NUCLEAR INSPECTIONS IN THE MATRIX: VIRTUAL REALITY FOR THE DEVELOPMENT OF INSPECTION APPROACHES IN NEW FACILITY TYPES

M. KÜTT
Princeton University
Princeton, NJ, USA
Email: kuett@princeton.edu

A. GLASER
Princeton University
Princeton, NJ, USA

T. PATTON
Princeton University
Princeton, NJ, USA

M. GÖTTSCHE
RWTH Aachen University
Aachen, Germany

Abstract

Virtual reality (VR) environments have been successfully used to support a variety of applications relevant to nuclear safeguards, safety, and security, including IAEA inspector training, dose estimates for personnel, and facility evacuation planning. There are two particularly relevant challenges for VR: first, simulating the functionalities of the radiation detection equipment that an inspector might use, ideally in real-time; and, second, enabling interactions with virtual equipment so that the experience becomes truly immersive and meaningful. In this paper, we report results from the use of multiplayer VR applications in simple inspection exercises. The VR applications include a number of functional replicas of inspection devices, and a two-layered radiation simulation. The simple layer is used to estimate realistic count rates in Geiger and neutron counters. The complex layer uses a hybrid approach combining pre-computed radiation signatures and detector response functions, based on MCNP Monte Carlo simulations combined with deterministic methods to handle shielding and attenuation effects. This will allow the movement of sources, detectors, and shielding materials during exercises.

We make a case for exploring the further potential of VR environments to support innovations in developing facility architectures, nuclear safeguards and verification protocols for treaties that do not yet exist (such as an FMCT); and for future tasks such as establishing verification measures related to weapon-origin fissile materials (as envisaged for material declared excess for weapon purposes), the application of safeguards to former weapons-related facilities or materials, and verification protocols verifying the absence of treaty accountable items or materials. Virtual environments, in particular, could make critical contributions to the development of effective inspection protocols without running the risk of exposing proliferation-sensitive or classified information, which would be a plausible concern in inspection trials in physical facilities. Virtual environments can also offer levels of accessibility and flexibility typically much more difficult to achieve in actual facilities, and they can allow for more substantial collaboration amongst research groups and governments working to find solutions to existing verification challenges.

1. INTRODUCTION

Recent years have seen rapid developments in virtual and augmented reality, with a transition from a niche technology to readily available commercial products and an active community of developers. Virtual reality (VR) offers new pathways to address existing safeguards challenges and to develop state-of-the-art approaches for both current and future verification protocols. VR allows experts from governments, international organizations including the International Atomic Energy Agency, think tanks, and academia to experience multiparty interaction in realistic environments, including virtual visits to existing and planned facilities, and hands-on use of verification equipment. Experience gained in VR can be the basis for live exercises and new policy initiatives.

VR exercises can be planned and carried out remotely, avoiding the difficulties of foreign-personnel visits to high-security sites and the risks of inadvertent disclosure of sensitive information. New collaborations become possible even under difficult political circumstances, enabling confidence-building measures that would be challenging without VR application.

Virtual reality has been used in this field for more than fifteen years [1]. Typical applications are training and operation planning including training of plant security staff, plant operators, and other personnel [2, 3, 4, 5]. VR has also been used to plan decommissioning operations [1, 6, 7]. The possible role of virtual environments to support the development and application of nuclear safeguards has also been recognized [8, 9]. Previous work has often included virtual radiation fields or functions to estimate dose rates in the environment. Most of these implementations are static and rely on stochastic or deterministic simulations or interpolated measurements that overlay a radiation map onto a predefined and non-changing virtual environment. While this allows quick estimates of radiation doses for individual avatar trajectories, it is not suitable for simulations where the source-detector configuration can be varied in a non-predetermined manner during an exercise.

2. INSPECTION PROTOCOL DEVELOPMENT IN VIRTUAL REALITY

Inspection protocols determine the interactions between host and inspecting parties, reflect the design of relevant facilities, and describe the use of necessary equipment. Protocols are required for a variety of existing and future verification tasks. These tasks include inspections of facilities offered for IAEA safeguards, application of safeguards to former weapons-related facilities or materials as part of Voluntary Offer Agreements, and confirmation of the absence of treaty-accountable items or materials (for example, as part of complementary access under the Additional Protocol). Protocol development tasks also include those related to future efforts such as an FMCT, the elimination of weapons from a state or region, and other disarmament measures.

