Virtual Reality for Transport Emergency Response Training – 25349

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ABSTRACT

Extended reality, including virtual reality (VR) and augmented reality, is increasingly used in education and training, particularly for emergency response to incidents. VR is ideally suited for simulating various emergency scenarios which are prohibitive to set up physically for safety, cost or other logistical reasons. Conducting transport emergency response training in VR allows training to address scenarios that are not suitable for field exercise because of radiation hazards and operational risks. With the sponsorship of the U.S. Department of Energy (DOE) Packaging Certification Program (PCP), Office of Packaging and Transportation, Office of Environmental Management (EM), Argonne National Laboratory staff has developed and convened a graduate-level training course, NP-652 Response to Radioactive Material Transport Emergencies, since 2022. The objective of this one-week course is to teach participants the principles, technical basis, and requirements for emergencies during the transport of radioactive material. The course emphasizes the interaction between engineering controls and radiation protection in emergency preparedness and response in the context of U.S. domestic and international requirements. It also expands on training, such as the DOE-EM's Transportation Emergency Preparedness Program (TEPP), by emphasizing the roles of technical experts working with all hazards emergency response organizations in conducting package assessments and technical response actions.

This paper will highlight the recent development of VR scenarios associated with a transport incident involving a truck carrying radioactive material, during which the package was ejected and potentially damaged. Multiple emergency scenarios have been developed that address the damage to the package, particularly its shielding component and function, and other hazards such as fire, contamination, personal injuries, and concurrent security hazards. Each scenario includes a model Type-B package, appropriate equipment (e.g., dose monitor), and narratives illustrating the course learning objectives. Tasks carried out virtually by trainees include, for example, identifying and assessing hazards; conducting radiation surveys; taking steps to control contamination; and determining action alternatives. These VR scenarios provide examples of the breadth of potential for diverse and interdisciplinary training, including the ability to dynamically cover "what-if" scenarios, with simultaneous participation of multiple agents in real-time, web-based classroom exercises.

INTRODUCTION

When responding to an emergency, prompt assessment, decision making, and action are critical in regaining control of the situation and protecting the lives and health of affected persons. One key success factor is the training of response personnel at the preparedness stage. This need for training presents something of a dilemma: practice and practical experience are indispensable in preparing personnel to respond to real-world situations with flexibility and confidence, but when an emergency occurs, it is too late to practice. Thus, it is common practice to simulate emergency conditions (as well as routine conditions that would not be safe or practical to practice "live") in a safe environment. Such simulations can range in complexity from fire drills, in which participants informally pretend there is a fire as they rehearse evacuation procedures, to comprehensive flight simulators used in the training of pilots.

A central concern in training simulations is the question of realism. By definition, a simulation cannot be identical to the real-world conditions it simulates. At the same time, it needs to be sufficiently faithful to them to be useful as preparation within the scope of its training goals. VR technology offers unique options in this respect through its ability to replace a user's visual perception with a completely fabricated environment. This means the potential fidelity and complexity of at least the visual aspect of a simulated scenario are limited primarily by the employed hardware's graphical performance rather than cost, time, or safety considerations. Scenarios are also not limited by available physical space, extant infrastructure, and so on—the developer has full control over the details, including the ability to create highly specific, unlikely, or dangerous scenarios or to prepare several scenarios with significant differences that can be used within the same space in succession without having to alter the real space itself.

Indeed, VR systems are already in use for training first responders. A recent survey of 21 VR products intended specifically for emergency response training is found in [1]. The emergencies mainly targeted by these systems fall into three categories:

- Fire
- Law enforcement
- Emergency medical services

Of those systems focusing on fire-related emergencies, a few [2, 3] also include training related to hazardous materials, concentrating on toxic gases and chemical spills. In comparison, VR training options for emergencies involving radioactive materials are rare, except as specific applications for more general hazmat programs, even though research in this area has been reported [4-6].

The specific advantages of VR environments make them attractive for simulating the presence of radioactive materials that can come in any number of shapes and forms, especially in the case of radioactive waste, which could include any object that happens to have been contaminated. Shielding or the source itself might have been damaged. It would not be practical to stage such situations with real radioactive material, but for training purposes, it is still desirable to simulate a radiation field which can be detected using appropriate instruments. Because radiation fields are undetectable to humans except using such equipment, it is an important visual element of the scenario. By simulating the presence of radioactive sources, the shielding effects of intervening objects, and the resulting readings on a dosimeter, all within the virtual scenario, one can create sensory feedback for the users that is practically indistinguishable from what they would receive in a real emergency involving radioactive materials.

