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Nuclear Disarmament Verification in Virtual Reality

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ABSTRACT

Any future nuclear disarmament treaty will most likely include a comprehensive verification regime. Since 2015, more than 25 states are engaged in the International Partnership for Nuclear Disarmament Verification (IPNDV) developing possible verification approaches, strategies, technologies and procedures. This work includes exercises such as the Nuclear Disarmament Verification (NuDiVe) Exercise, hosted by France and Germany. Organizing and running such exercises is complex, time-consuming, and logistically difficult. To simplify the participation in these exercises, an implementation in virtual reality is highly attractive. The participants will not have to meet at a nuclear facility, and safety and radiation protection restrictions will not become an issue. The scenario can be easily adapted, modified, and extended. On the other hand, developing a nuclear disarmament verification virtual reality requires substantial effort.

In this paper, we present our project on developing a virtual reality, which is based on the scenario of the NuDiVe exercise and simulates the dismantlement of a nuclear warhead using the concepts developed by the IPNDV. An indispensable verification option are radiation measurements, as both gamma and neutron radiation may be used to verify the fissile material declarations.

Our strategy for implementing spatial neutron flux densities in our virtual reality simulation is presented for specific scenarios. It is based on calculating neutron fluxes of fissile materials using the simulation toolkit GEANT4 within a small cube voxel grid. These data are fed into the virtual reality software in Unity, scaled according to the scenario (e.g. mass of weapons grade plutonium present) and converted to a detector readout.

INTRODUCTION

Despite the reduction of nuclear weapons in the past decades, no verification regime for the disarmament of nuclear weapons exists at the present day. Nevertheless, there are international efforts (e.g. the International Partnership for Nuclear Disarmament Verification) to develop verification approaches, technologies and procedures. An important step during the development is the proof that the technologies and procedures work out as planned. Therefore, technology demonstrations have taken place during the second phase of the IPNDV [Int20] and procedures were tested in disarmament exercises. One example is the Nuclear Disarmament Verification (NuDiVe) Exercise, which was hosted by Germany and France in September 2019. Experts from more than 11 countries participated in this exercise which focused on the dismantlement phase of the 14-step framework and the application of the developed chain-of-custody concepts [Int20].

The planning and the execution of disarmament exercises are complex and need a lot of time, manpower, and fissile material. Safety regulations in general and for radiation protection are complex. To reduce the complexity, costs and safety regulations, an implementation in virtual reality (VR) is highly attractive. Using VR, no nuclear facility or nuclear weapon laboratory and no nuclear weapon or surrogate is needed to conduct the exercises.

To relocate the disarmament verification exercise into virtual reality, it is vital to keep the experience as realistic as possible. One challenge are radiation measurements which must be possible at every position in the facility and show the correct detector signal.

In this paper, we will present the first steps in the development of the disarmament verification related virtual reality. We will explain how the radiation fields are generated and how we implemented the radiation detectors.

DEVELOPMENT OF OUR VIRTUAL REALITY SIMULATION

Our focus will be on the dismantlement of the warhead and potentially associated gamma and neutron measurements. To verify the absence of nuclear material, gamma and neutron counting can be used. It is assumed that both techniques are combined to increase the confidence in the process, as gammas and neutrons are shielded by different materials. To identify nuclear material and to verify that it is special nuclear material as used in warheads (highly enriched uranium or weapon-grade plutonium), gamma spectrometry and neutron counting can be used. In the following we focus on neutron counting. Gamma measurements will be included later.

Generation of Data

To simulate measurements in virtual reality, we chose to include radiation data gained by simulations using the software GEANT4, which is a simulation toolkit for the passage of particle through matter. It was developed at CERN and originally designed for high energy physics. Today it is used widely including medical, nuclear, and accelerating physics [AAA+03].

The simulated radiation fields from GEANT4 are exported to the virtual reality simulation in Unity where the detector signal is calculated.

