Utilizing Physical Props to Simulate Equipment in Immersive Environments

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ABSTRACT

Whereas consumer virtual reality (VR) systems can support scenarios that are quite visually and aurally realistic, most of today's VR hardware is lacking when it comes to physical touch. This shortfall is especially critical when training for the use of real-world tools, where the lack of physical interaction can result in negative training effects. Although not widely done, enhancing existing VR systems with physical props and other physical cues can enable users to feel the equipment that they see. This can lead to users feeling more grounded and trusting of the virtual world as if they are actually present. We believe such physicality is important for use cases where learning by doing is optimal, experience is normally difficult to gain (e.g., high-risk low-frequency incidents), and task performance must closely match real world performance.

This paper provides a basis for integrating physicality into VR simulations. We summarize different ways to implement haptics in VR simulations, provide a taxonomy that differentiates between different haptic categories, and define six tiers of complexity. We exemplify these tiers through a number of case studies that we built for public safety research. These include simulating a new firetruck pump panel, monitoring for gases using a tracked air monitor device, searching a vehicle where users must reach within a confined space, riding out to a hot zone on a vibrotactile seat for simulating vehicle rumble, and prototyping a futuristic armband-touchpad interface for triaging a mass casualty incident. We conclude by detailing an ongoing user study that explores how adding physical props to VR can result in performance closer to real world performance.

ABOUT THE AUTHORS

Jason Jerald is CEO at NextGen Interactions and serves on multiple advisory boards. He has been creating VR systems and applications for over 20 years with over 70 VR-related projects across more than 40 organizations including Valve, Oculus, Virtuix, Sixense, MergeVR, AT&T, NASA, General Motors, Raytheon, Lockheed Martin, three U.S. national laboratories, and seven universities. Jason's work has been featured on ABC's Shark Tank, on the Discovery Channel, in the New York Times, and on the cover of the MIT Press journal "Presence". He has held various technical and leadership positions and has served on the ACM SIGGRAPH, IEEE Virtual Reality, and IEEE 3D User Interface Committees. Jason earned a Bachelor of Computer Science degree with an emphasis in Computer Graphics and Minors in Mathematics and Electrical Engineering from Washington State University. He earned a Master's Degree and a Doctorate in Computer Science from the University of North Carolina at Chapel Hill with a focus on perception of motion and latency in VR. Jason has authored numerous publications, most notably the best-selling book "The VR Book: Human-Centered Design for Virtual Reality."

Jason Haskins is Creative Director at NextGen Interactions, where he tackles day-to-day challenges of conceptualizing, designing, and implementing VR solutions using tools such as the Unity Game engine and Autodesk Maya. His design focus is in training and educational research in New Media and his technical proficiencies help him ideate on a broad range of projects, enabling him to better empathize with his team mates while generating solutions that fit with big picture thinking. Jason has worked for multiple research companies including BTEC and the Center for Educational Informatics (CEI) as a Game designer using the Unity engine. Jason has a degree in Art and Design from North Carolina State University and a background in Computer Science, Information Technologies, and hands on training in health care as a Corpsman in the US Navy.

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Bolin Zhu is Lead Programmer at NextGen Interactions, where he helps with conceptual design, implements features and functionalities, and develops VR applications. Degrees in Computer science and Interactive Media & Game Development from Worcester Polytechnic Institute paved the way for him with a solid background to enter the VR/AR industry. With the enthusiasm about VR/AR built up during college with research works and grant projects using Vive, Oculus, Hololens and so on, he also attended various VR-related events and Hackathons to further extend his knowledge about the industry and improve the related skills in programming and skills. The work at UMass Medical enabled him to pioneer a good number of innovative medical VR/AR applications that made him believe the VR/AR industry can help various aspects of lives.

Will Huse started his journey into XR as a co-founder of Moment XR where he worked as a designer and user tester to create a VR tool for designers to prototype interactive XR experiences. His degree from the University of North Carolina at Wilmington in Entrepreneurship and Small Business Development has given him a deep understanding of identifying market needs while his curiosity as an avid technologist has given him a wide view of the technological landscape. Combining these two allows him to create the applicable solutions to diverse problems.

