Nuclear Inspections in the Matrix

Working with Radiation Detectors in Virtual Reality

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ABSTRACT. Virtual 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. We have recently begun to explore the potential of virtual reality (VR) to support innovations in nuclear arms control, in particular, the role it could play in developing facility architectures and verification protocols for treaties that do not yet exist. For most of these applications, there are two particularly relevant challenges: first, simulating the functionalities of the radiation detection equipment that an inspector might use, ideally in real-time; and, second, enabling interactions with this virtual equipment so that the experience becomes truly immersive and meaningful. In this paper, we discuss the respective developments made for our VR system. To illustrate these features, we report results from a simple inspection exercise that involved two players (host and inspectors) with co-presence using two HTC Vive kits. In the default scenario, a number of storage containers contained nuclear components with characteristic radiation signatures, and the task of the inspector was to confirm the authenticity of these components using a gamma (sodium-iodide) detector behind an information barrier. To model real-time radiation fields in VR, we use a hybrid approach combining precomputed radiation signatures and detector response functions based on MCNP Monte Carlo simulations combined with deterministic methods to handle shielding and attenuation effects allowing the movements of sources, detectors, and shielding materials during the exercise.

1. Background

Twenty-five years after the end of the Cold War, there are still more than 15,000 nuclear warheads in the arsenals of the weapon states. Similarly, while Cold War peak stockpiles of military fissile materials have fallen, the military material available for weapon purposes today is still sufficient for more than 200,000 weapons. Warhead dismantlement programs and fissile-material elimination are proceeding very slowly, and some are stalled, suggesting these stockpiles will continue to exist for many decades unless something changes. At the end of the Cold War, cooperative approaches to nuclear security and verification were widely recognized as key to building confidence and addressing technical obstacles vis-a-vis future arms-control and disarmament measures. However, these programs have all ended, and cooperation on nuclear-weapon issues continues only on a very small scale between certain interested parties. New approaches are needed to revitalize nuclear security and arms-control initiatives at the government level. This paper presents initial results of a project that uses immersive virtual reality (VR) to enable new collaborations, especially at the government-to-government expert level, going beyond the traditional exchange of ideas at conferences and workshops.

Virtual reality is an emerging technology that offers an exciting new pathway to support experts and governments in developing a shared, hands-on understanding of the challenges involved in nuclear security and verification. VR offers a means to interact in flexible and realistic environments, allowing parties to safely explore new concepts and approaches and build confidence, laying a basis both for live exercises and for new policy initiatives. Further, VR exercises can be planned and carried out remotely, avoiding the difficulties of allowing foreign personnel into sensitive high-security sites and the risks of inadvertent disclosure of sensitive information. As such, VR offers opportunities for collaboration even under politically difficult circumstances. It offers, in particular, a way to overcome some of the confidence-building challenges that may hinder direct cooperation between countries on how to approach nuclear-weapon and fissile-material monitoring. For example, joint security and verification exercises between the United States and the United Kingdom already take place, but such exercises would be challenging for the United States and China where issues of confidence, access and classification would be central. Access and classification also limit opportunities for physical collaboration between academic programs and national laboratories in all nuclear weapon states.

These goals and objectives for the virtual environments require several distinct development efforts conducted and coordinated in parallel. Broadly speaking, these include the development of virtual radiation to enhance the realism and utility of the environments, development of the interactivity and networking features of the environment, and development of frameworks and protocols for inspection exercise implementation and evaluation. The following sections detail each of these three ongoing work streams and provides an update on our previous work in this area.[1]

2. Acquiring Gamma Spectra in Virtual Reality

Nuclear facilities are unique because they involve radioactive materials in a variety of ways. The radiation signatures of these materials are relevant for many aspects of nuclear verification, and it is therefore important to include radiation in our models. Extensive work has previously been done on including radiation fields into virtual facilities to obtain accurate dose information for training and planning applications.[2,3,4] Most of these implementations are static and rely on stochastic or deterministic simulations that overlay a radiation map onto a predefined and non-changing virtual environment. This provides dose-rate information at fixed points on an invisible grid filling the modeled three-dimensional space. The static nature of the radiation map disqualifies this method, however, from being used in simulations where the source-detector configuration varies in a non-predetermined manner during the simulation.