There are two options to include the required data in virtual reality: the simulations can run when the readout of the detectors is needed or the radiation fields are generated beforehand and the data is only read when needed. Running simulations in a virtual reality in realtime has the advantage that all parameters like the size of the room, objects in the room and the position and geometry of the used detector are known. The main disadvantages are (1) the time intensive calculations of the simulation with calculation times of several minutes up to hours, (2) difficult to impossible validation of the obtained data, and (3) possible failure of the simulation due to abnormal termination if the automatic transfer of the geometry or the input data from Unity to GEANT4 does not occur correctly.

Generating the radiation data beforehand is complex because the exact geometry of the room is needed to simulate the radiation correctly. This leads to a great number of data sets to cover all possible scenarios and the implementation of new scenarios require additional simulation work. However, interpolation and simplification reduce the number of data sets. The advantage of this option lies in the speed in which the detector signal can be provided, and in the validation that a correct detector signal will be provided.

We decided to generate the radiation fields beforehand to develop a robust virtual reality simulation and limit the waiting times inside the virtual reality.

During a verification process, detectors with differing active volumes may be used for radiation measurements. For example, during the NuDiVe exercise two detectors (a handheld and a stationary one) have been used. To simplify the implementation of new detectors, the simulated dismantlement room is divided into small cuboids (voxels) with a resolution of 1 cm^3. The neutron count of each voxel is recorded, and the detector signal will be calculated using the voxel based neutron count.

Getting voxel based simulation results using GEANT4 is easy as it provides a feature called *build-in scorer*. Scorers divide the simulated ”world” into cuboids and a chosen quantity is counted for each cell. The size of the cells is freely selectable for each dimension.

A neutron detector counts the neutrons entering its active volume and reacting there. A similar quantity for the scorer is the *number of tracks* passing through each cell. The simulation results can be saved as csv-file which states the position of the cell in all three dimensions and the value of the scored quantity in the corresponding cell.

Selection of the first scenarios

During a nuclear disarmament verification, two scenarios need to be considered: the nuclear weapon state dismantles the warhead correctly and places the nuclear material in the designated container or the nuclear weapon state tries to divert some of the nuclear material. To simulate the warhead before or the special nuclear material after dismantlement information about the containers and the geometry of the warhead is needed which is classified. Therefore, we started with the scenario that some nuclear material is diverted, which could be realized by removing the fissile material from the room by a worker or inside a container declared to contain only scrap material. Alternatively, it could be hidden inside the dismantlement room. We focused on the two scenarios in which the nuclear material is removed from the dismantlement room because they are more challenging.

GEOMETRY OF THE SCENARIOS

It is assumed that the fissile material is plutonium with 95% Pu-239 and 5% Pu-240. As diverting small amounts of plutonium at each dismantlement process could already lead to a substantial clandestine stock and therefore has to be detected, a plutonium mass of 50 g shaped into a sphere with a radius of 8.4 mm is simulated. If the plutonium is carried out of the room by a worker, the bare plutonium sphere will be simulated in GEANT4. If the plutonium is hidden in a scrap container, the container is realized as a *55 gallon drum* (in the following called *barrel*) with a diameter of 58.5 cm, a height of 88 cm and steel walls of 1.4 mm thickness. The scrap is a composition of 80 % air[1], 10 % iron, 5 % aluminum and 5 % polyethylene with a density of 1 g/cm^3. The plutonium sphere is placed at the center of the barrel.

For neutron detection the handheld KSAR1U.06 detector used in the NuDiVe exercise is simulated. It includes three tubes with a diameter of 3.2 cm and a length of 20 cm filled with helium-3 gas with a pressure of 3 bar. As simplification we used an active volume of $20\times9.6\times3.2$ cm^3 with results ideally in an active area of 20×9.6 cm^2 facing the neutron source.

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[1] A study of metal brackets thrown into a chute has shown that approx. 80 % of the chute still contains air [Gro17].

