

## 3D User Interfaces for Public Safety: Addressing Fidelity in Virtual Testbed Development

Katelynn A. Kapalo<sup>1,2</sup>, Jack Lewis<sup>2</sup>, Chris Johnson<sup>2</sup>, Jeff Karhoff<sup>2</sup>, and Scott Ledgerwood<sup>2</sup>

<sup>1</sup>Brown University, School of Engineering

<sup>2</sup>National Institute of Standards and Technology, Public Safety Communications Research Division

Boulder, CO

[Scott.Ledgerwood@nist.gov](mailto:Scott.Ledgerwood@nist.gov)

### ABSTRACT

First responders work in high-hazard environments that can rapidly change, endangering life and threatening property. Due to the costs and potential dangers of testing and evaluating technology in hazardous conditions, technology developers and designers identified virtual reality (VR) as a potential medium for training emergency response since VR environments mimic low-frequency, high-risk events. However, designing virtual scenarios for public safety requires a detailed understanding of the operational environment in which first responders work. This paper addresses some of the benefits and challenges of using VR to develop 3D user interfaces for public safety. We introduce some of the key design elements that are not often considered in the context of public safety training and research. The paper concludes with a brief discussion of current and future research directions related to VR for public safety.

### ABOUT THE AUTHORS

**Katelynn A. Kapalo** supports the Public Safety Communications Research Division (PSCR) at the National Institute of Standards and Technology (NIST) as the lead user experience (UX) researcher within the User Interface/User Experience (UI/UX) research portfolio. Prior to her role at NIST PSCR, she worked as a Research Statistician for Orange County Fire Rescue Department and as a Research Psychologist for the U.S. Navy. Katelynn has supported large-scale research and development programs focused on the integration of virtual and augmented reality (VR/AR) capabilities across the defense and public safety industries. She earned her Ph.D. in Modeling and Simulation from the University of Central Florida.

**Jack Lewis** is the lead developer for the VR development team in the UI/UX portfolio at NIST PSCR. He is responsible for production and pipeline development, and various other development tasks such as technical art, lighting, and visual effects (FX). Jack has a background in game development, a degree in Game Art and Design from the Art Institute of Colorado, and an MS in Creative Technology and Design from the University of Colorado Boulder.

**Christopher Johnson** serves as the lead designer on the UI/UX portfolio team at NIST PSCR. He is responsible for the mechanics, systems, environments, audio design, and menus of the virtual reality experiences, and handles both design and in-game implementation. His goal is to create VR experiences that are intuitive, engaging, immersive, realistic, and insightful from a research perspective. Chris holds a BS in Video Game Design and Programming from Champlain College and has worked as a virtual reality designer in the game industry since 2015 before joining NIST in 2018.

**Jeff Karhoff** is the 3D modeler and UI/UX designer for the UI/UX team. His digital design career started in architectural visualization and interior design. Jeff's prior experience building interactive virtual reality scenarios for builders, architects, and developers led naturally into his role at PSCR as the team's environment artist.

**Scott Ledgerwood** leads the UI/UX research team at NIST PSCR, focusing on improving usability and user interface testing for first responders. His team is developing new test methodologies leveraging VR/AR to enable improved research, testing and development of first responder technologies. The team is also conducting research and development on technology systems like camera and video capture devices for improving user experiences. Scott holds a BS in Applied Information Technology from George Mason University, an MBA from Bellevue University, and an MS in Telecommunications from the University of Colorado Boulder. Scott moved from the Washington, D.C. area to join NIST in 2015.

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## INTRODUCTION

The Grenfell Tower tragedy occurred on June 14, 2017, resulting in the loss of 72 lives and 74 citizens requiring hospitalization for their injuries. Recent investigations have demonstrated the importance of providing opportunities for first responders to train on low-frequency, high-risk scenarios such as Grenfell (Galea, 2019). Although training was only one of the contributing factors, it is important to consider how we can best support first responders in training for these types of high-profile structure fires and emergencies. Virtual reality (VR) affords this opportunity due to the ability to create and deploy scenarios rapidly, in a fiscally responsible way.