An alternative method, and the one used in our implementation, 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 most basic implementation that determines the uncollided flux using a ray-casting method. In this case, the count rate C observed at the detector location can be approximated by:

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

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 media due to absorption and scattering appears in the exponential term. This approach is more commonly known as the point-kernel method and can be implemented assuming a point-source or multipoint-source approximation.[5,6] In preparation for our VR simulations, we perform extensive Monte Carlo MCNP calculations to determine the gamma flux and infinite-resolution gamma spectrum emerging from each radiation source to be modeled in the virtual environment. Figure 1 shows such an infinite-resolution spectrum for a solid five-kilogram ball of weapon-grade plutonium. These reference spectra are added to a library.

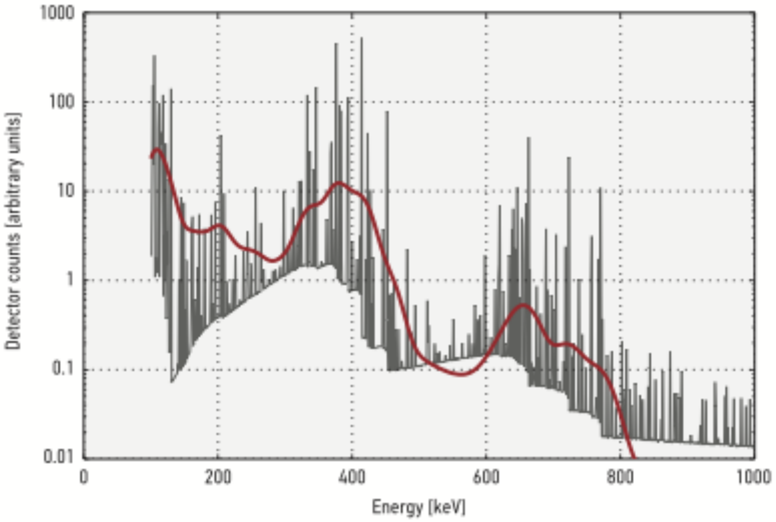


Figure 1. Infinite-resolution gamma source term (gray) and simulated spectrum acquired with a sodium-iodide detector (red) for a solid five-kilogram ball of weapon-grade plutonium. The infinite-resolution source term is pre-computed once with MCNP and added to a library of known radiation sources. Ray-casting techniques are used to determine the uncollided flux at the detector location, where it is convoluted with the detector-response matrix, which is also pre-computed with MCNP for each detector type of interest.

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 (Figure 2). 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 is pre-computed with MCNP 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 MCNP simulation of a specific incoming energy. Our library includes matrices for high-purity germanium (HPGe), lanthanum-bromide ($LaBr_3$), and sodium-iodide (NaI) detectors, but any type of detector can be added to the library. Figure 1 shows a simulated spectrum acquired with a typical sodium-iodide detector.