VALIDATION OF NEUTRON FLUX USING VOXELS

The simulated neutron flux (number of neutrons per unit time) is recorded using a grid of small cuboid voxel of the size $1\times1\times1$ cm^3 to ensure a high spatial resolution. This results in a high number of voxels, e.g. 8 million voxels would be needed for a dismantlement room of $2\times2\times2$ m. This results in large data files (ca. 150 MB) and the import into the virtual reality has to be optimized.
To convert the neutron flux per voxel to a detector signal, the voxels which form the active area of the detector need to be identified. The detector signal is then calculated as the sum over the flux of all involved voxels.

Bare plutonium sphere
To verify that the sum over many small voxels results in the correct detector signal, the easiest scenario with just a plutonium sphere was used and two different voxel grids (which cover the very same space) have been compared: one grid has voxels of the requested size of $1\times1\times1$ cm^3, the other one has (approximately) the size of the active area of the detector ($20\times10\times1$ cm^3). The active area of the detector faces the plutonium sphere. The results from both voxel grids are shown in fig. 1 as function of the distance between the active area of the detector and the plutonium source. If the distance is greater than 60 cm, the sum over 200 voxels gives a good result compared to the one large cell and the deviation is less than 10 %. At smaller distances, the deviation increases, exceeding 50 % at $\lesssim$ 10 cm. This shows that the detector built of many small voxels becomes accurate if the detector is placed in a large distance.

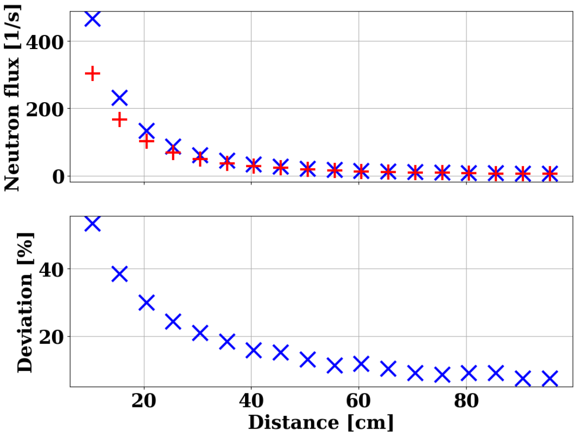


Figure 1: Validation of detector signal using a voxel grid when only plutonium is simulated. Shown are the voxels of $1\times1\times1$ cm^3 (crosses) and of $20\times10\times1$ cm^3 (plus signs). The deviation is calculated as $\frac{\text{flux}(1\times1\times1)-\text{flux}(20\times10\times1)}{\text{flux}(20\times10\times1)}$.

This deviation originates from the fact that some neutron pass through more than one voxel of the active area, cf. fig. 2. Neutrons emitted in a nearly normal direction to the active area will most likely only pass through one voxel in the first row (gray voxels in fig. 2). If a neutron is emitted in a greater angle to the voxel edges, it might pass through several voxels. This probability is smaller if the distance between the voxels of the active area and the plutonium source is greater because the same number of voxels at a greater distance covers a smaller solid angle. Looking at the tracks of all

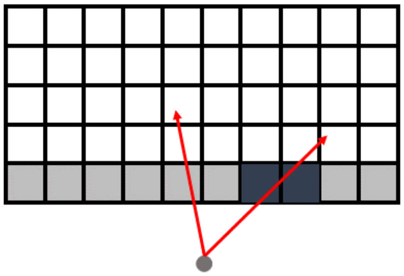


Figure 2: Multiple counting in voxel grid. The gray voxels form the active area of the detector. The red arrows indicate the path of two neutrons. The dark gray cells illustrate doubled voxel length.