The cost to train and test first responders in hazardous scenarios is a financial burden for many public safety agencies. For a single-phase test, consumer testing firms can expect to pay between \$10000-\$30000. Renting a facility for controlled fire testing can cost upwards of \$50000 for a single day. For hazardous scenarios, training and testing can range from \$40000-\$60000. While VR is not a substitute for live testing, it presents opportunities for first responders to train in these hazardous conditions without risk to life or property.

Our work focuses on addressing some of the design recommendations and considerations necessary for working with public safety end-users in virtual environments. In this paper, we capture design considerations for the VR community to leverage in future work. We designed a large-scale, open-source VR environment that others can leverage to test and rapidly prototype user interfaces for first responders. We refer to this environment as a testbed to describe the research and development focus of the virtual environment. In this context, a testbed is a virtual platform that will allow academic, government and industry stakeholders to conduct experimental research related to human performance and usability in the context of public safety.

## RELATED WORK

Milgram et al.'s virtuality continuum conceptualizes the composition of environments based upon the presence or absence of virtual and real objects (1995). VR is composed of an entirely computer-generated environment, while augmented reality (AR) can be conceptualized as computer-generated visuals superimposed in the users' real-world environment. These differences are critical to recognize due to the implications surrounding user interaction. Because users employing head-worn VR devices cannot see the physical world around them, traditional interface paradigms, such as the mouse and keyboard, impractical and inconvenient for controls. 3D and non-traditional computing environments require careful consideration of the operational context; however, these considerations are even more critical for first responders operating in dangerous and unpredictable environments. To situate our work in the extant literature, we describe areas that identify how and why technology designers and developers must carefully consider the public safety operational environment. This environment, also known as the incident scene, is often chaotic, demanding, and dynamic.

## Virtual Reality for First Responders

Virtual environments have been used to train first responders for over two decades. Seminal work in this area focused on training firefighters in navigational tasks using virtual environments (Bliss et al., 1997). As technology advanced, developers expanded these virtual environments to not only train wayfinding and navigation skills but also emphasize training and learning in the context of situation awareness (King, 2009), biometric and physiological monitoring (Bayouth et al., 2013), and team coordination (Toups et al., 2009). Additional work in this area has focused on training the cognitive and leadership skills necessary for new incident commanders to successfully manage the incident scene (Tarr et al., 2014). More recent work has addressed the importance of training procedural tasks on domain-specific tools such as pump panels (Suhail et al., 2019). Similarly, work in human-computer interaction (HCI) has focused on evaluating the utility of augmented reality and virtual reality (AR/VR) for rapidly prototyping user interfaces for public safety end-users (Bailie et al., 2016; Grandi et al., 2019; Haskins et al., 2020).

## **Presence and Immersion**

In our work, we distinguish between three key concepts: presence, immersion, and fidelity. Presence refers to the subjective or psychological sense of being in the virtual environment (Slater, 2003). Immersion refers to the level of engagement with the simulation and can be conceptualized as the objective level of sensory realism the virtual environment provides (Bowman & McMahan, 2007). Fidelity refers to the degree to which the virtual environment matches the real-world environment (Hays & Singer, 1989). Because the extant literature in leveraging VR for public safety training remains relatively nascent, it is critical to understand how presence and immersion connect to the concept of fidelity in a virtual environment. We describe our approach to defining fidelity in the context of public safety training; however, it is important to operationalize how these concepts relate to human performance in terms of testbed design. Ultimately, this testbed aims to create an environment that the research and development communities can utilize to test and iterate new technologies for first responders. The testbed will also allow us to determine how immersion and presence influence performance. Therefore, the goal of this testbed is to create enough fidelity to encourage the collection of metrics that can support the design of future first responder technologies.

## **Understanding the Public Safety End-User**

To design effective 3D user interfaces that support first responders, we must understand their operational environment and technology needs before creating effective training and testing environments. Cognitive task analysis is one approach researchers use to gather information and user requirements from first responders (Prasanna et al., 2009). One of the most comprehensive studies collected information from 7000 first responders across multiple disciplines (law enforcement, fire, emergency medical services, and communications) (Choong et al., 2018). These user requirements help to inform the design of technology for emergency response. We leveraged these studies to better support first responders by focusing on the unpredictable nature of the operational environment (the incident scene).

