Refining New Concepts in Nuclear Arms-Control Verification Through Full-Motion Virtual Reality

Tamara Patton, Bernadette Cogswell, Moritz Kütt, and Alexander Glaser

Program on Science and Global Security
Princeton University, Princeton, NJ

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. Here, we explore the potential of these environments to support innovations in nuclear arms control, in particular, the role they could play in developing facility architectures and verification protocols for treaties that do not yet exist. These treaties are likely to require new types of onsite inspections, including at nuclear warhead dismantlement facilities, or envision "managed access" to other military nuclear sites. Virtual environments could make critical contributions to the development of adequate inspection protocols without running the risk of exposing proliferation-sensitive or classified information, which would be a plausible concern 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. As an example, this paper discusses the use of the *Vizmove Walking Virtual Reality System,* a wide-area VR system that combines the *Oculus Rift* head-mounted display with motion trackers for up to 2500 square meters of real space. Users can walk around in real space, and the motion trackers translate their movement to the virtual environment, enabling a more immersive and realistic virtual collaboration experience. This paper illustrates how virtual nuclear facilities can be employed in FMVR to simulate and help refine a number of developing concepts related to arms control verification, including weapon authentication, tracking and monitoring mechanisms, as well as an overview of how virtual radiation could be constructed and employed in this type of VR system.

Background

There are many unanswered questions surrounding verification options for future nuclear arms control measures at lower numbers, including whether reductions should emphasize warhead counting or fissile material inventories, how states will balance transparency and security, and how future measures will be implemented in cohesion with existing nonproliferation and arms-control agreements. Accordingly, as researchers and policy makers work to design verification approaches, there is a significant need for a framework and toolsets to facilitate orientation, design, and testing, and to help explain the context in which particular verification technologies are relevant.

An ongoing project, launched as part of the *Consortium for Verification Technology* and based at Princeton University, seeks to use two primary toolsets in conjunction to develop verification approaches. The first is a mapping tool in the form of a fictional nuclear weapon state called *Nu,* which is used to compose verification approaches from a broad, strategic perspective (Figure 1). The second toolset, and the focus of this paper, is full-motion virtual reality. This system uses immersive virtual reality as a means to assemble and simulate technology, architecture, and protocol options in greater detail at the facility level. Combined, the two toolsets offer the ability to design cohesive verification approaches. Both toolsets are inherently flexible, and readily allow for adjustments when gaps or inconsistencies are discovered throughout the development process.

