Crossing Realities: Connecting the Virtual and the Physical World for Remote Inspections

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ABSTRACT. Nuclear disarmament is the only solution to the threat of a global nuclear war. Traditional verification approaches of nuclear arms-control agreements towards disarmament have placed a strong emphasis on onsite inspections. Considering the large numbers of U.S. and Russian warheads as well as situations of political tensions or restricted global travel, in-person onsite inspections require a significant amount of time, resources, and trust between parties. As an alternative, remote inspections could facilitate and accelerate the verification process without the same requirements. While prior work has discussed how virtual reality could potentially be used for training and capacity-building in nuclear verification, we extend this idea by using virtual reality to combine virtual and in-person activities into remote nuclear verification inspections that reduce the intrusiveness and cost of inspections. Our approach utilizes bidirectional data flows and interaction between the inspector's virtual environment and the host's physical nuclear facility. We implement a full virtual reality environment and a physical demonstration to explore the technology and challenges of remote inspections conducted in virtual reality. For one direction of data flow, we use fiducial markers to estimate the position and orientation of key inspection elements in the physical world (e.g., warhead, robot, room) via an RGB camera, provide the estimated position and orientation data to a virtual reality project in *Unreal Engine 5*, and use 3D models of the tracked objects to show their relative positions and orientations in an immersive virtual reality environment with real-time updates. This provides inspectors in virtual reality with the key information from the physical world without revealing sensitive information. For the other direction of data flow, we use a mobile robot that can be controlled from the virtual reality environment so that it moves in the physical world. The robot acts as a placeholder for objects relevant to interact with during inspections (e.g., a radiation detector) and provides inspectors with a way to interact with the physical world even though they are not present. Combined, this work demonstrates and discusses how virtual reality could be used for remote nuclear verification inspections.

1. Background

Nuclear weapons have shaped and threatened the world since their development as part of the U.S. Manhattan Project in the 1940s. The testing, use, or threat of use of these weapons did not come uncontested and has faced persistent calls for nuclear disarmament, as most recently highlighted by the humanitarian initiative that led to the 2017 Treaty on the Prohibition of Nuclear Weapons.[1]

Past and current discussions on nuclear disarmament foresee inspections of nuclear weapons and facilities as promising means of building trust and confidence between states that currently still own nuclear weapons as well as states that do not (Figure 1). Such inspections are intended to happen by one party observing and verifying the presence and absence of nuclear material in the other party's weapons and critical infrastructure through radiation measurements. Inspections currently require physical presence which is connected with time efforts, costs, and safety and proliferation concerns. In-person inspections can be perceived as intrusive and thus require an elevated basis of trust between participating parties.

Figure 1: Warheads in storage. Mk21 reentry vehicles and containerized W87 warheads at F. E. Warren Air Force Base, Cheyenne, Wyoming, October 1992 (left); Demonstration of the B61 nuclear weapon disarming procedures using an inert training version in an underground vault at Volkel Air Base in the Netherlands in June 2008 (right). In both cases, it is possible that physical access for international inspectors to these or similar facilities and objects would be difficult, if not impossible. Source: Paul Shambroom (paulshambroom.com) and U.S. Air Force.

The idea of remote inspections has occasionally been discussed as a way to make International Atomic Energy Agency inspections more efficient, especially, when they focus on routine tasks dealing with low-grade nuclear materials. More recently, a study by the U.S. National Academy of Sciences also alluded to remote inspections for warhead storage facilities, with regard to capability needs for nuclear arms control:[2]

> *"Treaties that include weapons in storage or weapons designed for shorter-range delivery systems are anticipated to require new MDV [Monitor-*

> *ing, Detection, Verification] techniques. As a minimum,* ***such treaties would likely require access to storage areas either directly or remotely****, and confirmation of warhead count (either a baseline confirmation or through routine/challenge inspections)." [Emphasis added]*

Such a preference for remote access could be motivated by sensitive features present in some of these facilities. Similarly, the global lockdown and related travel restrictions during the first years of the pandemic have demonstrated that remote collaborations can be effective substitutes for in-person meetings. Rising tensions between major nuclear powers, i.e., the United States, Russia, and China, could point to a new era where non-intrusiveness of inspections is preferred or even become a *sine qua non.* Under these circumstances, remote inspections could help enable further progress in arms-control and disarmament discussions. This project explores one possible way of implementing remote inspections by connecting the virtual and physical world via object tracking, virtual reality, and teleoperated robotics.