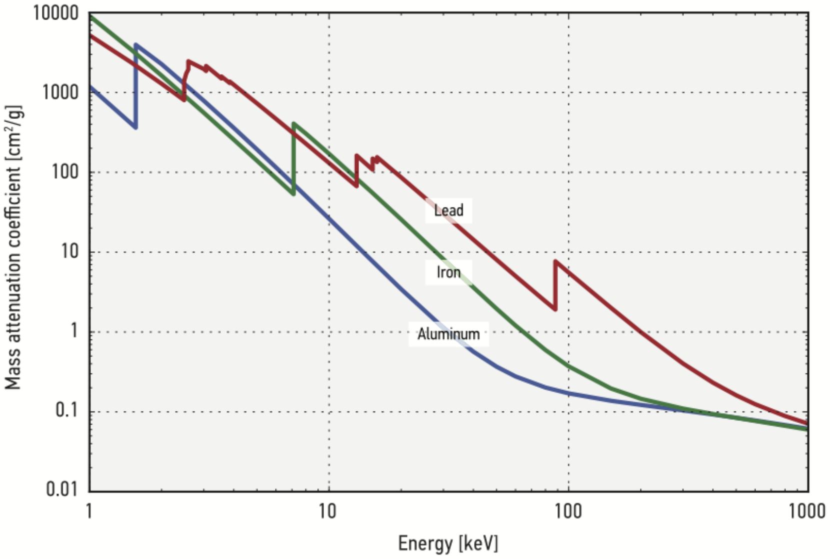


Figure 2. Attenuation coefficients for aluminum, iron, and lead. In quasi real-time, the ray-casting code determines objects and materials that the gammas pass on their way from the source to the detector. The code adjusts gamma intensities based on their energies and the path lengths in intervening materials. *Data: physics.nist.gov/PhysRefData/XrayMassCoef.*

In our virtual exercises, detector systems can be operated in a virtual quasi-instantaneous mode, which provides updated measurements about once per second, even when the source and detector are moving or when intervening materials are introduced or removed (see nuclearfutures.princeton.edu/vr for a demonstration). Alternatively, the system can be operated in a real-time mode, in which detector counts are sampled from the source distribution using a Monte Carlo method. In this mode, measurements that would be conducted as part of an inspection can take minutes before adequate statistics are achieved.

3. Virtual Environment

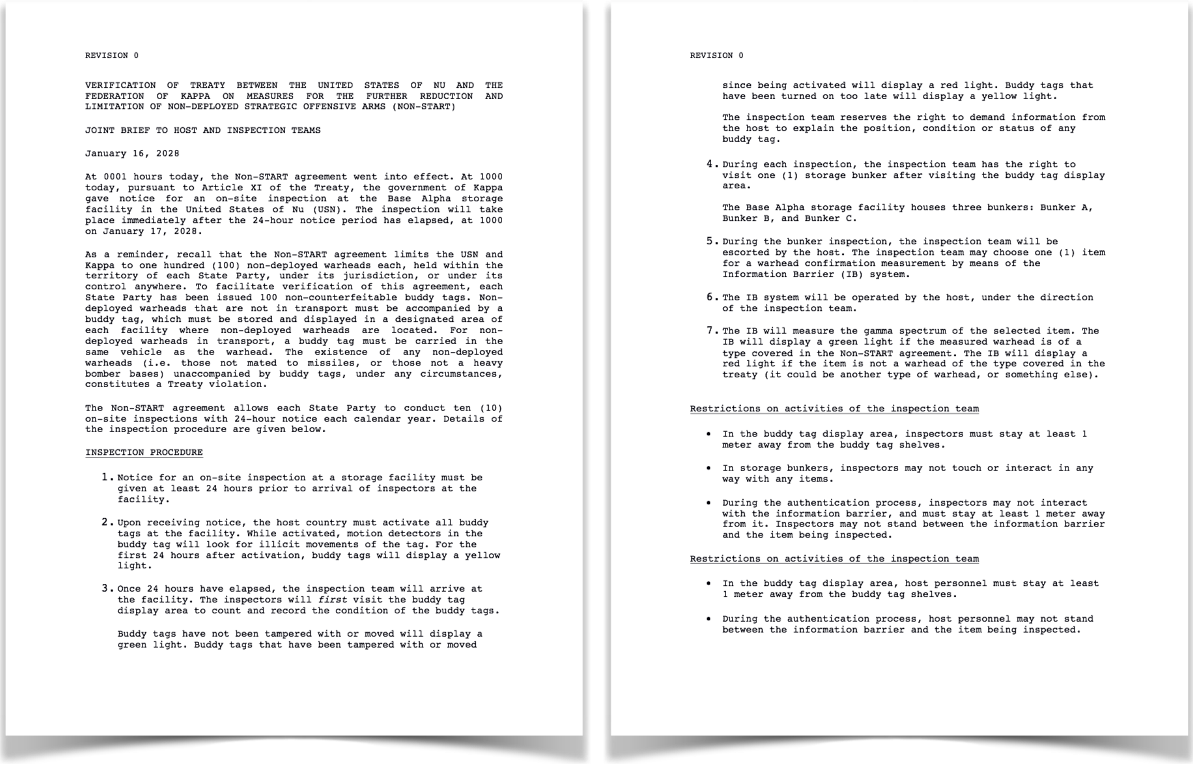
This work on VR pairs with another project on mapping verification at a strategic level using a representation of key nuclear infrastructure and pathways (verification.nu). While this mapping tool allows for an overview perspective, VR environments usefully allow us to dive a level deeper and examine verification concepts within an immersive virtual environment at the facility level. Together, these toolsets offer a novel approach to designing and refining verification option sets that comprehensively account for a state's nuclear enterprise and are sensitive to on-the-ground details.