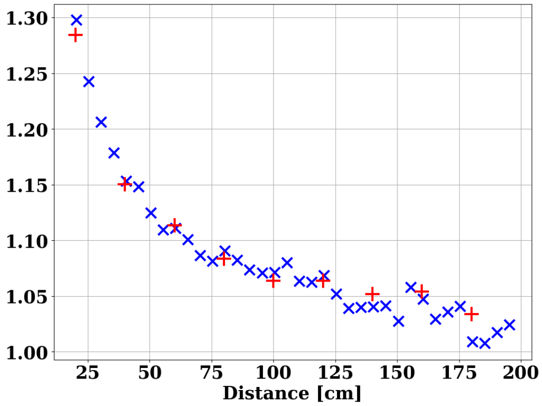


Figure 3: Average number of traversed voxels (plus signs) compared to the ratio of the two voxel grids (crosses).

neutrons, one can identify through how many voxels each neutron passes. This trend can be quantified by the mean of the traversed voxels, which is presented in fig. 3.

If the size of the voxels becomes larger, the probability that one neutron passes through more than one detector voxel should become smaller. This is shown in fig. 2, where the neutron, which passes through two voxels if small voxels are used, only passes though one voxel if the voxel length is doubled (dark gray voxels). Therefore, using a grid with larger cells should improve the calculation of the detector signal. Results for different voxel sizes are presented in fig. 4. The thickness of the cells is not changed to maintain the spatial resolution in the direction in which the detector is moved away from the source.

Enlarging the voxel volume by a factor of four (going from $1{\times}1{\times}1\,\mathrm{cm}^3$ to $2{\times}2{\times}1\,\mathrm{cm}^3$) already decreases the deviation by a factor of approximately two. Using a voxel grid of $10{\times}10{\times}1\ \mathrm{cm}^3$ or $10{\times}5{\times}1\,\mathrm{cm}^3$ results in no deviation from using only one voxel for the detector. The disadvantage of using large voxel sizes lies in the reduced spatial resolution which results in higher uncertainties of the detector signal.

As deviations $\leqslant 10\%$ are acceptable because they correspond to the accuracy of the GEANT4 simulations, a grid with a voxel size of $1{\times}1{\times}1\,\mathrm{cm}^3$ is adapted.

As stated before, the data files containing the neutron flux per voxel might become very large if a large space needs to be covered, e.g. for large dismantlement rooms. Therefore, one might take advantage of the symmetries of the room. The geometry of the room includes a spherical plutonium sample at the center of the room and a cubical room. Therefore, the space can be divided into eight symmetrical cubes and only one cube needs to be covered by the voxel grid which reduces the file size to an eighth. The results while taking advantage of the symmetry are presented in fig. 5 for two different voxel sizes. At small distances between the plutonium sample and the detector, the symmetry grid gives accurate results, but some deviation becomes apparent. As the number of events decreases with distance, small errors in the neutron flux in one voxel, which will be counted multiple times when

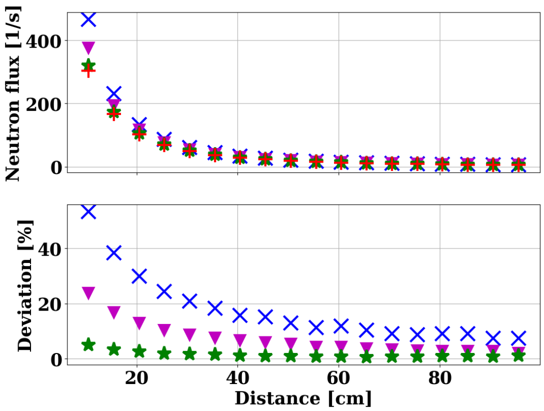


Figure 4: Impact of different voxel sizes. Shown are the voxel sizes of 1×1×1 (crosses), 2×2×1 (triangles), 5×5×1 (stars), and $20\times10\times1\,\mathrm{cm}^3$ (plus signs). The deviation is calculated as $\frac{\mathrm{flux}(x\times x\times 1)-\mathrm{flux}(20\times 10\times 1)}{\mathrm{flux}(20\times 10\times 1)}$.