VR environments and exercises provide new, innovative, and effective ways to prototype, test, and improve inspection protocols for all of these verification tasks. Layout and architecture of planned or proposed facilities can benefit from VR exercises during design stages. Changes to the environment can be made easily, and repetitions of exercises can be precisely controlled and are not restricted by facility access. Inspection protocols can be optimized for efficiency to meet potential resource constraints of both parties. They can be tested without risk, ensuring the inspecting party of a protocol's effectiveness and the host party of the agreed limits on intrusiveness.

The full-motion virtual environment developed for this project is based on the *Unity* game engine, which offers extensive support for VR. We use two sets of the *HTC Vive Pro* head-mounted displays and tracking stations. The application itself consists of a server and a client component. The server is responsible for distributing data and events between different clients and for setting up the initial configuration of the virtual world. It can also be used by an external person (i.e., the "game master") to control the inspection experience and trigger events that may or may not be expected by the players. The client is executed in separate instances for each active headset in the environment. The client connects to the server, receives and sends data and events, renders the current view of the world for a single participant, and records this participant's control actions. Communication among players is possible using the *HTC Vive Pro*'s built-in microphone and headphones. A third-party software (*Discord*) enables real-time audio communication over network connections.

The reference virtual world highlighted in this article is designed primarily to examine arms-control verification measures, but it also includes tasks relevant to safeguards such as verifying the absence of nuclear material. It consists of a set of three different larger sites: A naval base, a dismantlement site, and a disposition site. Each of these sites includes multiple buildings that would be relevant to an inspection. The naval base includes a submarine bay with an adjacent inspection room, as well as three storage bunkers that can be used for various purposes. The dismantlement site has a warhead storage bunker, a large dismantlement facility, and a pit storage bunker. The disposition site has a pit storage bunker, a decommissioning facility, and a fissile material storage bunker. Each site also includes a briefing room, which is used as a neutral ground for discussions among participants. This space can also be used to familiarize new participants with the VR controls.

In each instance of a virtual environment, it is possible to distribute a predefined set of treaty accountable items, including warheads, pits, and non-nuclear components. The distribution of these items is organized via so-called "World Settings" in an XML-file, which is read upon launch of the environment. During an exercise, these settings cannot be modified. While objects can be moved, containerized, and dismantled during the exercise, it is not possible to remove them or add additional treaty accountable items. This paradigm increases realism as the inspection environment does not change in unrealistic ways, and it ensures that objects are not accidentally created or deleted during an exercise.

Besides treaty accountable items, various types of inspection equipment are available during the exercise. Using a specific menu, the host can add equipment whenever needed. In the arms-control setting discussed here, the inspector can see the host's menu but is not able to select equipment directly; instead, the host can hand over the equipment to the inspector. Through a modular program design, additional objects and functionalities can be easily added. As an example, Figure 1 shows the information barrier experimental (IBX), a functional information barrier for gamma spectroscopy-based item comparison. This virtual instrument is based on a functional, physical prototype that was also developed by the authors [10].

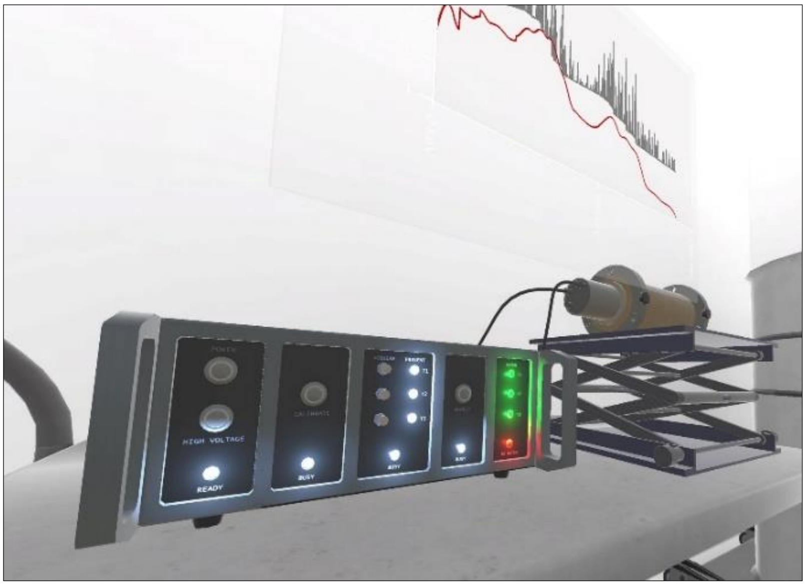

FIG. 1. Information Barrier Experimental and simulated spectrum.