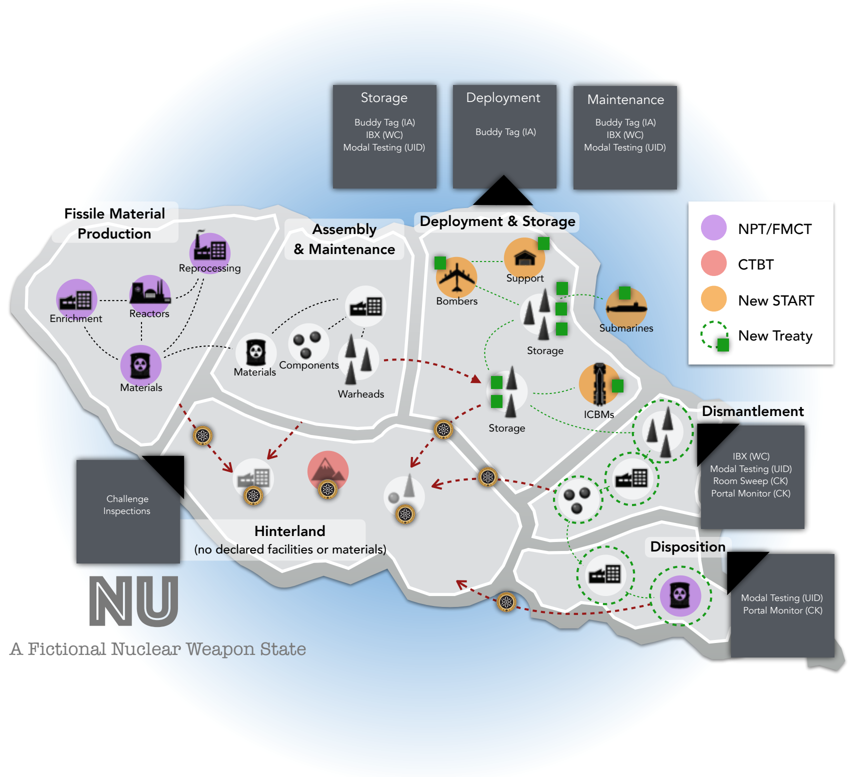

Figure 1: The *Nu* mapping tool represents a fictional nuclear weapon-state and can be used to compose and compare verification approaches at a broad level. The inserts highlight the technologies considered in a case study verification approach for a future arms control treaty below. Red lines indicate possible diversion pathways, with most addressed by the case study approach or other treaties. Green lines indicate verified transfers under the case study approach. The *Nu* mapping tool will go live in early 2017 at www.verification.nu.

Full-Motion Virtual Reality

For the virtual-reality toolset, our project currently uses the *WorldViz Walking Virtual Reality System.* This wide-area or full-motion virtual reality (FMVR) system combines the *Oculus Rift* head-mounted display with motion trackers for up to 2500 square meters of real space.[1] Users can physically navigate the available space, while the motion trackers translate their movement to the virtual environment. In the current setup at *StudioLab,*[2] four optical cameras mounted in the corners of the VR floor track active (infrared) LED markers, which are placed on the user's headset and on the hand-held controller used to interact with the virtual environment (Figure 2). As markers move within the room, the cameras determine the coordinates of the markers and render the first-person stereoscopic view for the user in real-time. VR environments are built through a multi-step construction process, which includes architectural design *(Autodesk Revit)*, 3D modeling *(Autodesk 3DS Max)*, and a game engine *(Vizard, Unreal,* or *Unity).* This workflow allows for a flexible development of facility architectures, including the ability to quickly change floor plans and easily modify the arrangement, dimensions, and properties of all relevant parts of the building including, for example, walls and doors.

A valuable utility of virtual reality is the ability to conduct live exercises with multiple users. Past exercises conducted at real facilities, such as the UK-Norway Initiative and the UK-US Cooperation, have shown that such step-by-step walkthroughs can be important for examining the feasibility of potential verification approaches.[3] However, because of the resources required to conduct such exercises and the security risks of bringing foreign personnel into a secure facility, such exercises have not been organized often. VR offers the opportunity to conduct inspection exercises at a significantly lower cost and with much more flexibility. Exercises can be conducted with users acting through virtual avatars in addition to non-player characters (NPC), representing hosts, inspectors, technicians, and security personnel. Research in social psychology has shown that, if a person in virtual reality believes that another person is an avatar, i.e., controlled by another player, she will "interact more or less as she would interact in the physical, face-to-face situation,"[4] even when she remains fully aware of the computer-generated nature of the experience. This phenomenon is particularly pronounced in the case of FMVR, where most human-to-human interactions (such as interpersonal distance, but also many other human gestures and attitudes) are accurately represented given how players move through physical space. Also, replays of a particular scenario can be used to examine the impact of curveballs or other precisely controlled changes of the events unfolding during the inspection.[5] Combined with the intuitive experience of interacting with other players and objects in natural ways, FMVR provides the most realistic and intuitive VR experience, which allows virtual reality to be more useable for complex applications such as designing verification approaches.