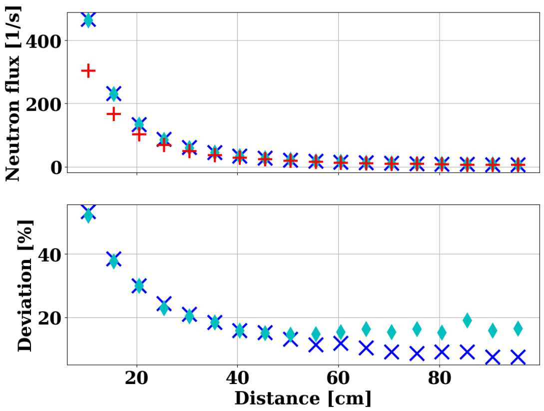


Figure 5: Impact of taking advantage of symmetries. Shown are the voxel sizes of 1×1×1 (crosses) and $20\times10\times1\,\mathrm{cm}^3$ (plus signs) as well as the symmetry grid of $1\times1\times1\,\mathrm{cm}^3$ (diamonds). The deviation is calculated as $\frac{\mathrm{flux}(1\times 1\times 1)-\mathrm{flux}(20\times 10\times 1)}{\mathrm{flux}(20\times 10\times 1)}$.

taking advantage of symmetries, will lead to larger deviations.

Scrap barrel with hidden plutonium sphere

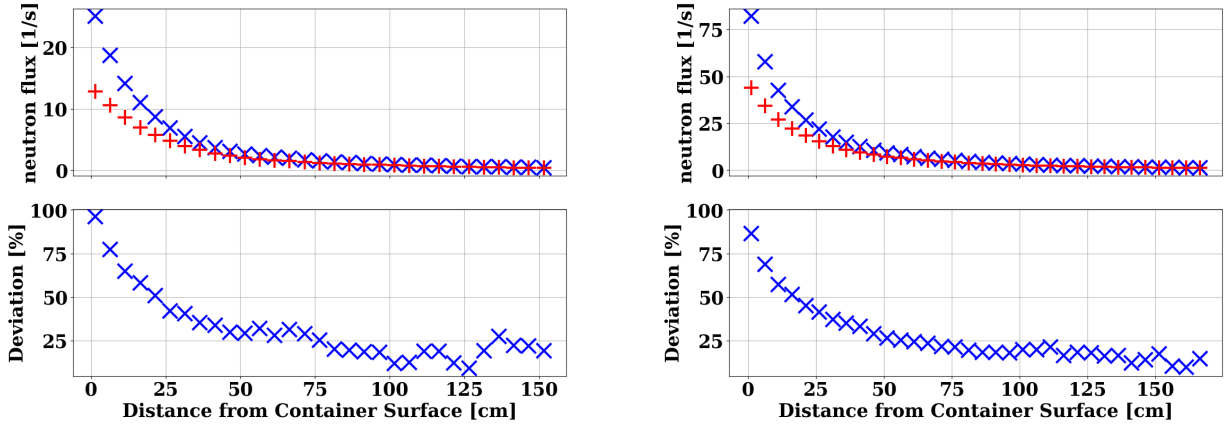
In a more complex scenario, 50 g plutonium are hidden inside a scrap barrel. As the scrap contains metals and plastic, neutrons are scattered before they leave the barrel. As this geometry differs considerably from the bare plutonium sphere, our method of calculating the detector signal has to be validated for this scenario. Again, two different voxel grids of $1\times1\times1\,\mathrm{cm}^3$ and $20\times10\times1\,\mathrm{cm}^3$ have been compared. The results are shown in fig. 6.

The neutrons can leave the barrel at two different surfaces: the top (symmetric to the bottom surface) and the lateral surface. These have different distances from the plutonium sphere located at the center of the barrel, therefore they will be looked at separately.

Outside the barrel, the reconstruction of the detector signal gives good results. For distances greater than 1 m from the barrel wall, the deviation is less than 20 % at the top side. At the lateral side the deviation drops faster and the deviation at 75 cm from the barrel wall is approx. 20 %. This deviation is acceptable for our application.

