optimization, Figure 3 shows two possible trajectories through the TNC tunnel. The dose contracted during the trajectory visualized in Fig. 3(a) proves to be 25% higher than the dose contracted when following the trajectory in Fig. 3(b). These hypothetical trajectories are merely an illustration of the principle but indicate that small changes in an intervention can lead to much smaller exposure: in this case passing at the right side of an activated piece of equipment leads to a considirable reduction in dose. The volume rendered data is coming from a realistic simulation of the dose levels in an existing facility.

3.4 Calculation of the Equivalent Dose and Trajectory Report

The core of the application is the calculation of the equivalent dose H received by a worker over a user-defined trajectory $\mathcal{T}$ through the simulation volume, as defined in Section 2.2. To calculate H, the trajectory spline is discretized into n segments, creating a series of consecutive points s_j on the spline, with $j = 0, 1, \ldots, n$. The number of discretization steps can be controlled by the user; the default value is $n = 1000$. Using the trapezoidal rule, equation (2) can now be calculated as:

$$\hat{H} = \sum_{i=0}^{N} t_i \dot{H}(m_i) + \frac{1}{v} \sum_{j=0}^{n} \frac{\dot{H}(s_j) + \dot{H}(s_{j+1})}{2} \|s_j s_{j+1}\|. \tag{3}$$

Increasing the value of n has a positive influence on the accuracy of $\hat{h}$. However, one should keep in mind that the overall accuracy of equation (3) also depends on the accuracy of the radiation rates $\dot{h}$, which are obtained from simulations or from (sparse) manual measurements, both with limited accuracy.



(a)

(b)

Figure 3: Two possible trajectories for a maintenance intervention in the TNC tunnel at CERN. The equivalent dose contracted during the trajectory depicted in (a) proves to be 25% higher than the dose contracted during the trajectory depicted in (b).

At the end of an intervention planning, the software offers the possibility to generate a trajectory report. This report lists the sources of the trajectory planning (input files, units, ...); the trajectory information and the results of the planning (computed received dose, trajectory length, ...).

4 USER TEST

Since the use of a 3D visualization tool for the planning of interventions in facilities emitting ionizing radiation is not implemented yet in the facilities it is designed for, a user test is needed to prove that the application is useful to the intervention planner. The main goals of the user test we are proposing are, first, to qualitatively prove the usefulness of the 3D visualization for the user, and second to make way for a larger user test, using more quantitative variables, in order to discover the optimal settings for the 3D visualization. We also set a secondary goal, namely the quantitative comparison of two different color maps for the volume rendering visualization of the radiation level simulations. We evaluate this using the quantitative measures that are subject of the optimization during the planning of the maintenance operations. The appropriate use of color visualization is seen as a very important, and one of the most fundamental subjects in visualization (Silva et al., 2007). We thus want to test whether the choice of the colormap has indeed an important effect on the user experience, and if it has an effect on the optimization process that the user is performing in this application.

In scientific visualization literature, many publications of user tests and user test designs can be found. However, these user tests deal almost exclusively with the effectiveness of one visualization method on the user perception, without incorporating the context of a concrete application. For instance, many user studies can be found on the influence of different illumination models on 3D visualization on user perception of static computer-generated images (Wanger, 1992; Gribble and Parker, 2005; Ropinski et al., 2010; Lindemann and Ropinski, 2011; Šoltészová et al., 2011). In contrast to this, our user test design is conceived to take the interactive context of the trajectory planning application into account. Furthermore, the user test will also contribute to abate the relative scarceness of volume rendering applications user studies. Indeed, perceptual studies are scarcer in volume rendering applications than in surface rendering applications (Lindemann and Ropinski, 2011).

4.1 Material and Methods

As the user test is mainly a feasibility test for the developed software concept, the most important variable that was recorded was the qualitative appreciation of the user on the usability of the tool. This was done by asking for comments after the user test instance was performed. The other recorded variables were:

- H_{rec}: the computed expected integrated equivalent radiation dose received by the radiation worker when he would run this trajectory at a constant speed,
- l_{rec}: the length of the trajectory that was constructed by the user and
- n_{rec}: the number of control points the user used to construct the trajectory.

In addition to this, the full session information is recorded: all of the variables that are needed to reproduce the view the user had at the end of his session, including visualization, camera and interaction parameters.