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INTRODUCTION

Although first responders (firefighters, law enforcement, and emergency medical services) can be well-trained, they are not often able to practice their skills in the context that those skills are required until actual real-world incidents occur. Live action training does occur but is rare due to requiring significant resources. Even when such training does occur, it does not typically occur in the full context of difficult-to simulate incidents, most notably dangerous situations where there may be toxic gases, explosions, fire, etc. Because high-risk low-frequency incidents are rare, it can take many years of experience to reach proficiency that other professions are able to reach in months.

Virtual Reality (VR) can help to solve for many of these challenges and is more commonly becoming used to immerse trainees in audio/visual experiences. However, COTS (Consumer Off The Shelf) VR systems are not always appropriate for more active hands-on training where there is a need to manipulate physical tools. A lack of physical touch in VR can result in sensory conflicts that can lead to negative training effects, discomfort, and injury (Jerald, 2015). For example, if a trainee leans on a large piece of equipment that is assumed to be real, but that does not exist physically, then there is danger of falling.

Fortunately, there are ways to represent physicality in VR simulations through the use of haptics (physical forces). Although not as common as immersive audio and visual experiences, integrating haptics into VR can be especially appropriate for learning by doing, such as for teaching the use of physical tools. By building upon consumer VR hardware, physical props that are congruent with virtual objects can increase presence, cognitive mapping, spatial knowledge training, and performance (Insko et al., 2001). In short, haptics can help users feel more grounded and trusting of a virtual world so that they feel more like they are in a real incident gaining actual experience.

Although adding haptics to VR simulations has the potential to better prepare workers for risky jobs, we know of few resources that provide an overarching view of the many different options. Thus, for organizations to achieve the full potential of VR haptics, a more structured approach of integrating physicality into VR simulations is paramount. This paper aims to provide a basis for integrating physicality into VR simulations. Although our research focuses on first responders and use of their equipment, we hope this paper will provide insight of how physicality can be integrated into a broader set of use cases.

We first review prior work and summarize different ways researchers have implemented physicality in VR simulations. Next, we present a taxonomy of haptics where we discuss haptics properties as they apply to VR, six tiers of haptics implementations, and how we implement those tiers. We then describe some example uses of such haptics to enhance immersive scenarios for firefighters, law enforcement, and emergency medical services. These include simulating a new firetruck pump panel, monitoring for gases using a tracked air monitor device, searching a vehicle where users must reach within a confined space, riding out to an incident on a vibrotactile seat for simulating vehicle rumble, and prototyping a futuristic armband-touchpad interface for triaging a mass casualty incident. For future work, we discuss a user study we are conducting to explore how adding physical props to VR can result in performance closer to real world performance.

BACKGROUND AND RELATED WORK

Using fully tangible representations that match virtual/visual representations takes advantage of familiar senses and skills which have been learned by interaction with the real world (Englmeier et al., 2019). This is especially important for both 1) experts that have developed expectations and muscle memory through years of experience and 2) novices who need to develop skills that transfer to real situations without negative training effects.

Simeone et al. (2015) defined the term *Substitutional Reality* (SR) to be a class of mixed reality environments where the physical world is substituted with virtual counterparts. The concepts presented in this paper most closely match with their Aesthetic level of SR where the physical shape of real-world physical objects closely matches the shape of the corresponding virtual objects, but are visually different (e.g., the model colors can be different).

Using physical props with VR is not new and has shown benefits over virtual-only representations. Hinckley et al. (1994) used a physical plastic doll head as a proxy for rotational control of 3D models, which led to better understanding of the technique. Meehan et al. (2002) found that presence increased when users walk on a plank of wood on the floor that provided the tactile feeling of the feet extending over the edge into a deep pit. In other work, Lok et al. (2003) presented an approach for allowing virtual objects to dynamically interact with physical props. Zielinski et al. (2017) found that users controlling a clear acrylic box that contained projected virtual objects inside of it led to faster and more efficient manipulation as compared to a virtual-only technique. More recently, Englmeier et al. (2019) tracked two differently sized acrylic glass spheres by placing a Vive Tracker inside each sphere and compared handling the fully tangible spheres to a closely related controller-as-proxy interaction technique.