This paper presents the development of *Virtual Reality for Transport Emergency Response* (VR-TER), a set of prototype VR scenarios, by Argonne using a point-kernel model to simulate a radiation field in VR in real time. Requirements and considerations for VR applications intended for training in general, as well as for simulations of radioactive emergency scenarios specifically, are discussed. Then, the prototype scenarios are described and the features and choices motivated by these considerations are highlighted. We conclude with a review of lessons learned, areas in need of further development, and possibilities for expansion to support more types of radiological or nuclear hazards in incidents related to transportation.

BACKGROUND

This project is a continuation and synthesis of previous work in computer-based simulations to support training in nuclear safety and security. It builds on work by Chaput [7, 8] on digital visualization of radiation fields, Breitinger [9] on virtual training for x-ray operators, and Gelautz [10] on atmospheric dispersion simulations and response actions. After the proof-of-concept applications presented in these publications, the goal was to create a full-featured prototype training program and demonstrate its use in a real classroom environment for Argonne's training course on transportation emergency response, which is part of DOE-EM's Packaging University Program (https://rampac.energy.gov/home/education/packaging-university).

To achieve this goal, the prototype VR-TER embodies the following design requirements:

- **Multiple scenarios** with a common premise: the application should contain several scenarios, each with a well-defined focus and learning goals, that can be used on their own, in sequence, or in any combination depending on the needs and structure of the training program.
- A **real-time radiation transport model**: the Unity Point-Kernel (UPK) 1.0 model presented in [9] would be overhauled and expanded to serve as a general basis for simulating radiation surveys in addition to x-ray analysis.
- **Consumer-grade mobile VR**: the training application should be portable and usable with a minimum of additional setup or peripherals, to facilitate its use in classrooms.
- A **high degree of (visual) realism**: as the strength of VR is the degree of immersion resulting from the completeness of the visual experience, the simulation should be as visually realistic as practically achievable within the limitations of the targeted hardware.
- **Extensibility**: the underlying framework should be reusable to construct more complex scenarios than the ones in the prototype application for more powerful architecture or completely different scenarios and should allow for future additions to the model.
- **Real-time collaboration**: more than one user should be able to participate in the same scenario at a time, to support better communication between instructor and student, joint training, classroom and/or remote sessions.

The following section discusses how these requirements were implemented and the major considerations and trade-offs involved.

METHODS

VR-TER and both versions of UPK were built using the Unity game engine [11], a software development environment designed for creating video games. It provides tools to implement functionality necessary across a variety of video games and a graphical interface for designing scenes within a game. Unity Technologies also maintains the Unity Asset Store, a marketplace for visual assets, functionality not included in the engine, and other third-party content for use in creating games. Third-party assets were used extensively in creating the environments for each scenario and to implement networking and basic VR movement functionality. 3D models of dose rate monitors, x-ray equipment, and certified packaging were created from scratch using the 3D graphics software Blender.

Scenarios and Premise

Five simulated emergency scenarios have been developed so far for demonstration and prototype training. Each scenario depicts a variant of the same accident scene with different conditions intended to aid in discussing different aspects of emergency response.

The accident scene depicted involves a traffic accident in a residential district between a flatbed truck carrying a Type B radioactive material package and a civilian van. Both drivers failed to see the other approaching the intersection and swerved at the last moment to avoid a crash, causing the van to hit a tree by the roadside and the truck to topple over. The package has been ejected and potentially damaged. Figure 1 illustrates the layout of the virtual accident and a user's view of the scene.