These parameters are recorded as the result of the user test: a controlled possible real-life scenario of a planning of an intervention. The user was shown real-life simulation of example radiation dose rates in the TNC tunnel at CERN. The TNC tunnel is part of the infrastructure where the HiRadMat facility is located (Efthymiopoulos et al., 2011). The HiRadMat facility will be used to investigate the impact of high energy particle beams on different materials.The residual radiation dose rates originate from a FLUKA simulation of beam impact on beam equipment for the Large Hadron Collider (LHC) (Charitonidis et al., 2011). The radiation doses were shown using the GPU ray casting volume rendering algorithm as implemented in VTK (Schroeder et al., 2006; VTK, 2011). This volume rendering was overlayed on a transparent visualization of the geometry of the tunnel, as conceived and used for the FLUKA simulation.

For the secondary goal of the user test, two color maps were shown to the user: the standard, much-used and much-contested *rainbow* color map (Borland and Taylor II, 2007) and a continuous diverging color map claimed to be well suited to scientific visualization (Moreland, 2009). The order of the color maps in the user tests was randomized to mitigate the effect of familiarity the user might get the second time he perfoms the manual trajectory optimization. The qualitative of the colormap is measured according to the three recorded variables discussed above.

The scenario of the test is a scheme where a maintenance worker has to enter the facility through a given entrance location, go to a given location to performe a maintenance operation on a particular piece of equipment, and leave the facility through a given exit location. To let the user simulate this, the locations of the entrance, maintenance and exit points where given as fixed points on a dummy trajectory. This dummy trajectory had a number of control points that the user can move in order to alter the trajectory. In addition, the user is given the possibility to suppress or add control points in order to be able to make a more detailed trajectory (see figure 4). In every user session, the user had to perform these actions twice, using a visualization with different color maps.

In this context, the user was asked to construct a trajectory that he thinks is optimal, in terms of radiation the maintenance worker would undergo, given the constraints and the visualization of the simulated

Figure 4: The interface shown to the user performing the user test. The begin and end points and the control point marked "Maintenance Activity" are fixed. The user can alter the given trajectory by displacing the remaining control points, as well as any additional control points that he can add.

radiation dose rates. In order for the test to be as controlled as possible, most of the software user controlled settings/features were disabled. The user was given no real-time feedback in terms of resulting dose of the planned trajectory.

The user test was performed 10 times, by 7 different subjects. All of the subjects were more or less familiar with the type of facilities that our research is being done for, but only one of them was familiar with the particular facility used for the user test. 3 subjects did the user test twice. None of the subjects is professionally involved in maintenance planning, what gives us the possibity to assess if it will be feasible to use this tool not only in the intervention planning but also to give the maintenance workers an idea of the tasks they will have to perform and the relation of these tasks to the relative radiation levels they lead to. Furthermore, the fact that the user test subjects are not professionally involved in maintenance planning will allow us to have stronger indications on the user-friendlyness of the software. The interval between two tests performed by the same user was always more than 2 weeks.

4.2 Results

As for the qualitative feasibility test, all of the subjects were convinced of the potential of the given tool. None of them had comments on the visualization. There were some comments on the controls of the 3D navigation. These comments are very interesting and will be dealt with for the next version of the user test. They are however directly not relevant to the results of this paper.

As for the quantitative discriminatory test between the two color map, box plots of the measured variables, per color map, can be found in figure 5. We performed paired two-tailed t-tests on the three measured variables. The results found are:

- a t-value of $p(9) = 0.821$, $p = 0.43$ for the computed expected integrated equivalent radiation dose received by the radiation worker when he would run this trajectory at a constant speed, meaning that the computed expected integrated equivalent radiation doses are not significantly different for the trajectory plannings with the different color maps;
- a t-value of $p(9) = 0.609$, $p = 0.56$ for the length of the trajectory that was constructed by the user, meaning that the trajectory lengths are not significantly different for the trajectory plannings with the different color maps and
- a t-value of $p(9) = 0.137$, $p = 0.89$ for the number of control points the user used to construct the trajectory, meaning that the number of control points the user preferred to make the trajectory are not significantly different for the different color maps.