Utilizing physical props with VR does not necessarily result in better performance and that should not necessarily be the goal. Batmaz et al. (2019) found that adding a physical soft-surface wall increased time to hitting that wall (compared to a purely virtual wall), possibly due to concerns that reaching too quickly for the wall could hurt (like it could in the real world). For training of real-life incidents, a goal of physical props might be to better match real-world performance instead of trying to do better than the real world by using magical interaction techniques.

Ishii and Ullmer (1997) defined *tangible user interfaces* to be user interfaces that augment the real physical world by coupling digital information to everyday physical objects and environments. Because the focus of tangible user interfaces does not typically utilize head-mounted displays like the work described here, we utilize the term passive haptics that is more often used to describe physical props for VR research.

A TAXONOMY OF HAPTICS

Haptics are artificial forces between virtual objects and the user's body (Jerald, 2015). Many haptic systems also serve as input devices. Here we differentiate between some different forms of haptics as they apply to VR.

Passive and Active Haptics

Passive haptics provide a sense of physical touch in VR by creating real-world physical objects and matching the shape and pose of virtual objects to those physical objects (Lindeman, 1999). Developers sometimes utilize such physical objects and tangible interaction to enhance immersive experiences. Using passive haptics with VR improves presence, cognitive mapping, spatial knowledge training, and performance (Insko et al., 2001). What is surprising about passive haptics is how simple physical objects can add to presence. Once the user realizes those objects are real, they assume virtual objects they do not touch are real and that they would physically feel them if they did touch them (Jerald, 2015). Because of this, only adjacent objects that the user is likely to touch need to be physically represented.

Active haptics are forces controlled by a computer and are the most common form of haptics. Active haptics have the advantage that forces can be dynamically controlled to provide a feeling of a wide range of simulated virtual objects. *Vibrotactile* haptics are a form of active haptics that evoke tactile sensations using mechanical vibration of the skin. Electrotactile stimulation evokes tactile sensation via an electrode passing current through the skin. *Proprioceptive force* moves the user's limbs and/or provides joint/muscular resistance. More exotic forms of haptics (e.g., ultrasonic waves) also are typically considered to be active.

Tracked and Non-Tracked Haptics

Tracked haptics are tracked physical objects where the computer is aware of any change in those objects' pose, so their virtual representation can be made to match the physical one. Examples include hand-held props such as a flashlight, a moveable chair, and a hand-held panel.

Non-tracked haptics have no ability to inform the system if moved. If the object does not move, then the visuals can be matched to the physical via a calibration process. In some cases, objects may move but still don't need to be tracked; haptics can move with the body so that they apply forces consistently to an area of the body and may not have a need for a visual representation so there is no need to track them.

World-Fixed and Wearable Haptics

World-fixed haptics are physically attached to the real world and can provide a physical sense of fully solid objects that don't move. Examples are walls and large furniture. Such objects don't need to be tracked because they don't move, although the system does need to be calibrated in order to match the virtual with the physical. An excellent example of world-fixed haptics is The VOID (2020).

Wearable haptics are worn by and move with the body. Examples include haptic buzzers on the belt, pressurized bags in vests, and exoskeleton gloves. Although wearable haptics are typically active, that is not necessarily always the case—for example a holster can provide the sense of physically holstering a gun. World-fixed and worn haptics might or might not be tracked. Tracking world-fixed equipment can help automate the calibration process. Wearable haptics only need to be tracked if they are visually represented.

Sensory Compliance of Visual Hands and Haptics

Sensory compliance is the matching of sensory modalities across space and time (Jerald, 2015). Matching visual representations of the hands relative to physical props is important for grounding the user in the experience and for building the user's belief of what is real. When there is no visual representation of the hands, it can be difficult to know where the hands are relative to objects and thus be difficult to interact with those objects. When there is quality hand tracking, not only is interacting with physical props easier but the experience feels much more natural due to the hands' visuals being compliant with the physical sense of touch.