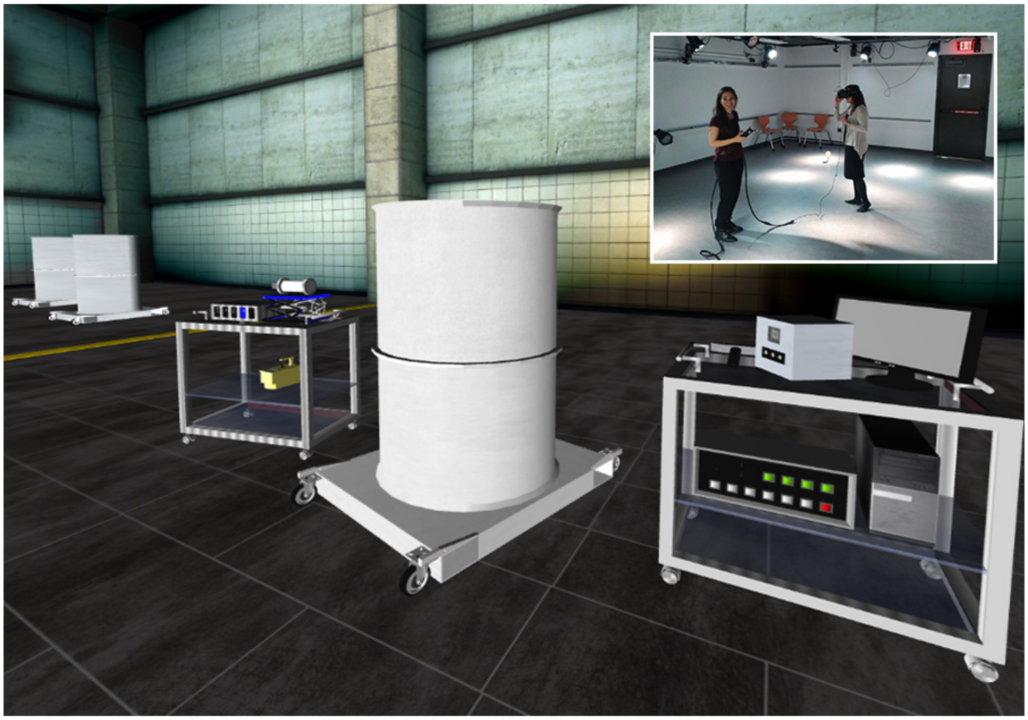

Figure 2: Scene from an inspection at a notional nuclear warhead storage site. Warheads are containerized, and several technologies are available for verification purposes. The insert shows the VR deck at Princeton's *StudioLab.* See also nuclearfutures.princeton.edu/vr.

Virtual Radiation

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.[6] Stochastic simulations propagate a collection of radiation particles, interaction-by-interaction, from a source to a detector using particle transport codes.[7] This method uses the Monte Carlo method and can include the full range of physical interactions. It therefore provides the most accurate predictions of the radiation field. Due to the Monte Carlo nature of such simulation codes, however, there is a heavy computational cost, which (currently) disqualifies this method from being applied in real-time simulations. In contrast, deterministic methods are much faster, and they can be either static or dynamic. Static deterministic simulations typically overlay a radiation map onto the virtual environment.[8] This provides dose-rate information at fixed points on an invisible grid filling the modeled three-dimensional space. This method has the fastest calculation time, since the radiation field information is preloaded. The static nature of the radiation map disqualifies this method, however, from being used in simulations where the source-detector configuration varies in an non-predetermined manner during the simulation. An alternative method, and the one used in our implementation, is the 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. The count rate C observed at this point can be approximated by:

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

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.[9] This approach is more commonly known as the point-kernel method and can be implemented assuming a point-source or multipoint-source approximation.[10] The most basic procedure, and the one presently used in our code, is to calculate the dose rate using a point-source approximation, which provides accurate real-time dose rates far from the source. An accuracy penalty of a few percent to tens of percent applies when the detector is very near the source, where self-absorption of the emitted radiation is high.

In our model, the dose-rate calculation is conducted a few times per second and takes into account any movement of the relative source-detector positions as well as the change in any intervening materials and object thicknesses penetrated.

Case Study: Refining a Verification Approach

The following section presents a case study of how the mapping and FMVR toolsets can be used to compose and assess a verification approach. Specifically, in this example, we examine the buddy-tag concept, which could be used to support verification of a notional treaty that places numerical limits on the total number of weapons a party is allowed to have, regardless of their status (deployed, non-deployed, strategic, tactical, active, inactive, awaiting dismantlement).[11]

As a starting point for giving purpose and structure to the approach, the example makes use of the following framework on potential treaty violations so that each approach can be evaluated in terms of completeness and potential gaps.