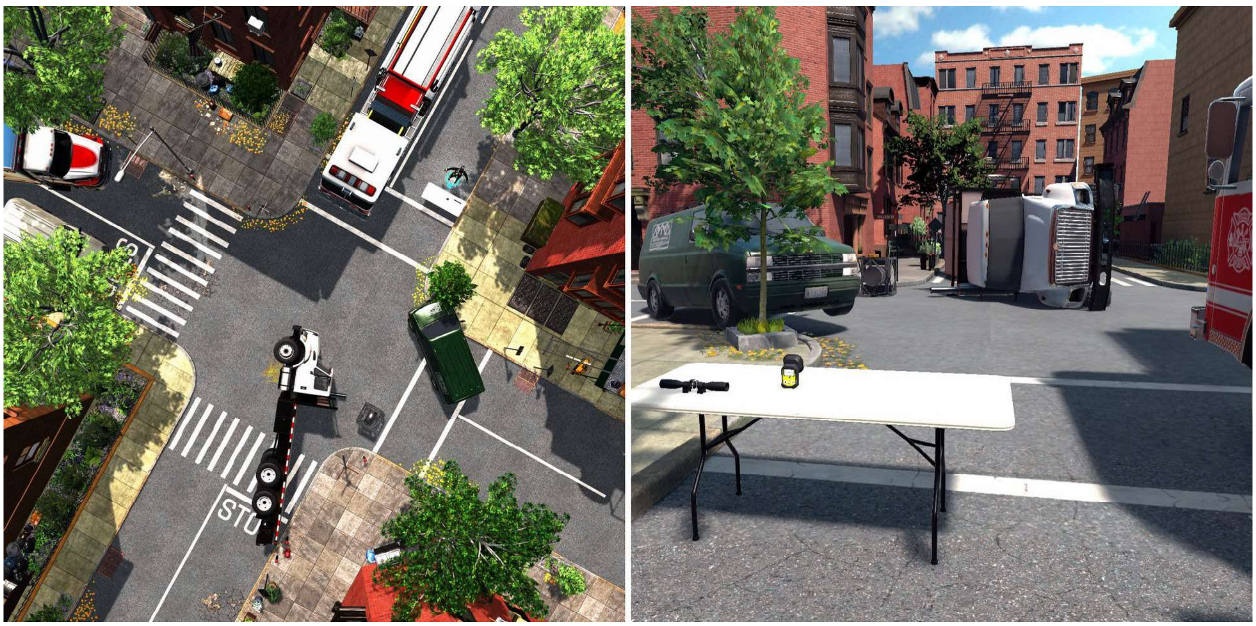

Figure 1. Left: bird's eye view of the accident scene in VR. Right: first-person view near the VR-TER user's starting position.

A training session using VR-TER is intended to use one or more scenarios based on the session's learning objectives. The same scenario may be repeated multiple times to explore hypotheticals and/or allow multiple students to work through it in first person; or multiple scenarios may be combined in sequence. Each scenario has been limited in scope to focus on a specific decision to be made.

The five scenarios developed for the prototype VR-TER to date and tasks to be completed in each are as follows:

- No danger: For introductory purposes. Confirm that the package is not visibly damaged and there is no elevated radiation and declare the package safe to remove from the scene.
- Damaged package: Identify a damaged package that presents a radiological hazard and discuss how to proceed.
- Collaborative: Coordinate between multiple students at once to identify and respond to a damaged package as above.

- Fire: Identify non-radiological hazards before approaching the package.
- Security: Use a portable x-ray generator to inspect suspicious luggage near the civilian vehicle and determine whether the accident scene includes a security risk.

Radiation Transport Model

The central feature of VR-TER is UPK 2.0, a detailed point-kernel model for simulating a radiation field at a given point in space. For purposes of the model, any given object in VR can be one or more (or none) of the following:

- A radiation **source** with a set activity and isotope;
- A radiation **shield** made of a set material; or
- A radiation **detector**.

To calculate the current dose rate at the position of a given detector, the model first calculates a straight path between that detector and each source in the scene (see Figure 2). If this path passes through any shields, the portion of the path lying within each shield is used to calculate an attenuation factor which is applied to the local dose rate contribution resulting from the total distance between source and detector. The formula used to calculate the attenuated dose rate contribution is the same as that for UPK 1.0 given in [9]. The total dose rate results from summing each source's individual contribution and, optionally, a randomly generated background dose rate.

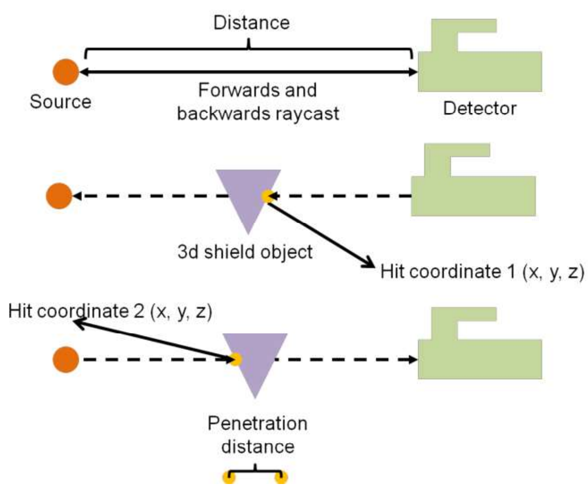

Figure 2. Illustration of how the linear distance between source and detector and the penetration distance through any shields between the two are determined, taken from [8]. A raycast is a method, common in video games, used to draw a line between two coordinates and determine its intersection points with other objects in an efficient manner.

The decay energies of isotopes, as well as attenuation tables and default density values for specific materials, are loaded from comma-separated values tables provided to the program. These can be supplemented or replaced in accordance with the needs of any given application.