Hands can be tracked via cameras or gloves, or in some cases hands can be assumed to be holding a prop and visually attached to the prop. The prop can be physically constructed to be held in a certain way so that the hand is mostly likely to grasp the prop with a specific pose. Although this can have the disadvantage of breaking presence when held differently than the assumed pose, this is often better than attempting to accurately place the fingers on the prop due to tracking challenges. A hybrid approach works well in many cases where hand tracking is utilized until the hand gets close to the prop at which point the virtual hand snaps to an assumed hand pose.

Implementation Levels

Here we present implementation options that range from simple and easily accessible to custom-designed and more complexly supported solutions.

Tier 0: Standard VR Controllers. Standard VR controllers can work well when there is no need to touch objects (other than the controllers) in the simulation. For use cases where physical realism is not important (e.g., games), this tier has the advantages of being easily distributed to a large audience (e.g., consumers).

Tier 1: Non-Tracked. Some objects have no need to be tracked if they do not move. Reaching out and physically feeling immobile objects (e.g., walls, furniture, large equipment) can significantly contribute to presence and help to ground the user in the experience. A simple calibration process is required to line up the virtual with the physical. Sensory compliance of matching a visual representation of the hands with the sense of physical touch is important for this tier and higher tiers. For tiers 1 through 5, we use Leap Motion for hand tracking and visual snapping of the hand to the prop when hands come close to a touch point.

Tier 2: Add on Tracking. Tracking can be added to existing equipment. Tracking is essential for any equipment that will be moved and touched in order to maintain sensory compliance of what is seen and felt. This option has the advantage of being simple and only requires attaching a tracker and a simple calibration process. We implement Tier 2 with HTC Vive Trackers.

Tier 3: Add On Tracking & Buttons. Tier 3 adds button input to Tier 2. The buttons can be added onto the equipment's existing buttons to provide input to the VR application without requiring disassembling and rewiring the existing equipment. We implement Tier 3 via HTC Vive Trackers and a Pogo pin peripheral interface that communicates through the Vive Tracker's Bluetooth connection or USB cable. Up to three buttons are supported.

Tier 4: Add On Tracking & Inputs/Outputs. Tier 4 enables adding a more diverse array of inputs/outputs that can be a better fit for specific use cases. Examples include adding more buttons, proximity sensors, pressure pads, dials, and actives haptics. We add such capability on top of lower tiers via attaching additional sensors and outputs, most often integrated with Arduino components.

Tier 5: Custom Built. Tier 5 consists of equipment that is custom designed and 3D printed. This level achieves the maximum customization and fidelity of the targeted prop. All components and wires are contained inside, protecting the user from accidentally disabling the tracker and the user not being able to feel those components and wires or tape as is the case for lower tiers. We implement such capability through the SteamVR HDK and compatible sensors. Additional capability can also be added to the prop such as a trackpad via Arduino.

Table 1 shows the different tiers and what types of haptics and input they support.

Table 1. Capabilities matrix displaying the different haptics implementation levels.

Capabilites Matrix

		Passive Haptics	Tracked	Buttons	Additional Inputs	Active Haptics	Development effort
Tier 1	Non Tracked	✓					🔨
Tier 2	Add-On Tracking	✓	✓				🔨🔨
Tier 3	Add-On Tracking & Buttons	✓	✓	✓			🔨🔨🔨
Tier 4	Add-On Tracking & Inputs/Outputs	✓	✓	✓	✓	✓	🔨🔨🔨🔨
Tier 5	Custom Built	✓	✓	✓	✓	✓	🔨🔨🔨🔨🔨

EXAMPLE USE CASES AND THEIR IMPLEMENTATIONS

Below we discuss some example first responder VR experiences we've built that incorporate haptics. These examples are exploratory research prototypes that are meant to inform the design of what might be integrated into future simulation and training systems.