2. Approach

Virtual environments have previously been proposed or used for education and training purposes in the context of nuclear safeguards.[3] In the field of nuclear disarmament, our earlier work has focused on the reproduction of nuclear infrastructure to facilitate collaborative approaches in virtual reality.[4] There also exists a virtual reproduction of the nuclear disarmament verification exercise NuDiVe that simulates a disarmament inspection.[5] Similarly, robotics have been used for various inspection tasks and sometimes combined with virtual reality interfaces.[6] Expanding on this body of work, we combine virtual reality and remote teleoperated robotics to create a basic framework for remote inspections.

We consider a scenario in which a nuclear weapon state allows for international inspectors to remotely participate in agreed verification activities, such as confirming the integrity of a seal or witnessing the dismantlement of a nuclear weapon. Representatives of this state that facilitate an inspection are further referred to as the "host". In principle, inspectors could participate using traditional communication channels, for example, using video transmissions; these would most likely raise serious security concerns, however. Here, we explore a possibly more secure approach, where the inspector is present in a virtual version or "digital twin" of the inspected facility; such a virtual facility could be a faithful reproduction of the physical facility or it could be purposefully simplified such that only relevant areas are represented and, perhaps most importantly, all sensitive features are never modeled.

The challenge is to enable meaningful real-time interactions between the local host and the remote inspector. As part of this project, we introduce two objects to demonstrate the basic concept. First, we introduce a mock-up nuclear warhead that exists in the physical world, where its pose (i.e., position and orientation) are tracked in real time and can be mirrored in the virtual environment. Second, we want specific interactions of the inspector in the virtual world to be transmitted to the physical world; for example, the inspector should not only be able to navigate the virtual environment within a defined area, but they should also be able to position specific objects relevant to the inspection (such as a radiation detector). As a placeholder for these objects, we use a mobile robot development platform that can be controlled from within the virtual environment and mirrored into the physical space.

3. Methods and Technical Architecture

We design and implement a technical architecture for our proof-of-concept system for remote inspections.[7] The main elements of the system are pose estimation, the virtual environment, robot control, and networking (Figure 2). For the purposes of providing a proof-of-concept system, these elements run independently on a single computer and communicate locally via reading and writing shared text files.

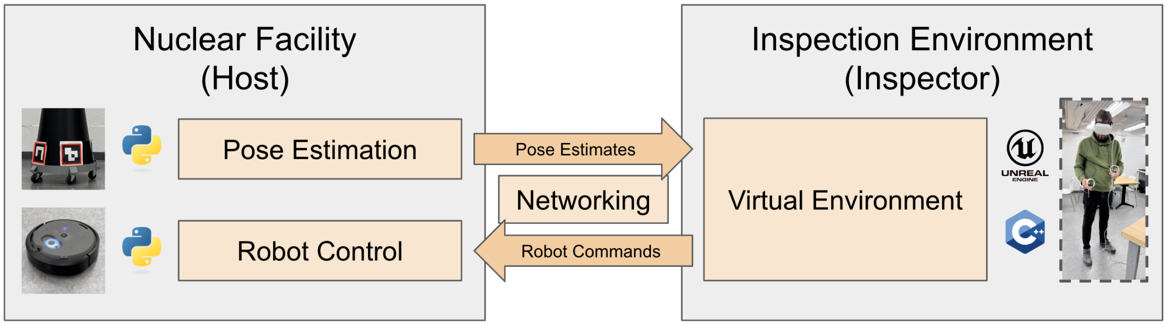

Figure 2: Technical Architecture. Our system consists of pose estimation, the virtual environment, robot control, and networking. These elements support bidirectional data flows between the nuclear facility with the host (left) and the inspection environment with the inspector (right). The warhead, robot, and any other relevant physical objects are located in the nuclear facility. Pose estimation (in Python) uses tracked fiducial markers (left, top image) to generate pose estimates for these objects that are then sent to the virtual environment (in Unreal Engine 5 and C++), which positions and orients virtual models of the objects in a virtual representation of the nuclear facility. The inspector, who is arbitrarily located in the world, access the inspection environment in virtual reality via a head-mounted display (right, dashed box), and interacts with the environment to inspect the nuclear facility by navigating virtually and sending robot commands with a motion controller to relocate relevant physical objects (e.g., with a radiation detector). The robot commands are utilized by robot control (in Python) to move the physical robot (left, bottom image) and any sensors attached to it in the nuclear facility accordingly.