So-called buddy tags are another example of a verification technology that can be added to an inspection in VR. Buddy tags are tokens that are physically separate from the treaty accountable item, but the host must be able to produce one tag for each item without delay. They are devices highly sensitive to motion and would be activated shortly before random inspections. If moved during an agreed stand-down period (i.e., during the time between an inspection is called and the inspectors arrive at the site), buddy tags would reveal such movement. Inspectors would expect to find same number of tags and treaty accountable items upon inspection of the site. The concept was first proposed by Sandia National Laboratories in the early 1990s, and work on an advanced buddy tag has recently resumed as part of a new development effort [11].

The virtual environment currently contains several other functioning pieces of equipment. These include two versions of portal monitors, which can be snapped to doors and visually indicate the transport of radioactive objects through the detector volume. Functional CCTV cameras can be used to record video from a simulation. This video is stored on the client computer for post-simulation review. The environment also includes two different handheld counters: a Geiger counter and a neutron counter. They both display the strength of radiation transmitted to a counter's position. They can be used by both the host and inspector avatars.

Interactions with both equipment and treaty accountable items are possible through menus, which are specific to each object. Objects can be moved around in a room and sent or escorted to different locations. Treaty accountable items come with the options to containerize, dismantle, or convert pits into fissile material. Specific objects like the IBX and the cameras have unique menu options to record gamma spectra or start recording of video. Other objects give feedback depending on events in the simulation. Portal monitors alert inspectors of the transport of a radioactive source, and Geiger and neutron counters show radiation levels depending on the sources present in the room and the distance to the counters. Counters can be handed over from host to inspector, so that inspectors can independently verify presence (or absence) of radiation. Figure 2 shows typical menus and an ongoing radiation measurement in the VR environment.

Based on the simulated facilities and equipment it is possible to simulate a large number of inspection protocols. In the following, three simple scenarios are briefly discussed. All of them are from the arms-control context and have been successfully simulated with the current VR setup.

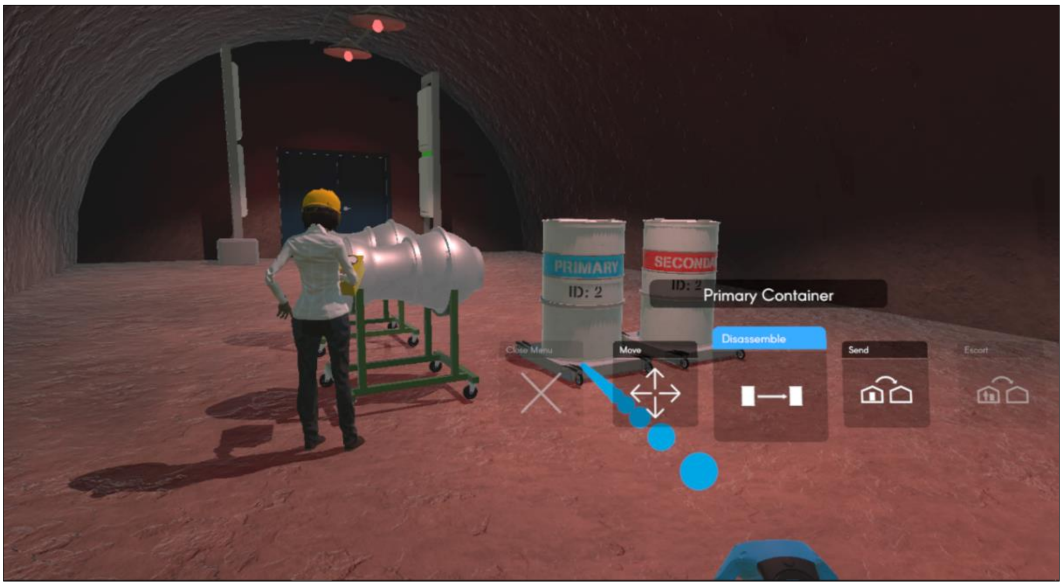

FIG. 2. Scene from a virtual inspection. On the left, an inspector measures radiation from an item using a Geiger counter. On the right, the host views the menu of options for a container holding a primary pit. A large portal monitor surrounds the bunker door in the background.