The following list details possible (but non-exhaustive) violation mechanisms to be addressed by a given verification approach:

- *Fake weapons (F):* The State passes fake items off as real weapons, possibly by using surplus fissile material or by removing a fraction of the fissile material present in the original design.
- *Diverted weapons (D):* The State diverts real weapons from the verification system after a treaty has entered into force, possibly through tampering with verification equipment or the treaty's data management system.
- *Undeclared weapons, active complex, observable (UAO):* The State does not declare certain weapons located in areas throughout its active weapon complex that are under verification and accessible to inspectors.
- *Undeclared weapons, active complex, hidden (UAH):* The State does not declare certain weapons located at facilities throughout its active weapon complex that are under verification, but in areas that may be hidden or not directly accessible to inspectors.
- *Undeclared weapons, hidden (UH):* The State does not declare certain weapons and locates them in non-verified sites before a treaty enters into force.
- *Undeclared weapons, clandestine production (UCP):* After a treaty enters into force, the State does not declare new, clandestinely produced weapons, which may then be located in the hinterland or in the active complex.

The following notation is used to represent the periods during which particular verification technologies are relevant:

- T_0 : The period of time before a treaty enters into force
- T_1 : The time at which initial baseline activities take place
- T_2 : The steady-state regime
- T_3 : The time at which any additional end-state verification measures take place

A basic verification approach designed to be minimally intrusive might envision the buddy tag used at weapon deployment, maintenance, and storage sites. The buddy tag is a trusted token that can be associated with a treaty-accountable item but is not physically attached to it. In practice, the tags are kept near the item so that during an inspection one tag could be presented for each item. The buddy tag would only be disassociated from a warhead at a dismantlement facility, where the warhead would be confirmed and then disassembled.

For the sake of this verification approach, warhead confirmation is performed with passive gamma-spectrometry combined with an information barrier (PG/IB). Continuity of knowledge on the confirmed warhead would be notionally performed by a combination of room sweeping, portal monitors, and inspector escorts of the item.

In this particular approach, a number of violation mechanisms are left unaddressed and exist as potential vulnerabilities in the verification approach. For example, before the point of dismantlement, there is a risk that fake warheads could be introduced into the system, given that buddy tags are not specifically paired with warheads that have been confirmed and uniquely identified.

To adapt the verification approach to be more robust (but also more intrusive), additional technology and inspection measures could be added to the system. This approach is illustrated in the mapping tool (Figure 1), visualized in virtual reality (Figure 2), and summarized in Table 1. One means to make the approach more robust is the addition of specific pairings between buddy tags and warheads through unique identifiers (UIDs) on the warheads. The pairing of buddy tags with a uniquely identified warhead that has been confirmed diminishes the risk of fake warheads in the accountancy system. As an example, the UID task could be performed through the use of modal testing, which is a specialized form of resonant vibration analysis often used for the purpose of structural identification, condition monitoring, and damage detection. From a chain-of-custody perspective, it has been postulated that a modal vibration signature might be used to identify a particular treaty-accountable container or container/object system, or provide evidence of tampering.[12] In the present example, during baseline inspection activities (T_1), warheads throughout the active complex would be confirmed by a radiation-based measurement, their containers uniquely identified through modal testing, and each would be paired with a uniquely identified buddy tag. Steady-state inspections (T_2) might then include inventory checks with inspectors only accessing the buddy tags as in the original scenario and possibly performing a UID link check on a randomly selected container-buddy tag pair. Because modal testing might only be performed on warheads in containers, warheads deployed at T_1 might initially be exempt from the UID process, but could be confirmed and identified as they move into storage or maintenance.

The more robust verification approach presented here still does not fully address the potential violation mechanism of undeclared warheads hidden in parts of sites that may technically be a part of a verification regime, but not directly accessible to inspectors (UAH). This vulnerability might require additional technology and inspection measures, for example, inspections to confirm the absence of undeclared items during T_1 and facility-level perimeter monitoring through portal monitors during T_2.