IMPLEMENTATION IN UNITY

The virtual reality is developed using the VR engine Unity. To calculate the neutron flux in a detector in the virtual reality, the radiation data has to be fed into the virtual reality environment. Therefore, the csv-file is read and the values are saved in a 3d-texture. It allows faster loading times and better performance compared to arrays. The radiation data is partitioned into bits and saved as 4×8 bits into the color channels of the texture starting with the transparency channel. A 3d-texture can be displayed in the VR engine which allows for easy checking whether the radiation field is placed in the correct location by mapping the texture to a cubic volume. As an example, the radiation field of a plutonium



(a) Top surface. The detector center lies at the extension of the barrel main axis.

(b) Lateral surface. The detector center is at the same hight as the plutonium.

Figure 6: Validation of detector signal using a voxel grid when plutonium is hidden inside the scrap barrel. Shown are the voxel sizes of $1\times1\times1$ (crosses) and $20\times10\times1\,\mathrm{cm}^3$ (plus signs). The deviation is calculated as $\frac{\mathrm{flux}(1\times1\times1)-\mathrm{flux}(20\times10\times1)}{\mathrm{flux}(20\times10\times1)}$.

containing scrap barrel is shown in fig. 7.

The detector signal is calculated from the data in the texture. Therefore, the area of the detector which is perpendicular to the connecting line between the radiation source and the detector center is identified. This projection of the detector volume to an active area allows for rotations of the detector, even if the detector boundaries do not coincide with the edges of the voxels. The voxels which belong to the tagged area are identified and their neutron fluxes are summed up.

Geometrical corrections

As described before, its sum over the voxels is in general higher than the correct neutron flux. There are two effects which can be corrected: the effective area of a voxel and the multiple counting.

If the connecting line between the radiation source and a voxel is parallel to the edge of the voxel, the area facing the source is a surface area of the cube. But if the voxel is translocated, no surface area faces the source. A projection of the voxel volume to an area which is perpendicular to the connecting line has to be used as effective area of the voxel. The maximum of this projection has an area of $\sqrt{3}\,\mathrm{cm}^3$. This correction factor which lies in the interval $\left[1,\sqrt{3}\right]$ is calculated for every voxel and used as a weight in the sum over the voxels.

Multiple counting occurs if the same neutron traverses more than one voxel and is therefore counted in every voxel it passed (cf. fig. 2). To correct for this, one has to calculate the probability that a neutron is counted repeatedly. The probability function which has to be integrated becomes complex in three dimensions. A good approximation is given by the average angle of the neutrons to the line of sight between the radiation source and the detector center.

Both correction factors are shown in fig. 8 if the detector is placed and moved along an axis parallel to the edges of the voxels and the connecting line between the radiation source and the detector center is perpendicular to the detector surface.

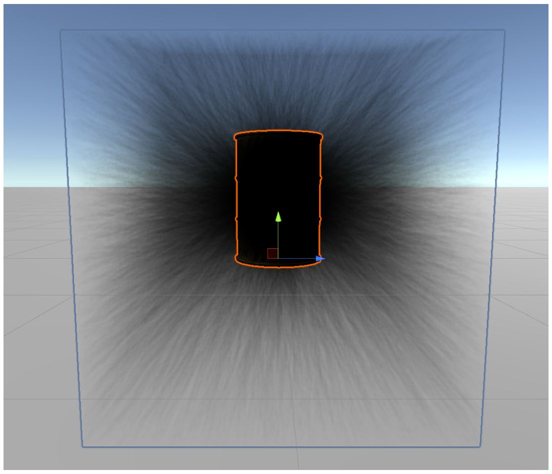


Figure 7: Display of the radiation field of a scrap barrel with hidden plutonium in Unity. 100 000 neutrons have been simulated.