A Futuristic Firetruck Pump Panel

We built a futuristic pump panel simulator (Suhail et al., 2019) using consumer VR hardware, an Arduino board, basic electronics components, and physical props. Figure 1 (a) shows the physical pump panel and Figure 1 (b) shows the corresponding virtual pump panel. This pump panel implementation is Tier 5 and includes experimental controls: three buttons, a twist dial, a push/pull lever, and a Vive-tracked pipe that fits inside a slot. Although the full pump panel can be tracked, the tracking is not necessary unless the pump panel moves.

The physical panel only needs to be a subset of the more complex pump panel. As is common with traditional pump panel simulators, only the pump panel is shown in a virtual representation of our office that does not include the context of the firetruck nor a dangerous incident. VR provides additional capability over traditional pump panel simulators where the pump can be attached to the side of a virtual fire truck (Figure 1 (c)). Because the trainee is unlikely to touch the firetruck in our scenario, we don't need to build a physical representation of the fire truck.

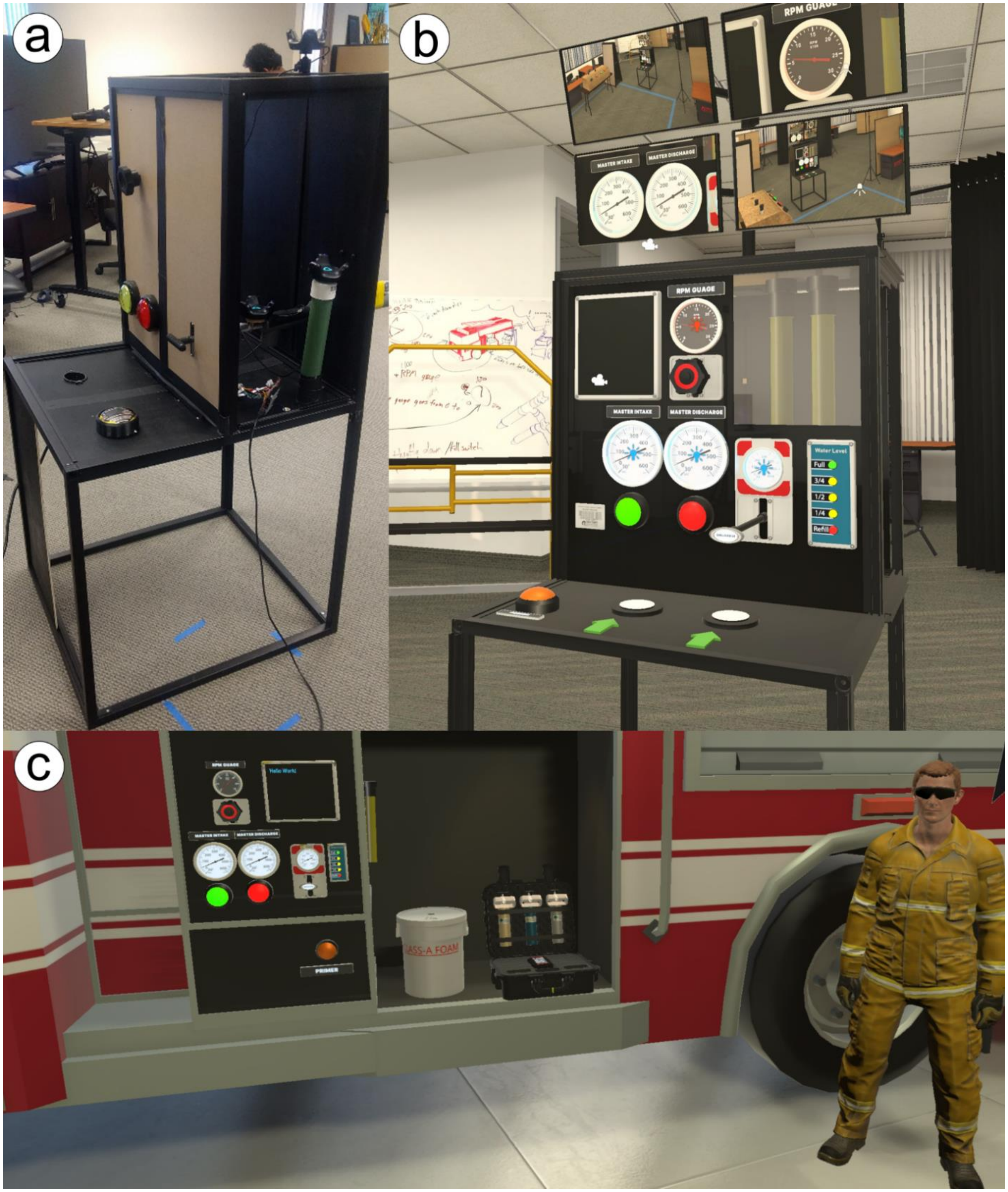

Figure 1. A Tier 5 physical pump panel (a), a virtual representation of that pump panel (b), and a different version of that pump panel attached to the side of a virtual fire truck (c).

Measuring Hazardous Gases Using a Hazmat Air Monitor

We built different versions of a simulated air monitor device. Figure 2 (a) shows a real air monitor device with a Vive Tracker attached and buttons wired as input into our VR system (Tier 3). Figure 2 (b) shows a 3D printed air monitor device with buttons (Tier 5) designed for a real air monitor rubber boot to fit over it so that it feels like a real air monitor. SteamVR compatible sensors are integrated inside of the device without the cumbersome external tracker, wires, and tape that are required for Tier 3.

The use of the simulated air monitor is only one part of the hazmat scenario. For the first few minutes, the user is not aware of the device. A virtual character that serves as a guide first introduces himself and assures the user that he will succeed though he is new to hazmat. The guide invites the user to listen in on the briefing by other first responders. After this discussion, the guide instructs the user to approach the air monitoring device (Tier 5) near a fire truck and to pick it up from a case (Tier 1) where the visual case is co-located to the