4.3 Discussion

From the results of the user tests, we cannot conclude that there is a significant difference between the two color maps. We can thus conclude that for this particular test, the color map is not of large impor-

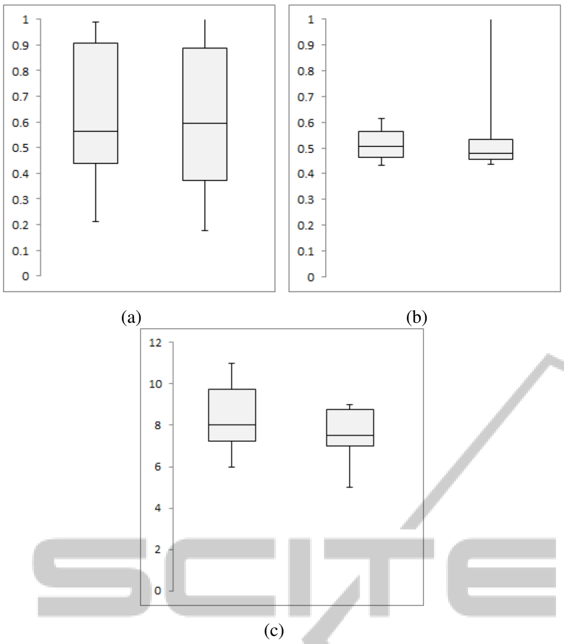


Figure 5: Boxplot of the measured variables: 5(a) the computed expected integrated equivalent dose (normalized), 5(b) the length of the constructed trajectory (normalized) and 5(c) the number of control points used in the trajectory. On the left the results of the user test, the data visualised using the continuous diverging color map, for the data on the right the rainbow color map was used.

tance for obtaining good results in operation planning in facilities emitting ionizing radiation. The result is however of limited strength, because of the relatively small sample of users and the very small number of scenarios. While we could have obtained more conclusive result with more users, we think that the main improvement in the user test can be made with letting the user optimize operation in more different facilities and scenarios.

The Student t-test for the number of control points is however leading to a p-value of 0.89, so that we can almost, with a significance level of $\alpha = 0.1$, exclude that the user prefers more or less control points with one or the other color map. This could have been a sign that the user is better able to minimize the radiation dose over the trajectory with one color map. This means that we can almost reject the hypothesis that the user uses more control points to specify the trajectory in the case of the continuous diverging color map, because he considers to be better able to constuct a detailed trajectory in this case. This conclusion is however also not evident when we plot the normalized computed expected integrated equivalent dose against the number of control points used per user test instance (see figure 6). More user tests are needed to confirm this hypothesis.

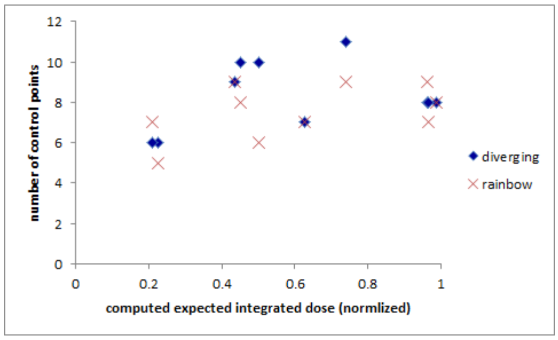


Figure 6: The number of control points plotted against the normalized computed expected integrated equivalent dose per user test instance.

In general, relying on the qualitative results of the user test, we can conclude from this test that the developed tool is well-suited for the intended purpose. The user comments are very positive and make the way for an extensive user test. Every user acknowledged the possibility to better plan maintenance interventions using this tool.

For the color map part of the user test, we cannot conclude that the continuous diverging color map is outperforming the rainbow color map, which was expected before the test. This can be caused by the relatively small number of user tests performed, or it can mean that the color map is not a critical factor in this application. Both outcomes are potentially interesting, but will have to be confirmed in a future, more extensive, test.

5 CONCLUSIONS AND OUTLOOK

Particle accelerators and detectors used in particle physics research are subject to ionizing radiation and their components can become activated. To protect the maintenance personnel from ionizing radiation during interventions, the radiation dose received by the workers during an intervention has to be minimized. Our goal is to provide interactive visualization means to plan an intervention which enables minimization of the contracted radiation dose, taking practical conditions concerning maintenance tasks into account. This optimization cannot easily be automated and therefore requires human assessment. The visualization of the several layers of data involved in the planning process, i.e. the facility geometry, the radiation levels and the trajectory, therefore needs to be clear, intuitive and interactive.

In this work, we started with a description of the important concepts of the planning of an intervention in an environment with ionizing radiation, and discussed how visualization plays an important role in this application. We proposed a software tool for this purpose in section 3, and discussed and explored the possibilities of a user test for the interactive visualization and intervention planning tool.

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