To prevent negative training learning effects and to improve knowledge acquisition, developers need to understand some of the cognitive theories that underpin decision-making in crisis response. Therefore, we explicitly adopt these theories in designing and developing scenarios for first responders. Extensive research in human factors has pointed to the idea that first responders leverage critical cues in the environment to make decisions. Due to the shared characteristics between military environments and the fireground (i.e., location of fire operations), seminal work in decision-making has focused on studying fireground incident commanders (Klein et al., 1986). Some recent work in this area has focused on identifying some of the more critical cues firefighters use in their attempts to evaluate the incident scene (Bayouth & Keren, 2019; Kapalo et al., 2018; Okoli et al., 2017; Perry & Wiggins, 2008). Our work extends this research by concentrating on several critical cues that first responders must leverage across multiple types of emergency situations: communication with teammates, objects within the operational environment, and the presence of smoke or fire conditions. Ultimately, these cues or conditions will drive the first responder's selection of fire control strategies and tactics.

## **DESIGN CONSIDERATIONS: CONTEXTUALIZING FIDELITY IN PUBLIC SAFETY**

In our approach to developing virtual testbed environments for public safety, we captured some of the important features that contribute to more positive user perceptions of the environment—namely, non-playable characters (NPCs), smoke simulation, and realistic props. Although most of these aspects have been assessed using formative evaluations in our work, the goal of our development process is to highlight some key areas that contribute to improved fidelity, resulting in a greater sense of presence and immersion when working with end-users in the public safety domain. Simulation fidelity refers to the degree to which a simulated (virtual) environment represents the real-world environment (Hays & Singer, 1989). To better characterize how it relates to our testbed, we focus on three core ways simulation fidelity can be qualified:

- **Cognitive Fidelity:** When considering cognition in terms of simulation and virtual environments, cognitive fidelity refers to the idea that the tool or technology should match the user's intended cognitive strategies. That is, the tool should be able to communicate the user's decision-making process by providing necessary affordances to carry out that process.

- **Physical Fidelity:** One of the more demanding areas in developing public safety simulations and virtual environments is matching the physical environment to a virtual environment. This presents challenges due to the complexity of public safety operations, including aspects like team coordination, equipment, etc. We explore using haptic devices and other input sensors as ways to add physical fidelity to virtual environments.
- **Scene Fidelity:** Although scene fidelity can be interpreted as physical fidelity, we take a nuanced approach to understanding how physical and scene fidelity affect a virtual scenario. Scene fidelity is a more focused version of physical fidelity in that it incorporates both cognitive and physical fidelity. Scene fidelity refers to the idea that physical and cognitive constraints have been implemented in the virtual environment design. This paper covers some of the more critical aspects for developing higher fidelity scenes and levels within a virtual environment for first responders. For example, our goal in developing these scenarios is to mimic a real incident scene by including time pressure, cognitive demands, and physical demands.

The below sections describe several critical aspects of the testbed that influence the simulation fidelity for first responder virtual environments. These key aspects are the design of non-playable characters (NPCs), simulated smoke, and prop creation. NPC design and smoke simulation are described in our primary search and rescue task, where users are attempting to locate a victim inside a building. The section on prop creation uses examples from a Special Weapons and Tactics (SWAT) scenario to describe how we implement different aspects of fidelity depending upon the needs of the public safety end-users.

### **Design of Non-Playable Characters (NPCs)**

Non-playable characters (NPCs) are computer-generated actors that respond and cooperate with the user. These interactions align with how operations and tasks would be conducted in the real world. For instance, a firefighter would never enter a structure fire or conduct a search and rescue alone. NPCs, acting as fellow firefighters, assist in picking up and carrying out the victims in the scenario. They also accompany the user throughout the scenario, resulting in a more realistic team environment and improving simulation fidelity.