The full-motion virtual environment developed as part of this project is designed to offer a flexible framework for use in inspection exercises. It allows for intuitive interactions between avatars and inspection equipment and enables rapid prototyping of potential verification approaches. All code is open source.[7] The framework is based on the *Unity* game engine, which offers extensive support for VR development and the *HTC Vive* head-mounted display.[8] We also use Valve's open-source software *SteamVR* to sync all controller input and locational data to *Unity* and the open-source *Virtual Reality Toolkit (VRTK)* to enable key VR functionalities, such as teleportation-based movement, laser pointers, and grab/drop for objects.[9,10] A key component of the software is the networking capability, based on UNET, which enables co-presence of two or more avatars and is required for the host-inspector interactions envisioned for our exercises. Networking functionalities are designed such that only vital information is sent over the network in order to optimize system performance.

To support navigation between scenes of the walkthrough application, a dedicated script checks for intersections between a user's pointer with pre-defined scene-change objects. If a user's laser pointer collides with one of these objects, a menu will pop up prompting the user with the location she or he can teleport to. Another dedicated script allows the users to interact with the virtual equipment during inspections. The script maps all buttons and LEDs onto the equipment to convey a realistic representation of what happens when the device is operated. In principle, the virtual equipment can run exactly the same code that runs on the actual hardware.

4. Exercise Framework

In April 2017, we conducted a first VR exercise with Princeton University undergraduate students at a virtual nuclear warhead storage site. The context for the exercise was a fictional arms-control treaty between two nuclear weapon states (Figure 3). Students, entering the environment two-at-a-time through a two-player networked experience, assumed the role of either a host or an inspector and performed an accounting inspection as part of a mechanism in the treaty to help increase confidence in the accuracy of baseline declarations. The exercise brought forth useful insights for how the environments and scenarios can be developed for a wider array of facilities.



REVISION 0

VERIFICATION OF TREATY BETWEEN THE UNITED STATES OF NU AND THE FEDERATION OF KAPPA ON MEASURES FOR THE FURTHER REDUCTION AND LIMITATION OF NON-DEPLOYED STRATEGIC OFFENSIVE ARMS (NON-START)

JOINT BRIEF TO HOST AND INSPECTION TEAMS

January 16, 2028

At 0001 hours today, the Non-START agreement went into effect. At 1000 today, pursuant to Article XI of the Treaty, the government of Kappa gave notice for an on-site inspection at the Base Alpha storage facility in the United States of Nu (USN). The inspection will take place immediately after the 24-hour notice period has elapsed, at 1000 on January 17, 2028.

As a reminder, recall that the Non-START agreement limits the USN and Kappa to one hundred (100) non-deployed warheads each, held within the territory of each State Party, under its jurisdiction, or under its control anywhere. To facilitate verification of this agreement, each State Party has been issued 100 non-counterfeitable buddy tags. Non-deployed warheads that are not in transport must be accompanied by a buddy tag, which must be stored and displayed in a designated area of each facility where non-deployed warheads are located. For non-deployed warheads in transport, a buddy tag must be carried in the same vehicle as the warhead. The existence of any non-deployed warheads (i.e. those not mated to missiles, or those not a heavy bomber bases) unaccompanied by buddy tags, under any circumstances, constitutes a Treaty violation.

The Non-START agreement allows each State Party to conduct ten (10) on-site inspections with 24-hour notice each calendar year. Details of the inspection procedure are given below.