Pose Estimation. We track the pose of physical objects using ArUco markers, a type of fiducial marker for augmented reality and robotic localization applications.[8] In our standard physical setup (Figure 3, left), three markers are arranged as a triangular prism on top of the robot and five markers are placed around the warhead to ensure that at least one marker for each object is always in view of the camera no matter its orientation. Additional markers on a wall help register the relative positions of all objects within the room. We estimate the pose of all markers relative to the camera using the ArUco module in the Python OpenCV package by analyzing the live camera feed from an RGB camera.[9] For all markers designated to an object, the ArUco marker ID, last estimated position in (x, y, z), last estimated orientation in (yaw, pitch, roll), and timestamp from the last estimation are saved in a single text file.

Virtual Environment. The virtual inspection environment that mirrors the nuclear facility is implemented as a level in *Unreal Engine 5*.[10] This level includes a digital twin of key aspects of the physical facility (e.g., room shape and size) and 3D models for the warhead and the robot (Figure 3, right). The models are positioned and oriented relative to the room using parsed pose estimates from the text files written by pose estimation. Specifically, we use the recorded pose estimation for each marker relative to the camera to calculate pose estimations for the objects relative to the room, only considering markers that were updated most recently and that were positioned and oriented to be sufficiently viewed by the camera. (Currently, this code is limited to objects rotationally symmetric in yaw.) The pose estimates relative to the room are used to position and orient the models in the virtual environment via their *Unreal Engine 5* Blueprints.

An inspector can enter the virtual environment using a standard VR headset, such as the *Meta Quest 2*[11] (Figure 2, right, dashed box). Standard motion controllers are used for navigation, interactions with the environment, and sending robot commands. Joystick values of the left motion controller are used as robot commands and saved to a text file (overriding the default controls that allows the player to rotated in discrete increments in virtual reality).

Robot Control. We use an *iRobot Create 3* programmable robot in the demonstration facility (Figure 2, left, top image) and its corresponding Python software development kit.[12] Robot commands, sent as joystick values, are read and parsed from the text file written by the virtual environment. If the x-values exceed a specified threshold, a corresponding turning command is issued to the robot; if instead the y-values exceed a specified threshold, a corresponding forward or backward translation command is issued to the robot. The thresholds and the movement are tunable for preference of control.

Networking. The Python script for pose estimation, the *Unreal Engine 5* level for the virtual environment, and the Python script for robot control run independently but simultaneously on a single computer and communicate with each other locally via reading and writing shared text files. Built-in Python file handling support file reading, writing, and parsing in pose estimation and robot control, and custom C++ classes support file reading, writing, and parsing in the virtual environment. Additionally, the computer hosting the system connects to the robot via its hosted WiFi network and via Bluetooth to issue robot commands.

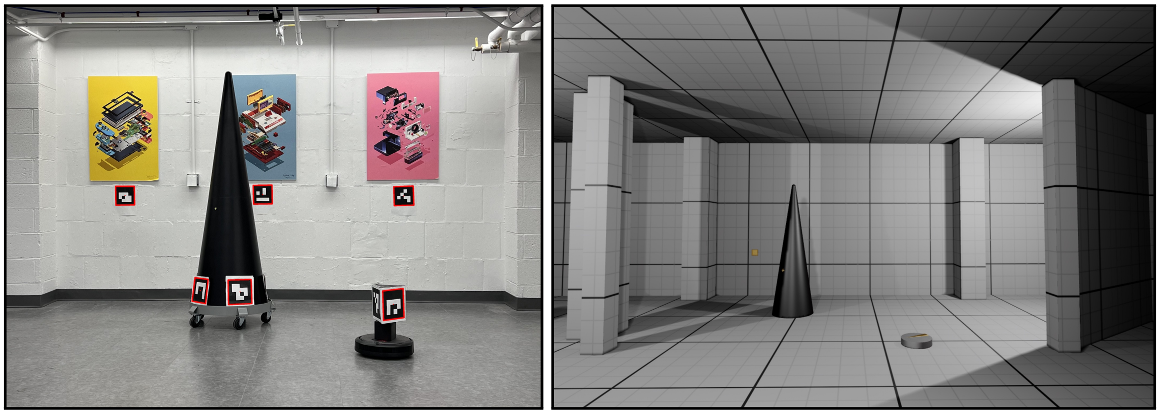

Figure 3: Physical facility and virtual environment, side by side. A frame from the video stream of the physical facility that is used for pose estimation is annotated (in the system code) to show visible markers that are having their pose estimated in red outlines (left). These pose estimates are used to position 3D models of the warhead and the robot in the virtual environment, such that they mirror the physical facility (right)