Non-Playable Characters (NPCs) are computer-generated characters controlled through artificial intelligence; using NPCs helps align our testbed with real-life scenarios. By adding characters who cooperate with members of the search team, we improve simulation fidelity, increasing the user's sense of presence and immersion. Because firefighters and other first responders never work alone, we designed the NPCs to provide a more realistic team environment. In our testbed environment, two NPCs assist the user in tasks like primary search.

We posed the following questions before developing the NPCs:

- What actions should each NPC be capable of performing in the testbed environment?
- When will the NPCs perform these actions in the scenario?
- How will the user interact with the NPCs?

In our primary search and rescue scenario, the incident scene is a structure fire where the user must work with the NPCs to conduct a primary search. We decomposed the search task into several smaller tasks (e.g., pick up the victim or put down the victim). To ensure that the tasks mapped to real-world firefighting tasks, we consulted a panel of certified firefighters. Our panel stressed the importance of distinguishing between automatic tasks (e.g., tasks carried out without explicit command from the end-user, such as general navigation) and end-user-directed tasks (e.g., directing the NPCs to pick up the victim). Because the fire service is grounded in a paramilitary organizational hierarchy and structural firefighter tactics are based upon standard operating procedures, the distinction between automatic and directed tasks is critical. We used NPCs in the testbed to provide a more realistic environment for first responders. By adding additional teammates, the scene aligns more closely with real-world structure fire conditions, resulting in higher levels of physical and cognitive fidelity.

### **Simulating Smoke in Virtual Reality**

For virtual testbed development, one of the core challenges is to present enough cues in the environment to create a high-fidelity training scenario to enhance immersion. To create a viable testbed for fireground training, one of our

core research and development efforts is the simulation of smoke in the virtual space. For the fire service, realistic smoke simulation is critical since many fireground tactics rely on the incident commander's evaluation of the smoke and fire conditions; simulating this cue is vital for successful training. We adopted an iterative approach to the design of smoke and fire conditions based upon our work with firefighter end-users. In the following paragraphs, we capture some of the lessons learned on modeling smoke in the virtual testbed environment.

We conducted informal user testing with approximately  $n = 5$  firefighters to begin the design process for more realistic smoke conditions in our virtual environment. From the data collected, the participants appreciated that smoke was included in this testbed environment because it is typically a feature that is not included or available. Additionally, the end-users mentioned that the smoke did occlude vision like it would in actual fire conditions. However, some participants suggested that smoke did not capture some of the dynamic features you would expect to see in real-world fire conditions. In real fire conditions, smoke darkens in color over time, banks down surfaces, and shows varying degrees of texture. We collected this feedback and used it to inform how we model smoke in our testbed environment. One of the more pressing challenges in the development of virtual environments for public safety is related to computing performance. Initially, we attempted to model smoke using individual particulate modeling, but this came with a heavy performance cost. Our initial smoke conditions required numerous particles. Draw calls and computational overhead became prevalent concerns and resulted in unacceptable performance decrements. Figures 1 through 3 provide a depiction of our smoke design progression.



**Figure 1. Initial Smoke Design**

To manage the dynamic nature of smoke and to better represent smoke in the scenario, our design process evolved to encompass volumetric textures. This design approach led to significant performance increases by focusing on volume texture instead of individual particles. Similar approaches have been adopted in industry and the gaming communities with success (Nowak et al., 2018). Using techniques and methods such as this communicates to the end-user that designers understand the first responders' operational and work environments, contributing to more effective user experience. Although we cannot ensure complete physical fidelity using virtual environments, dynamic smoke contributes to a higher sense of cognitive fidelity and immersion. This higher sense of immersion has been directly linked to better training outcomes in other fields, including medicine (Coulter et al., 2007). Therefore, it is possible to enhance simulation fidelity by focusing on the subjective experience of both presence and immersion. Our work addresses performance considerations and fidelity by balancing the computational overhead of smoke rendering with acceptable frame rate thresholds.