INSPECTION PROCEDURE

1. Notice for an on-site inspection at a storage facility must be given at least 24 hours prior to arrival of inspectors at the facility.
2. Upon receiving notice, the host country must activate all buddy tags at the facility. While activated, motion detectors in the buddy tag will look for illicit movements of the tag. For the first 24 hours after activation, buddy tags will display a yellow light.
3. Once 24 hours have elapsed, the inspection team will arrive at the facility. The inspectors will *first* visit the buddy tag display area to count and record the condition of the buddy tags.

   Buddy tags have not been tampered with or moved will display a green light. Buddy tags that have been tampered with or moved since being activated will display a red light. Buddy tags that have been turned on too late will display a yellow light.

   The inspection team reserves the right to demand information from the host to explain the position, condition or status of any buddy tag.
4. During each inspection, the inspection team has the right to visit one (1) storage bunker after visiting the buddy tag display area.

   The Base Alpha storage facility houses three bunkers: Bunker A, Bunker B, and Bunker C.
5. During the bunker inspection, the inspection team will be escorted by the host. The inspection team may choose one (1) item for a warhead confirmation measurement by means of the Information Barrier (IB) system.
6. The IB system will be operated by the host, under the direction of the inspection team.
7. The IB will measure the gamma spectrum of the selected item. The IB will display a green light if the measured warhead is of a type covered in the Non-START agreement. The IB will display a red light if the item is not a warhead of the type covered in the treaty (it could be another type of warhead, or something else).

Restrictions on activities of the inspection team

- In the buddy tag display area, inspectors must stay at least 1 meter away from the buddy tag shelves.
- In storage bunkers, inspectors may not touch or interact in any way with any items.
- During the authentication process, inspectors may not interact with the information barrier, and must stay at least 1 meter away from it. Inspectors may not stand between the information barrier and the item being inspected.

Restrictions on activities of the inspection team

- In the buddy tag display area, host personnel must stay at least 1 meter away from the buddy tag shelves.
- During the authentication process, host personnel may not stand between the information barrier and the item being inspected.

Figure 3. Mock briefing issued to students detailing the inspection scenario and context of the fictional “Non-Start Treaty.” Document available at nuclearfutures.princeton.edu/non-start. *Courtesy: Mark Walker.*

The exercise incorporated virtual representations of verification tools and technologies developed using the methods described in the previous sections. This included an early version of a virtual information barrier representing an actual device developed at Princeton as part of a different project.[11,12] These devices are being developed to meet the key challenge of making trusted measurements on nuclear warheads to confirm their authenticity without revealing design information. This particular barrier, both real and virtual, uses low-resolution gamma spectrometry (based on a standard sodium-iodide detector) combined with a template-matching approach. The template-matching approach first entails recording a radiation signature from a warhead trusted to be genuine. The signature of an inspected item is then compared against the reference signature, and depending on the agreement of the two signatures, a pass/fail signal appears.

The exercise also included the use of virtual buddy tags. Given that next-generation nuclear disarmament treaties may place limits on the total number of nuclear weapons, including both deployed and non-deployed warheads, verifying such agreements could require the ability to count warhead totals. Attaching unique identifiers directly to warheads could be problematic due to a range of concerns by the host related to safety, security, and intrusiveness. To resolve this dilemma, Sandia National Laboratories first proposed the so-called "Buddy Tag" concept in the early 1990s.[13] 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. Verification would therefore rely on short notice inspections. Sensors in the tag would show that it had not been moved to the inspected site after the inspection was declared (for example, within the last 24–48 hours). If the inspector counted more treaty-accountable items than buddy tags at the inspected site, a treaty violation could be asserted. Using a number of single-site inspections, an inspecting party can hold the host at risk for discovery of violating the treaty at an enterprise level by possessing more warheads than the treaty allows.

A third tool incorporated in the environment is a simple radiation detector, used for inspectors to be able to verify that containers are empty if the host claims them to be. Based on the principles laid out above, the virtual detector features a dynamic deterministic calculation 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. In the virtual environment, a basic detector of the Geiger-Müller-type can be picked up using the physical controller, and the student can then proceed to scan a container whilst receiving audiovisual feedback on radiation levels.