physical case. The guide instructs the user to turn it on by pressing the bright red button on the device. The device then virtually boots up and displays low gas readings. The guide then instructs the user to perform a "bump" test by pushing the air monitoring device up against the case lid (Tier 1) that is represented both physically and virtually in the environment. At this point the gas levels shown on the device increase to the expected number, validating that the device is properly calibrated. As the scenario unfolds and the pair travels to the location of leaked gas, the guide demonstrates usage of the device and asks the user to take measurements.

A Virtual Ride Out on a Utility Task Vehicle (UTV).

For the hazmat scenario described above, we modeled a UTV to match a physical bench for users to sit on (Tier 1) when riding from incident command out to the incident. Adding vibrotactile noise to the bench (Tier 4) when the vehicle moves significantly adds realism to feeling like being on a moving vehicle even when the person does not physically move. We anecdotally observed that this also improves comfort by reducing motion sickness, although we have not yet performed formal user studies to confirm this observation.

A Traffic Stop Vehicle Search

We explored a vehicle search for a police traffic stop scenario (Figure 3). We used the interior of a trunk obtained from a junk yard) to offer passive haptics of the scenario to the user. We then matched the visual representation of the car to the physical trunk (Tier 1). We added a Vive Tracker onto the wheel well cover so that the participant can lift the cover (Tier 2) to look for contraband. We are also exploring ultrasound sensors (Tier 4) in order to determine if the hand enters small crevices of the trunk that would be difficult to track with SteamVR lighthouse tracking or Leap Motion due to sensor line-of-sight challenges.

Triage for a Mass Casualty Incident

We are exploring the use of a wearable armband interface for entering triage information for victims of a mass casualty incident. Figure 4 (a) shows the 3D printed armband interface that contains integrated sensors and trackpad input integrated with an Arduino board and electronics (Tier 5). Figure 4 (b) shows the virtual representation of the armband. The user’s main task will be to gather and update crucial patient data in a triage area to better facilitate transparency for the receiving unit at the hospital. The user receives and enters information on the device.