**Figure 2. Warehouse Fire Virtual Environment without Smoke**

There are challenges associated with adopting new approaches to model high-fidelity, dynamic smoke in VR environments because of the processing power and video random access memory (VRAM) limitations of some hardware. First, processing limitations of some platforms result in inconsistent smoke rendering, adversely affecting the user's experience. Second, lower-end simulation hardware may not handle the performance demands associated with our approach to dynamic smoke modeling. For example, the Oculus Quest headset uses mobile hardware instead of a dedicated PC, putting significant limitations on the output performance of the rendering engine. In our case, we were unable to achieve volumetric smoke on the Oculus Quest device due to the lack of VRAM.



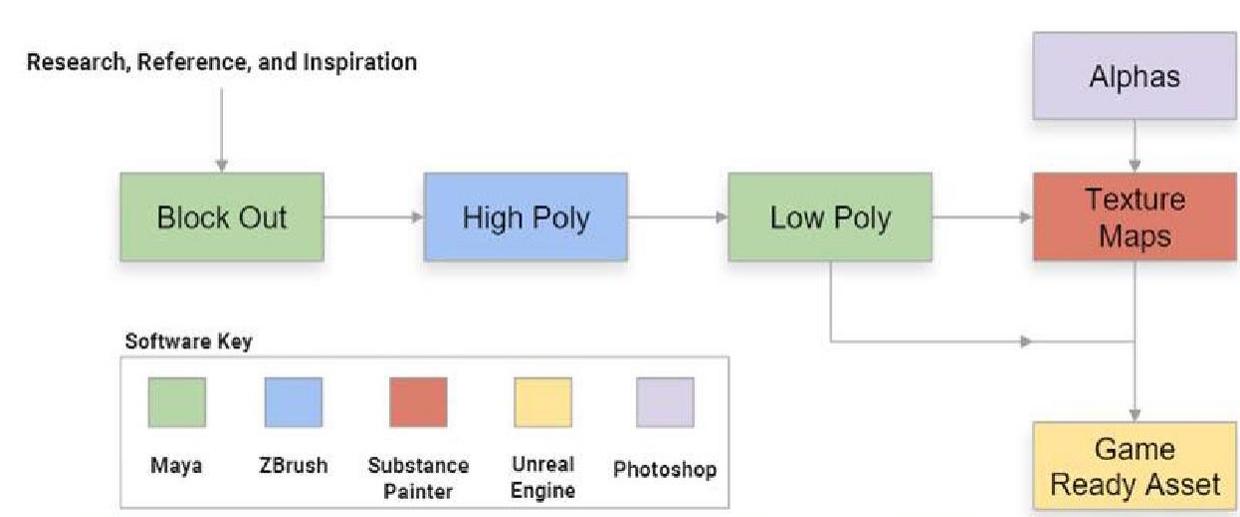
**Figure 3. Dynamic Smoke Design in Warehouse Fire Virtual Environment**

Based upon our initial work, we intend to expand our approach to better model the dynamic nature of smoke in future iterations of our scenarios. We identified several key areas that will contribute to more realistic smoke conditions within the testbed design:

- Ray Marching: Simulates light rays going through volumes
- Vector Fields for Airflow: Using vector fields to describe the airflow of a building
- Particles for Embers: Particles within the smoke that follow the airflow

**Prop Creation in Virtual Reality**

One of the methods we leverage to create higher fidelity in the simulated environment is the use of high-quality props. Props are objects that support the VR scene but are not part of the level layout (environment) or character set. The high-level workflow used to create props is included in Figure 4. Asset development begins with a low-detail version that is the building block for the rest of the process. Next, the asset is sculpted with high polygon details that will portray the final look of the asset. A low polygon shell is built around this final piece that is used in the game engine. Any additional texture maps, including black and white alphas, will be created in Substance Painter or Photoshop. The collection of these pieces will be combined in Unreal Engine to reach our game-ready asset.