In the exercise, the scenario specified that the inspecting country had given notice for an on-site inspection at a warhead storage facility in the host country with the inspection set to take place immediately after a requisite 24-hour notice period had elapsed. Upon receiving notice, the host country was to activate all buddy tags at the facility. While activated, motion detectors in the buddy tag will look for illicit movements of the tag. For the first 24 hours after activation, the buddy tags will display a yellow light, after which they will display a green light. Those that have been tampered with or moved since being activated will display a red light. Once 24 hours have elapsed, the inspection team was to arrive at the facility, beginning the virtual inspection exercise.

The first task of the inspectors was to count and record the condition of the buddy tags. The area of the warhead storage facility hosting the buddy tags, termed the Display Area, was in a separate building from the warhead storage bunkers. The Display Area featured a 3D-map of the site, orienting inspectors to the base and the three storage bunkers at the site, designated as Bunker A, Bunker B and Bunker C (Figure 4). The buddy tags in the Display

Area were sorted onto shelves associated with each bunker. The treaty afforded the inspection team the right to demand information from the host to explain the position, condition or status of any buddy tag.

After performing a visual assessment of the buddy tags and taking note of the number of tags associated with each bunker, the next task for the inspection team was to select a bunker to visit. Using the wand, the inspector could select a bunker on the 3D-map in the Display Area, which transported both the host and the inspector player to the bunker. At the bunker, the inspection team was to verify that the number of buddy tags recorded in the Display Area matched the number of warhead containers. The briefing instructions specified that the presence of any non-deployed warheads (i.e., those not mated to missiles, or those not at heavy bomber bases) unaccompanied by buddy tags, under any circumstances, constituted a Treaty violation.

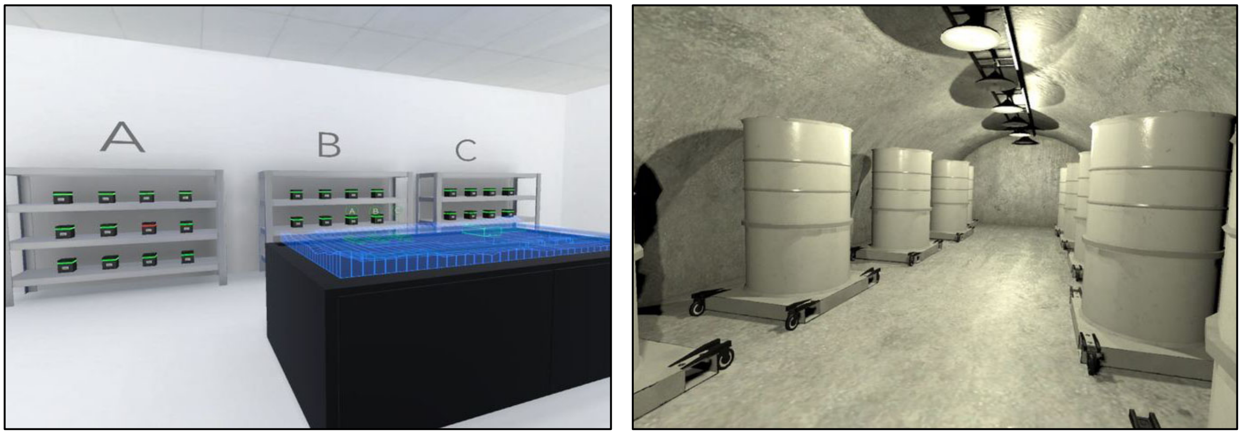


Figure 4. Stills from a virtual inspection: Display Area (left) and one of three warhead storage bunkers (right). Students playing the role of inspectors were tasked with assessing the state of the buddy tags in the display area and then selecting a bunker at random to verify that the number of tags and warhead containers were consistent.