Each component of the simulation can be considered as a unit and mixed freely. For example, a given source is assumed to be a point source consisting of a single isotope. The same object could also be a shield;

thus, sources can both emit radiation and attenuate radiation from other sources (though not from themselves). Multiple unit sources can be assigned to the same object to represent a mixed source. More complex source geometries can be modeled by subdividing an object into multiple components and declaring each a separate source. The main limitation on the simulation's complexity is the computing power of the hardware used, as discussed below.

The model is not restricted to displaying the dose rate at a given point in space to the user as a number. As the components are modular and low-level, elements can be added to make use of the basic components in different fashions. One of the scenarios includes a portable x-ray generator, which is modeled as a source that the user can actively turn on for a brief time to expose a receptor panel. This panel, in turn, calculates the dose at each of a set number of points on its surface as if each were a detector, and translates this matrix of values into a black-and-white x-ray image to be displayed on a connected laptop (within the simulation).

Mobile VR

The prototype has been developed with consumer-grade mobile VR devices in mind. The current iteration targets the Meta Quest 2 and requires only a headset with developer mode enabled and two controllers, but the standalone headset can still be connected to a personal computer to support more demanding scenarios.

Current VR hardware can be divided into mobile and stationary devices. Mobile devices are self-contained in that they contain their own processor and battery and VR software, "out of the box," without the need for any further electronics beyond the headset itself and controllers that come with it. Stationary devices must be connected to an external computer that runs the software and act as display and input devices only. This means that stationary VR devices are generally more lightweight than comparable mobile headsets and boast greater processing power, or rather, their processing power is effectively that of the personal computer (PC) they are connected to. The advantage of mobile VR devices lies in portability, as the headset can be used anywhere without needing to provide a computer, and in eliminating cables as restrictions on the user's movement and/or potential sources of distraction.

For prototype VR-TER development, a decision was made to prioritize portability and mobile VR. While performance can be enhanced in stationary VR by more realistic simulations, the "plug-and-play" nature of mobile VR is highly attractive when considering adoption of the technology for specialized purposes such as training. (Note: The performance advantage of stationary VR is dependent on the availability of a suitable PC, which needs to have a modern graphics processing unit and may well have to be acquired just for this purpose.) It must be noted, however, that an external PC is still necessary to create scenarios for mobile VR and install these on the headset—but this PC need not be in the room during training, or even owned by the same person or organization that owns the headsets.

Additionally, an application built for less powerful hardware will still run on more powerful hardware if it is available, while the reverse is not true. With the scalable prototype VR-TER presented here, a more computationally demanding scenario can always be built by adding more components to, for example, represent a geometrically complex source in greater detail as multiple point kernels.

Realism and Performance

As noted above, processing power is the main limiting factor for the detail level and realism of a simulation. "Realism" is a broad term, and there are many elements of a simulation that can be more or less realistic. For VR-TER, the two chief concerns are the level of visual realism supporting the student's feeling of immersion in the scenario and the realism in the results of the radiation transport model. It is less concerned with, for example, realistically modeling the spread of a fire, whereas a simulation aimed at training firefighters may be much more focused on that. The main performance considerations in VR-TER are graphics performance (which limits the visual realism and feeling of immersion in the scene) and the performance of the radiation transport model (which limits the realism of its results and therefore the utility of the model for training). Software optimization is a deep and complex topic, so this paper restricts itself to describing the fundamental design challenge and highlighting a few specific measures taken. Standard graphics optimization methods, such as the use of lightmaps to pre-calculate lighting conditions, have been employed.

The rate at which a digital display refreshes itself (its "frame rate") depends on how quickly the device can calculate the next image that should be shown to the user. If the frame rate is too low, the simulation will appear "choppy," as the eye can resolve individual still images and the illusion of continuous motion breaks down. When using VR, in addition to compromising immersion, choppiness can contribute to motion-sickness-like symptoms for the user. The more operations need to be performed to render the next frame of the simulation, the lower the frame rate. A device's performance, then, is a qualitative measure of how many operations its processing unit(s) can perform in a short time frame, while an application's performance is determined by the number of operations required to compute the next frame. Short of aftermarket upgrades, a device's performance is essentially fixed, so each step of a real-time simulation is effectively calculated on a deadline. The model's fidelity must be balanced against the complexity of the required calculations.

Every time VR-TER calculates the radiation field at the location of a given receptor, the underlying UPK model must iterate over every radiation source in the scene to determine its dose contribution, and—for each of those sources—over every shield between it and the receptor. The number of calculations required per update is thus proportional to the product of the number of detectors, shields, and sources in the scenario. Aside from optimizing the calculations themselves (touched on in the Conclusions), UPK 2.0 therefore supports approximations in the design of a scenario as effective trade-offs between detail level and performance.