4. Discussion

Remote inspections are a potential alternative to in-person onsite inspections that may be perceived less intrusive by allowing the host to control the amount of access provided to the inspector. We have demonstrated a proof-of-concept system for remote inspections via virtual reality that addresses some of the concerns related to that. In this section, we discuss how remote inspections via virtual reality can achieve a sufficient balance between providing the inspectors with meaningful interactions with a nuclear weapons facility and providing the host with security such that sensitive information is not disclosed.

A baseline for the acquisition of precise and accurate real-time information would be for inspectors to see visuals of the inspected facility in some capacity, allowing for object counting and further examination, e.g. via radiation measurements. A video transmission with minimal latency could allow for detailed, immersive interaction by providing inspectors with a way to navigate the camera view around the facility and/or to specify locations for radiation measurements. However, a video transmission could also disclose sensitive information and an edited video must be both real-time and trusted by the inspector.

Thus, we instead propose remote inspections via virtual reality. Viewing a virtual environment that mirrors the relevant aspects of the physical nuclear weapons facility in real-time would still allow for precise and accurate visual information during an inspection. However, additional aspects of the facility that are not relevant for the inspection can be omitted and abstracted away. Screenshots of out proof-of-concept system can be seen in Figure 3. While poses of a mock-up warhead and a robot (potentially carrying a radiation detector) as well as the room features visible in the physical facility (left) are reproduced in the virtual environment (right), three posters on the walls of the physical facility that represent sensitive information are omitted in VR. Information can be abstracted away by not showing it (like the posters) or by choosing the detail of representation (by setting the detail of 3D models).

Assuming that precise and accurate real-time visual information is provided in virtual reality, inspectors can safely navigate the virtual environment for immersive interaction during the inspection without affecting anything in the physical facility. This allows inspectors to have their choice of viewing angle in the facility (Figure 4), which can lead to more immersive and potentially more effective inspections. Additionally, inspectors can control a robot carrying a radiation detector or other equipment to extract further information. If concerns arise about a remote operator controlling a robot in a nuclear facility, a different system can instead allow inspectors to specify locations for the sensors that the host can then transfer in a more controlled method.

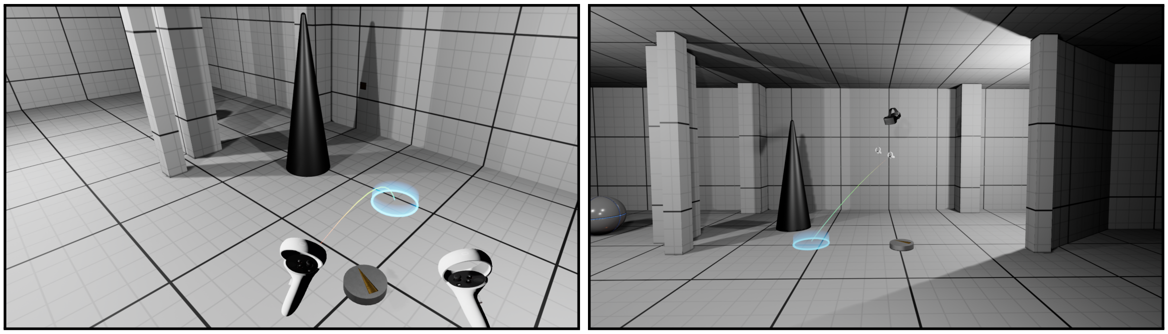

Figure 4: Immersive interaction. Remote inspections via virtual reality allow the inspectors to have immersive interaction in the virtual environment mirroring the nuclear facility. Inspectors can navigate, such as through the common virtual reality method of teleportation (shown as the arc pointing to a blue circle that represents the location to be teleported to) throughout the virtual environment. The view from the inspector is shown on the left and the view from a stationary camera is shown on the right.