As a final step of the inspection, to further increase confidence that the containers held authentic warheads, the inspection team was to select a container to perform a confirmation measurement using the virtual information barrier. Using the wand, the inspector could select a container, which transported both players and the chosen warhead container to a room where the information-barrier measurement could be performed (Figure 5, left). Students could operate the information barrier next to the selected warhead container and received either a pass/fail reading. The virtual radiation model described above has now been incorporated, allowing for an even more realistic implementation of the inspection protocol. The inspection system acquires the actual spectrum from the item in the container and compares it against templates stored in the device (Figure 5, right).

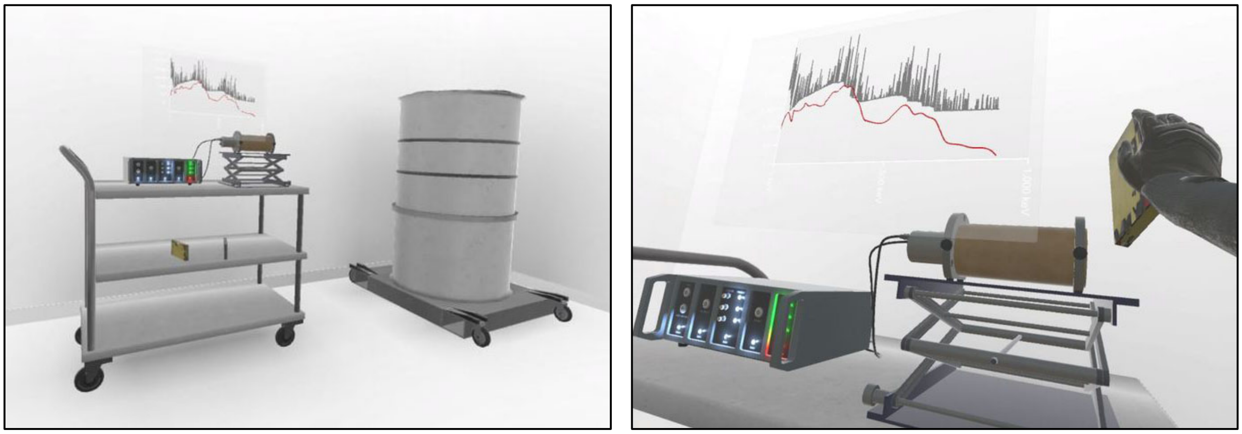


Figure 5. Stills from a virtual inspection. Warhead inspection (left) and close-up of information barrier and detector with simulated radiation spectrum (right). The information barrier can be operated just as the real device, including calibration, template acquisition, and inspection. The gamma spectrum is updated about once per second, but shown in the simulation for illustration purposes only. Different algorithms can be used with the information barrier to compare the acquired spectrum with the available templates to make a decision about match and mismatch. Lead and steel blocks are available for testing of the equipment.

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 and to observe how inspectors or hosts cope with obstacles or inconsistencies. The virtual inspection therefore incorporated randomized challenges into the inspection, 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 tag in the Display Area was associated with Bunker A, and students showed a high tendency to select Bunker A for the randomized inspection, despite the fact that 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 exercises as this work continues and would usefully inform both protocol and verification technology development.

Overall, this first student exercise offered a useful foundation for future work. As a starting point, the research team found it valuable to see that students with no prior exposure to the system were able to quickly catch on to the virtual controls and navigate the space. The students' management of the inspection protocol and the challenges that were presented to them also provided valuable insights to inform the development of a more rigorous evaluation framework as the virtual environment expands to include additional warhead facilities, technology options and protocol options. Most importantly perhaps, we have found great enthusiasm among the 70+ students in the class to participate in this exercise.

5. Outlook

Given the current uncertainty surrounding both near 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 multi-player 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, given security concerns, necessity of resources, 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.

The development steps described here include operationalizing virtual equipment with simulated radiation, enabling multi-player capabilities, and engaging student users in an initial exercise scenario. Future development efforts for the system will include expanding the array of equipment, facilities, and means of interactivity, including optimizing user interactions with one another and the equipment, and navigation of the virtual world. This work will continue to aim to create and demonstrate how VR can serve as a new space and new opportunity for policy development for technical and institutional engagement on arms control and disarmament.

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