**Figure 4. Workflow for Prop Design**

When designing virtual reality props, there are several key considerations to keep in mind. Many of the techniques that artists and developers use can contribute to poor performance and reduced frame rates which, in turn, create fewer satisfying experiences and increase the risk of simulator sickness. For prop design, there are two main types of considerations: performance and visual. We captured the major considerations in Table 1 and Table 2 below. We illustrate these factors using a common prop in the law enforcement (SWAT) scenario, the M4 rifle (see Figure 5).

**Table 1. Examples of Major Performance Considerations**

Polygon Count	Refers to the number of triangles that make up a 3D element. For example, in the case of the SWAT team scenario, the polygons are denser in areas that are rounded and in corners. Too many polygons can result in performance decrements.
Texture Size	Textures are flat images applied to 3D models. Props are often made up of multiple textures depending upon their visual importance to the scene. For example, the rifle body was given a more detailed texture because of its prominence in the user’s view. The magazine, which is mostly hidden from view, was given a lower detailed texture. Too many detailed textures can result in performance decrements.

Draw Calls	Each prop component has its own texture, which requires one draw call per material and one draw call per model. These draw calls are expensive in terms of computational overhead.
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**Table 2. Examples of Major Visual Prop Considerations**

Scale	Dimensions and proportions need to be accurate to ensure user immersion and to maximize the feeling of “presence.” Close adherence to realism also allows the weapons training and familiarity of real-world shooters to transfer more easily from the physical world to VR.
Missing Geometry	Users in VR can move their viewpoint more freely than with a traditional first-person camera, which typically cannot change height or clip (e.g., collide) through geometry. Traditional approaches do not render geometry which will always be obscured from the user’s view. However, it is necessary to render this geometry so that user immersion will not suffer due to incomplete or missing geometry.
Transparency	In this example, the scope on the M4 rifle must mimic the real-world specifications, materials, and related reflective properties because it is a tool that will be frequently used and looked at.

In this section, we described some of the challenges in creating higher quality props, necessitating a brief discussion on how prop creation relates to enhanced fidelity. In our testbed design, we leverage props to ensure that our end-users can interact with the system using similar strategies, tools, and equipment that they would use in real-world scenarios. By focusing development efforts on creating a higher quality rifle, we can ensure that participants can suspend disbelief long enough to participate in the scenario and complete their tasks successfully. In this case, the transparency of the lens on the rifle’s sight was a critical feature due to the frequency with which a participant uses this prop. By focusing on the design of the features in the environment, we can create a higher sense of presence, potentially leading to better training outcomes (Grassini et al., 2020).



**Figure 5. SWAT M4 Rifle Prop Design with UV (Texture) Mapping**

## DISCUSSION

Taken together, the design of NPCs, simulated smoke, and prop creation represent essential design considerations for enhancing fidelity in first responder training. However, it is important to note that we only described a small subset of the features and cues available in our testbed environment. As part of our ongoing research, we intend to expand

and iterate on this environment, focusing on three public safety disciplines: emergency medical services, fire, and law enforcement. We discussed two scenarios to demonstrate examples from our work, but this does not comprehensively explore all areas relevant to simulation fidelity. We plan to extend our work to enhance fidelity and immersion in VR and incorporate additional aspects of the environment, such as 3D user interactions. This paper describes the iterative approaches we have taken to ensure that scenarios are designed realistically. The next phase of our work will focus on verifying and validating these aspects of the testbed with formal, summative evaluations and user studies.

## **CONCLUSION**

When designing virtual environments for first responders, it is necessary to address the concept of fidelity from multiple perspectives. This paper illustrated several key areas that traditionally are not emphasized in the design of virtual testbeds for research and development with public safety end-users. Our goal is to share these lessons with the broader development community to better support developers and designers working in the public safety domain. By focusing on aspects of fidelity that are not typically considered, we highlight areas where future simulations can leverage work to create higher-fidelity, user-centered training scenarios for first responders operating in dangerous and unpredictable environments.

## **ACKNOWLEDGMENTS**

Certain commercial entities, equipment, or materials may be identified in this document in order to describe an experimental procedure or concept adequately. Such identification is not intended to imply recommendation or endorsement by NIST PSCR, nor is it intended to imply that the entities, materials, or equipment are necessarily the best available for the purpose.

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