2.1. Verifying the absence of nuclear material

As part of safeguards and complementary access inspections under the Additional Protocol, as well as for possible future arms-control or disarmament measures, inspectors may have to confirm the absence of nuclear material or weapons at a given site. Depending on the nature of the facility, inspections may not be easy to carry out, as parts of a site could be off limits to inspectors due to the presence of sensitive items that are beyond the scope of a treaty. In most circumstances, inspectors will have available radiation detection equipment and can survey a facility for relevant radiation signatures. They have to take into account background radiation and, due to time constraints, may not be able to visit all parts of a facility. In our VR environment, inspectors can use Geiger or neutron counters and search rooms for radiation sources. Rooms can be populated with additional (decoy) objects, for example, empty warhead containers. This setup can be used to determine the level of confidence that inspectors report after a time-limited walkthrough. It also provides the ability to test an inspector’s response to possible cheating scenarios involving, for example, a hidden source and a host who tries to lead the inspector away from this source.

2.2. Denuclearization of the Democratic People’s Republic of North Korea (DPRK)

An important first step for a possible denuclearization of the DPRK would be to ensure that the country’s warheads are stored separate from delivery systems while awaiting dismantlement. There are several options to implement this using existing verification technologies. In the prepared VR scenario, a small number of thermonuclear weapons are stored in a bunker. Both host and inspector can navigate to this bunker. The inspector can verify that the weapons contain radioactive material using a Geiger and/or a neutron counter (Figure 2). If desired, they can request the host to containerize the weapons. Then, for example, the host can deploy a portal monitor at the entry door of the bunker and install cameras at opposing walls. The inspector can watch the host adjusting the field of view and start the recording, possibly including other live video authentication measures. After the demonstration is finished, both users can review the recording.

2.3. “Get the Golden Warhead”

Warhead confirmation measurements and the verified dismantlement of nuclear warheads are among the most difficult verification challenges. Typically, the inspecting party has limited information and limited access to the dismantlement facility, as well as little knowledge about the weapon itself. One approach to confirm warhead authenticity under these circumstances is based on comparing the radiation signatures from different objects. Such a comparison requires at least one item for which the inspecting party has high confidence that it is a nuclear weapon (“golden warhead”); it also requires a trusted device to carry out the comparison. The following scenario has been proposed as one way to introduce such a reference item in the verification process. In this scenario, the host takes the inspector to a notional naval base. At a submarine bay of the naval base the host is prepared to unload an inspector-chosen missile off the submarine. The unloading is shown as a short, animated sequence in VR. The inspector’s task is then to maintain continuity-of-knowledge on the missile through measures such as visual observation and by inspecting areas where it is being transported beforehand. After the warhead bus is removed from the missile, the inspector can choose one of the warheads to be containerized without direct visual access. The host carries out actions as requested and seals the container under the inspector's supervision. The inspector should now have high confidence that the particular container holds an actual nuclear warhead.

3. RADIATION MODELLING IN VR

Inspections of nuclear materials for safeguards and arms-control purposes have a unique feature: they involve radioactive materials, and many instruments used for inspection can rely on the gamma and neutron signatures from these materials. It is therefore natural to include a simulation of such signatures in the virtual reality model, which requires both an adequate model of radioactive sources (for example, fissile material in its various forms found throughout the fuel cycle, as well as assembled warheads) and ways to simulate shielding and scattering phenomena in the virtual environment. Depending on the verification technology, the relative strength and the energy distribution of the emitted particles are the main characteristics of a radiation signature. To simulate these two components, our VR environment provides two layers of programming, reflecting the differences in computational complexity.

The basic layer characterizes radioactive sources by their signal strength only. Portal monitors will automatically detect when such an object is transported through the detection volume. Geiger and neutron counters receive a signal accumulated from all sources in a room. The signal is attenuated based on the distance of these sources to the detector using a simple $1/r^2$ law. No attenuation due to shielding is implemented for this layer. Detectors give visual feedback through movement of a detector needle or a numerical display. The Geiger counter also has an audible feedback, clicking with a frequency proportional to the source intensity. The basic model allows for updating the measured value for each rendered frame.