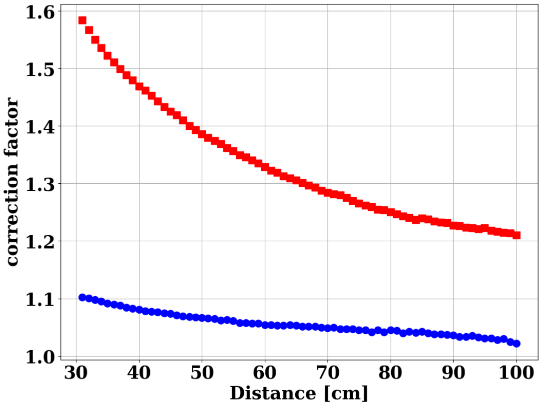


Figure 8: Correction factors for (average) effective area (blue circles) and multiple counting (red squares) for a detectors placed at an axis.

Validation

To validate the calculation of the detector signal in Unity, the VR-calculated neutron fluxes are compared to the ones obtained in GEANT4. This is done for a passive measurement of a scrap barrel with hidden plutonium and for three different detector movements: (1) the detector is held at fixed height and moved towards the barrel, (2) it is moved vertically at fixed distance and (3) it is held at a fixed height and distance and moved around the barrel while the detector rotates so its active area faces the barrel at all positions. The validation for all three cases is shown in fig. 9.

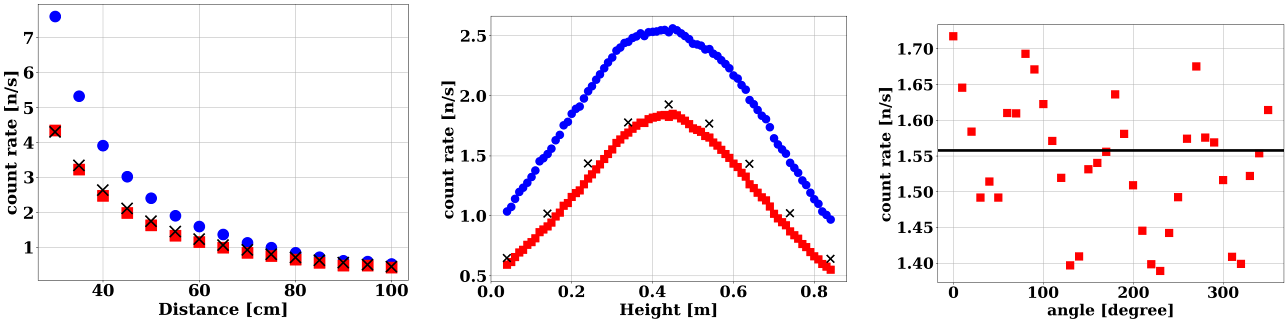
As fig. 9a and 9b indicate, after corrections the Unity data does correspond well to the values from GEANT4 and only small deviations up to 15 % occur.

The rotation of the detector around the barrel (fig. 9c) shows another problem: one can see periodical deviations, which are caused by the mismatch between the detector edges and the voxel edges. After the correction the maxima lie at the angle at which the two edges match (0°, 90° etc.). However, the deviations from the GEANT4 data are small (up to 10 %) and can be accepted in our case.

CONCLUSION AND OUTLOOK

We are developing a virtual reality environment in which nuclear disarmament verification procedures can be tested and trained and which can be used as addition to physical exercises like the NuDiVe exercise. To relocate these exercises to virtual reality, the measurement processes, in particular the detection of the nuclear materials, have to be implemented correctly. It has been shown that the use of voxel based radiation fields pre-generated in GEANT4 is effective. To calculate the detector signal, two correction factors for the voxel sum are needed: (1) the effective area of a voxel facing the radiation source has to be used as weight and (2) the multiple counting has to be considered. Therewith sufficient accuracy for the nuclear disarmament verification virtual reality is achievable.

In the next steps the implementation of other objects in the room and different scenarios is planned.



(a) Horizontal movement of detector.

(b) Vertical movement of detector.

(c) Rotation of detector around barral.

Figure 9: Validation of detector signal calculated in the virtual reality environment. Given are the raw data (circles) and the corrected data (squares) from Unity as well as the data from GEANT4 (crosses, black line).

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