It is important to be cognizant of the fact that detectors do not generally update their readings for every single frame. Real dosimeters integrate their readings over a period and update their displays every few seconds. Detectors in the model mimic this behavior by also updating at set intervals (set when creating the scenario), but do not integrate readings; the dose rate at the detector's location is calculated only when it needs to update. This sacrifices some realism in the behavior of detectors, but in a way largely invisible to the user. In exchange, while the computational load of any given detector update is unchanged, this approach limits the number of detectors that must be updated in any given frame when more than one is present in the scenario. Additionally, when compositing a scenario, the modular design of UPK 2.0 allows significant flexibility in determining the level of detail in its simulations. For example, a composite shield or one with complex geometry could be represented in the model calculations as a simple shape approximating its contours and consisting of a single material with an average density value, or as a group of connected objects, each treated as a separate shield of possibly different materials. Figure 3 illustrates this point, using the package involved in the accident as an example.

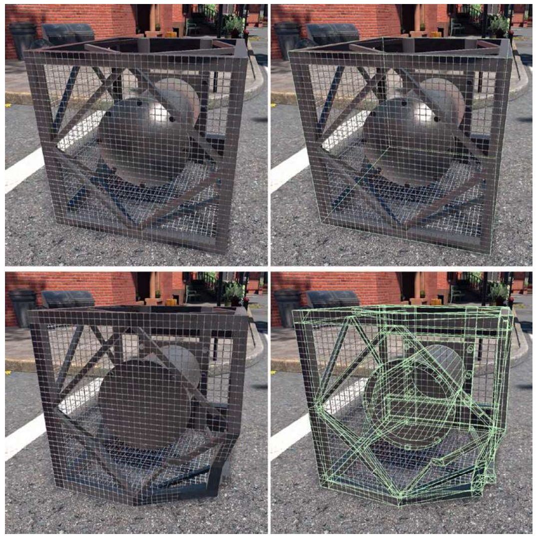

Figure 3. Visualization of the Type B package in VR. Top row: the intact package, which is not a radiation hazard, is approximated as a simple cube shape for physics purposes. Bottom row: the damaged package is composed of multiple parts of its structure, each of which attenuates radiation leaking from the damaged package independently, resulting in a complex radiation field.

Extensibility

The UPK 2.0 model uses a "building blocks" approach to composing scenarios, with its basic structural components being sources, shields, and detectors. It is intended to allow for defining additional components within this paradigm that exhibit more specialized behavior or alter the behavior of other components attached to the same object in the simulation. For example, the x-ray generator used in one of the scenarios is modeled by combining a strong x-ray source component with a script that activates this source only for a specific period after the generator is activated to start an exposure. Outside the exposure time, the source is treated as if it did not exist. The receptor panel in the same scenario is a variant detector that requests many dose calculations at slightly different positions across its surface, which are processed over several frames to distribute the computational load. The function to calculate dose rate at a given position is exposed, such that any piece of code can make use of it and only has to supply the position of the reading.

The model components can be attached to arbitrary objects in the scene, and the calculations make use of standard properties of objects in Unity game engine that define an object's position and its physical extents for purposes of collisions. They can therefore easily be added to both third-party and custom-made 3D models, and the scenarios in VR-TER feature several of both from multiple sources.

Collaboration and Remote Training

A third-party library is used to provide basic networking functionality and allow multiple users with their own devices to connect to the same scenario simultaneously over the internet. Each connected user can both independently interact with the scenario and communicate with the others via voice chat. Thus, users can participate in VR training simultaneously to address collaboration and division of duties in an emergency scenario. Even if the instructor guides one student at a time through the scenario, other users can watch and follow along as they would in a classroom. Networking functionality also allows users to participate in training remotely without having to be physically present in one place, if their internet connection allows.

SUMMARY AND CONCLUSION

We presented a working prototype VR-TER demonstrating the use of VR technology as an effective tool for training responders to an emergency involving radioactive material. The ecosystem of third-party assets and graphic scene editors supplied by game engines such as Unity significantly lessen the challenges to creating training simulations using building blocks and virtual models of specialized equipment such as dosimeters or certified packaging. While Unity was selected for the availability of documentation and the depth of its asset ecosystem, it would be worthwhile to reassess other options on the market as well, especially open-source alternatives such as Godot. VR-TER has been applied in the delivery of graduate-level training on emergency response involving the transport of radioactive material. Experiences so far have been positive [12, 13]. More use of VR-TER over a longer period will be necessary to obtain feedback from users and data to improve its impact in applications in a real classroom environment.

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