The complex layer uses dynamic deterministic calculations of the dose rate using a classical formula that treats direct radiation from the source as a collection of rays originating from one or more radiation sources and reaching a point of interest, for example, the location of a radiation detector. Here, we use the ray-casting methods to determine the uncollided flux. In this case, the count rate C observed at the detector location can be approximated by the point-kernel method:

$$C(E_j) = C_j \approx \sum_i S_{i,j} \, \frac{1}{4\pi r_i^2} \, \exp\big(-\sum_k \mu_{k,j} \, d_{k,i}\big)$$

In this equation, $S_{i,j}$ is the relative strength of source i at energy j, $\mu_{k,j}$ is the linear attenuation coefficient for material k at energy j, and $d_{k,i}$ is the thickness of material k as seen by source i in the direction of the detector. The intensity drops with the source-detector distance $1/r_i^2$, while the attenuation of the beam in the media due to absorption and scattering appears in the exponential term [12], [13].

In preparation for our VR simulations, we performed extensive Monte Carlo calculations with MCNP6 to determine the gamma flux and produce a high-resolution gamma spectrum for each radiation source to be modelled in the virtual environment. Figure 3 shows such a spectrum for a solid five-kilogram ball of weapon-grade plutonium.

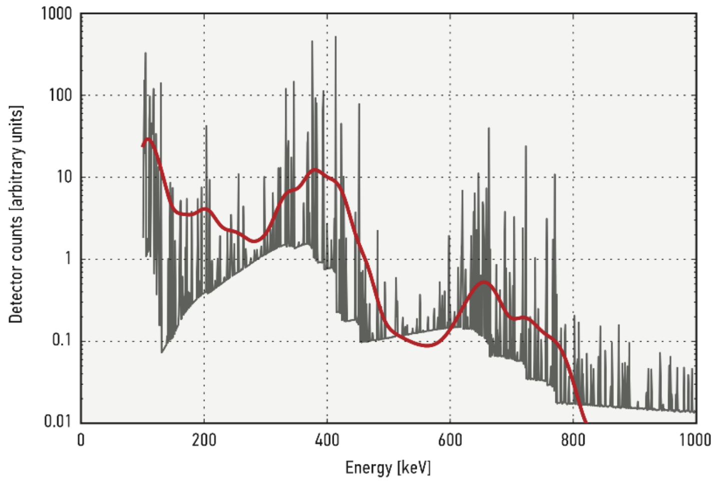

FIG. 3. High-resolution gamma source term (gray) and simulated spectrum acquired with a sodium-iodide detector (red) for a solid five-kilogram ball of weapon-grade plutonium

Ray-casting techniques are then used to determine the uncollided flux at the detector location, using appropriate attenuation coefficients for all intervening objects and materials. At the detector location, the detector response is determined using the response matrix for the detector type of interest, which is used to produce the detected spectrum. This matrix, too, needs to be pre-computed with MCNP6 calculations and takes into account detector geometry, efficiency, and energy-dependent resolution. Specifically, each row of the matrix corresponds to the measured gamma spectrum for mono-energetic radiation, so one row corresponds to one MCNP6 simulation of a specific incoming energy. In our current environment, we use a matrix for sodium-iodide (NaI) detectors, but any type of detector can be added to the library. Figure 3 shows a simulated spectrum acquired with a typical sodium-iodide detector. As part of a demonstration, users in the VR environment can pick up shielding materials (iron or lead plates) and observe the impact of these materials in real-time when they are placed in front of the detector.

4. EXPERIENCE FROM LIVE EXERCISES

The VR setup was continuously tested internally. During the development, two exercises have been carried out involving Princeton University undergraduate students, and we demonstrated the setup to a larger audience of diplomats and other personnel at the United Nations in Geneva.

The first student exercise was carried out in 2017, using an early version of our VR environment with a limited set of equipment and a small number of facilities. Students were provided with a fictional, bilateral arms-control agreement and a detailed inspection scenario. Students, entering the environment two-at-a-time, assumed the role of either a host or an inspector and performed an accounting inspection as part of this treaty. The inspection scenario involved the use of buddy tags.