Nu Map Site	Verification Task	Time Period	Technology	Violation mechanisms addressed	Violation mechanisms unaddressed
Deployment	Item accountancy	T1, T2	Buddy tag	D, UAO	F, UAH
Maintenance	Item accountancy	T1, T2	Buddy tag	D, UAO	UAH
	Warhead confirmation	T1	PG/IB	F	
	UID confirmation	T1, T2	Modal testing		
Storage (non-deployed)	Item accountancy	T1, T2	Buddy tag	D, UAO	UAH
	Warhead confirmation	T1	PG/IB	F	
	UID confirmation	T1, T2	Modal testing		
Dismantlement	Warhead confirmation	T2	PG/IB	F	UAH
	UID confirmation	T2	Modal testing		
	Continuity of knowledge	T2	Room sweeping Room portal monitor	D	
	New UID on pit container	T2	Modal testing	D	
Waste storage	UID confirmation	T2	Modal testing	D	UAH
	Secure long-term storage	T2, T3	Room portal monitor	D	
Hinterland	Absence of undeclared weapons	T2	Challenge inspections	UH, UCP	None from framework

Table 1: Examining the details of a verification approach. Each site and its associated tasks and technologies would be good candidates for a VR simulation toolset.

After establishing the basic framework of technologies addressing potential violation mechanisms, FMVR provides researchers a means to begin developing appropriate inspection measures and options for managed access by allowing them to (literally) walk through the steps that might be involved. Figure 2 features scenes from the FMVR process at a notional storage site, featuring the technologies indicated in Table 1. Through this process, designers of the verification approach are able to flesh out details that may not be immediately obvious when composing an approach at an abstract level. These details can include, for example, what inspectors must observe and what may need to be shielded in different areas of a facility, what unique steps would occur for different inspection types, or how inspectors and hosts will maintain continuity of knowledge for verification equipment in addition to warheads. These details become especially significant when they translate to broader resource requirements, such as how often inspectors would be required to be present at facilities and how many individuals would be required for various combinations of tasks. Being aware of such details as part of a broader verification approach can allow designers to better compare different approaches in the effort to achieve more efficient systems.

Conclusion

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. FMVR 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, design and evaluation can comprehensively take place at both broad and detailed levels. Virtual environments in particular can also offer levels of accessibility typically much more difficult to achieve in actual facilities, given security and resource concerns. Accordingly, they can allow for more substantial collaboration amongst research groups and governments working to find solutions to existing verification challenges.

Future development efforts for the FMVR system will include adding additional interactive features to the equipment, such as basic operation and feedback mechanisms, as well as enabling seamless integration between virtual facilities, which could allow for tasks such as examining how developed procedures translate to the movement of equipment and treaty accountable items between facilities.

In the medium term, we see these virtual nuclear facilities as useful tools for verification system design, simulation, and collaboration between academic, laboratory, and government partners. The system will also be used for teaching students about the complexities of designing trustworthy verification systems by giving them a flexible and immersive tool to work with. Further down the road, we can also envision virtual environments serving as visual aids for negotiating details of an agreement, and possibly for training both hosts and inspectors in the details of negotiated inspection protocols.

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Endnotes

[1]The maximum area depends on the number of motion tracking cameras available.

[2]StudioLab, Council on Science and Technology, cst.princeton.edu/studiolab.

[3]*Joint U.S.-U.K. Report on Technical Cooperation for Arms Control,* U.S. Department of Energy, Washington, DC, May 2015; *UK/Norway Initiative on Nuclear Warhead Dismantlement Verification,* UK Ministry of Defence, March 31, 2010.

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[5]On the notion of trust in nuclear arms-control verification, see C. Hobbs, H. Elbahtimy, and M. Moran (eds.), *Trust in Nuclear Disarmament Verification,* Palgrave Macmillan, 2017.

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[11]J. Brotz, S. DeLand, A. Glaser, A. Kim, D. Steingart, and B. Reimold, "Minimally Intrusive Verification of Deep Nuclear Warhead Reductions: A Fresh Look at the Buddy-Tag Concept," *57th Annual INMM Meeting,* July 24–28, 2016, Atlanta, Georgia.

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