For any form of remote inspection, verification of received information being recorded live (i.e., in real-time with minimal latency) and locally (onsite) from the correct facility would be crucial. This concept has previously been discussed in a broader sense for video transmissions,[13] but must be tailored specifically for remote inspections via virtual reality for them to effectively provide inspectors with confidence about the authenticity of the information they are witnessing. Live verification techniques could include a challenge-response strategy where inspectors requests that the host send certain complex signals, such as through the pose of an object that is being shown in the virtual environment. Local verification is potentially the hardest challenges for remote inspections. One potential method is a "virtual peephole" into the physical world so that inspectors could verify the integrity of a unique identifier previously installed in the facility (Figure 5). The prior application of the unique identifier would probably need to happen under in-person inspector observation though.

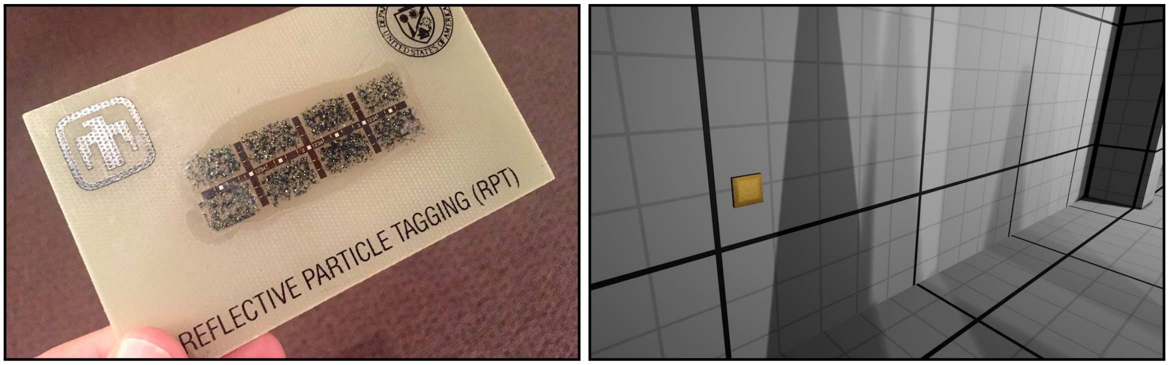

Figure 5: A "virtual peephole" into the physical world from within virtual reality could allow inspectors to verify the integrity of a unique identifier previously installed in the facility (left). Such a "virtual peephole" could be shown in virtual reality in some form, such as a limited video transmission. The golden plaquette (right) is a placeholder for such a peephole. Source: Authors.

Finally, providing precise, accurate, real-time information about the facility to inspectors must be transmitted through a secure data transmission channel to ensure non-manipulation and security from third parties. This can be achieved through cryptographic means and has been previously discussed in related academic literature.[14]

5. Conclusion

In this work, we propose conducting remote nuclear verification inspections via virtual reality to reduce the cost and intrusiveness of in-person onsite inspections. We design, implement, and demonstrate a proof-of-concept remote inspections system, and we discus how such systems in general can achieve a sufficient balance between effective inspections under limited access conditions for the inspectors and security concerns of the host.

While we have shown that remote inspections via virtual reality have potential for real-world applications, substantial future work must be done to implement them beyond our proof-of-concept system with more sophisticated, robust technology.

A real-world remote inspection system must allow for secure networking with minimal latency between the host facility and the virtual inspection environment. Our preliminary local networking utilizes modularity with separate code for pose estimation, the virtual environment, and robot control. Maintaining modularity in a real-world system such that the only dependency between elements is that they use a consistent data formatting scheme, would allow for the elements to be replaced as needed (e.g., if different facilities have different pose estimation methods, or if one element is to be upgraded).

Additionally, a real-world remote inspection system must allow for accurate, precise, real-time object tracking. Instead of fiducial markers (as used in our proof-of-concept system), this can be better achieved either with either more advanced motion capture systems that utilize markers throughout the facility or with multiple high-resolution RGB-depth cameras covering various angles of view and learning-based techniques to recognize objects of interest. Motion capture systems would potentially allow for more general, off-the-shelf object tracking but would require markers and tracking hardware to be set up onsite at the facility. RGB-depth cameras would potentially allow for a more transportable system but would require recording video footage that might be undesirable if sensitive information is present. In both cases, the system should be host controlled to provide them with security about its use within the facility, such that only the host and trusted operators either set up the tracking hardware or manage the video footage and only the relevant information (e.g., object poses, radiation readings) are transmitted to the inspectors.

Thus, using appropriate technology to create systems for remote inspections via virtual reality can achieve a sufficient balance between providing inspectors with meaningful interactions with the facility and providing the host with security such that sensitive information is not disclosed, increasing the effectiveness and efficiency of real-world nuclear verification inspections.

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