In the exercise, the scenario specified that the inspecting country had given notice for an onsite inspection at a warhead storage facility in the host country. Upon receiving notice, the host country was to activate all buddy tags at the facility. In VR, host and inspector would visit a room where buddy tags for a notional site where stored. Inspectors could then visit actual warhead storage sites (Bunker A, B, or C) and compare number of stored warheads to number of buddy tags. Also, individual items could be authenticated using the IBX.

A valuable element of the virtual environment is the ability to easily introduce challenges into the scenario to test the strength of the inspection protocol. The virtual inspection therefore incorporated randomized challenges, including a disturbed buddy tag with a red light and extra warheads in one of the bunkers. Students dealt with these challenges within the boundaries of the inspection protocol, with some initial patterns emerging in their behavior. For example, the red (alerted) buddy was placed in a shelf marked “Bunker A.” Students showed a high tendency to select Bunker A for the randomized inspection, even though the tag could have been “nudged” (i.e., turning it red) to throw off an inspector from a different bunker in which the host was cheating. This type of observed behavior could be more rigorously tested in future.

The second exercise was conducted in April 2018, using the full version of the environment described above. This time, students were given a fictional scenario in which they were inspection teams from five nuclear weapon states that had decided to join the Treaty on the Prohibition of Nuclear Weapons. As part of the process of eliminating their nuclear arsenals, countries would carry out bilateral inspection visits. These visits were simulated in virtual reality. One goal of this exercise was to test the possibility of quickly adjusting the simulated world based on a variety of different inspection protocols. To achieve this goal, students negotiated protocols adjusted to the situation and interests of their respective country, including a declaration of the number of warheads to be dismantled. Inspection protocols could make use of all inspection equipment that the application provided. Prior to the inspection in VR, unique world setups were created, one per inspection protocol, including the necessary equipment and the required number of treaty accountable items. In addition to specifying the number of items globally, it is also possible to save the current status of an inspection and to resume the exercise later. This function was used to prepare and load the equipment. The inspection protocols developed by the students used information barriers, buddy tags, cameras, and Geiger and neutron counters. One group of students proposed a setup where the country tried to fool inspectors by hiding a single warhead in a set of containers declared to be empty. Although the inspectors had Geiger counters available, the violation was not caught during the actual inspection.

In May 2018, we brought a setup of two VR environments to Geneva and demonstrated it in the Palais des Nations where diplomats and other experts in disarmament verification were able to experience the environments. Because of the limited time each user would have in VR, predefined inspection scenarios were demonstrated by an experienced user taking the role of the host. The inspection scenarios included the inspection of nuclear warheads using an information barrier and a demonstration of possible monitoring options to be used during a DPRK denuclearization.

All exercises succeeded in their objectives to design and implement tailored verification protocols. Participants quickly became acquainted with the use of the VR headset and accompanying controllers. Although no formalized way of assessing participants' impressions has been used so far, users seemed to immerse into the exercise and could quickly assume the role of inspector or host in each case. Currently, we plan to hold future exercises and demonstrations with international audiences. As the setup is portable and offers remote connectivity, activities with multiple partners should be easily possible.

5. CONCLUSION

Given current uncertainty surrounding both near-term and long-term measures in arms control, the design of verification approaches and managed access measures must be pursued with innovation and flexibility. States will eventually need to reach compromises in terms of balancing transparency and security, and each may have different views on the feasibility of various options. This situation can be improved by having a greater number of viable options available. Virtual reality, enhanced by full-motion capabilities and multiplayer networking, provides a flexible and powerful new way to extend the research community's ability to examine larger numbers of options and technology combinations for verification approaches. When combined with other toolsets, such as the Nu mapping approach (verification.nu), design and evaluation can comprehensively take place at both broad and detailed levels. Virtual environments in particular can offer levels of accessibility typically much more difficult to achieve in actual facilities due to security concerns, transportation of equipment, costs, and travel constraints. Accordingly, networked VR can allow for more substantial collaboration amongst research groups and governments working to find solutions to existing verification challenges. They provide a cost-effective way to test complex inspection protocols prior to real world exercises or actual inspections.

The development steps described here include operationalizing virtual equipment with simulated radiation, multiplayer capabilities, and a set of facilities and equipment that is large enough for numerous meaningful exercises. Student exercises and other demonstrations showed that it is easy to use, and adjustments for different inspection protocols can be made quickly. While our examples were taken from an arms-control context, similar exercises can involve more traditional IAEA inspections. Future development efforts for the system will include expanding the array of equipment and facilities, as well as further optimization of the simulation layers for radiation. In upcoming exercises and demonstrations, we aim to present, but also further improve, ways that VR can serve as a new space and new opportunity for policy development for technical and institutional engagement on nuclear safeguards, arms control, and disarmament.

ACKNOWLEDGEMENTS

The research presented in this article has been funded by a grant by the John D. and Catherine T. MacArthur Foundation, G-1703-151718, which also establishes our ongoing partnership with Games for Change (gamesforchange.org). Additional work has been made possible through DOE/NNSA's Consortium for Verification Technology, DE-NA 0002534. The authors wish to thank PHL Collective (phlcollective.com), Drew Wallace, and Luke Petruzzi for their development work. Special thanks also go to the class of WWS/MAE 353 for their contributions to the inspection exercise in April 2018 and to UNIDIR for making possible the demonstration in Geneva in May 2018.

REFERENCES

[1] RINDAHL, G., JOHNSEN, T., ØWRE, F., IGUCHI, Y., "Virtual reality technology for and nuclear decommissioning" (International Conference on Safe Decommissioning for Nuclear Activities, Berlin, Germany, 2003).

[2] AUGUSTO, S.C., MOL, A. C. A., MOL, P. C., SALES, D. S., "Using virtual reality in the training of security staff and evaluation of physical protection barriers in nuclear facilities", (2009 International Nuclear Atlantic Conference, Rio de Janeiro, Brazil, 2009).

[3] KRIZ, Z., PROCHASKA, R., MORROW, C.A., VASQUEZ, C., WU, H., RIZWAN-UDDIN, "Unreal III Based 3-D Virtual Models for Training at Nuclear Power Plants", (International Nuclear and Renewable Energy Conference, Amman, Jordan, 2010).

[4] DING, A., ZHANG, D., XU, X.G., Training software using virtual-reality technology and pre-calculated effective dose data, Health Physics, **96** 5 (2009) 549-601.

[5] HANAI, T., YAMAGUCHI, Y., "Development of a Virtual Reality System for Training in Nuclear Security", Integrated Support Center for Nuclear Nonproliferation and Nuclear Security (ISCN), Japan Atomic Energy Agency (JAEA), Tokai-mura, Ibaraki, Japan, 2013.

[6] CHABAL, C., SOULABAILLE, Y., "Virtual reality: a way to prepare and optimize operations in decommissioning projects", (PREDEC 2016, Lyon, France, 2016).

[7] LI, M.-K., LIU, Y.-K., PENG, M.-J., XIE, C.-L., YANG, L.-Q., A fast simulation method for radiation maps using interpolation in a virtual environment, Journal of Radiological Protection **38** 3 (2018) 892-907.

[8] GONÇALVES, J.G.M., MOLTÓ-CARACENA, T., SEQUEIRA, V., VENDRELL-VIDAL, E. "Virtual reality based system for nuclear safeguards applications", (IAEA Safeguards Symposium, Vienna, 2010), IAEA-CN-184/233.

[9] TACKENTIEN, J.K., "Virtual Reality Developments for the International Atomic Energy (Member States Support Programs Supporting the International Atomic Energy Agency)", (54th Annual Meeting of the Institute of Nuclear Materials Management, Palm Desert, CA, USA, 2013), BNL-100634-2013-CP.

[10] KÜTT, M., GÖTTSCHE, M., GLASER, A., Information barrier experimental: Toward a trusted and open-source computing platform for nuclear warhead verification, Measurement **114** 1 (2018), 185-190.

[11] JORDAN, S.E., "Buddy Tag's Motion Sensing and Analysis Subsystem", Sandia National Laboratories, Albuquerque, New Mexico, 1991.

[12] INGERSOLL, D., User's Manual for PUTZ: A Point-Kernel Photon Shielding Code, Oak Ridge National Laboratory, ORNL/TM-9803, 1986.

[13] CARACENA, T.M., GONÇALVES, J.G.M., PEERANI, P., VENDRELL VIDALL, E., A variable point kernel dosimetry method for virtual reality simulation applications in nuclear safeguards and security, IEEE Transactions on Nuclear Science, **60** 5 (2013) 3862–3871.