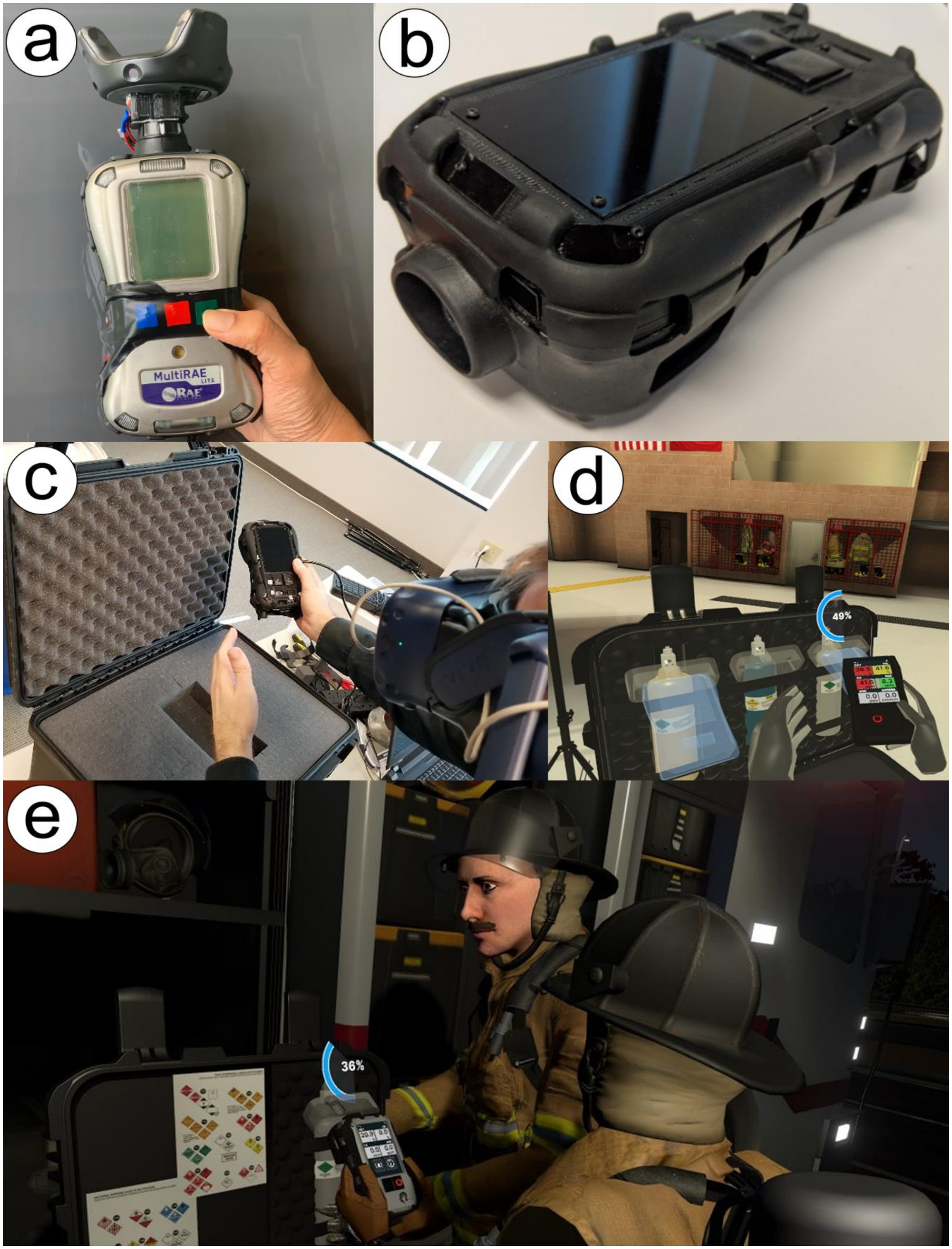

Figure 1. A Tier 3 real air monitor with tracking and buttons (a), a Tier 5 3D printed air monitor with integrated tracking sensors and button input (b), a user physically using the prop (c), a virtual representation (d), and a guide demonstrating how to use the air monitor in the context of a simulated incident (e).

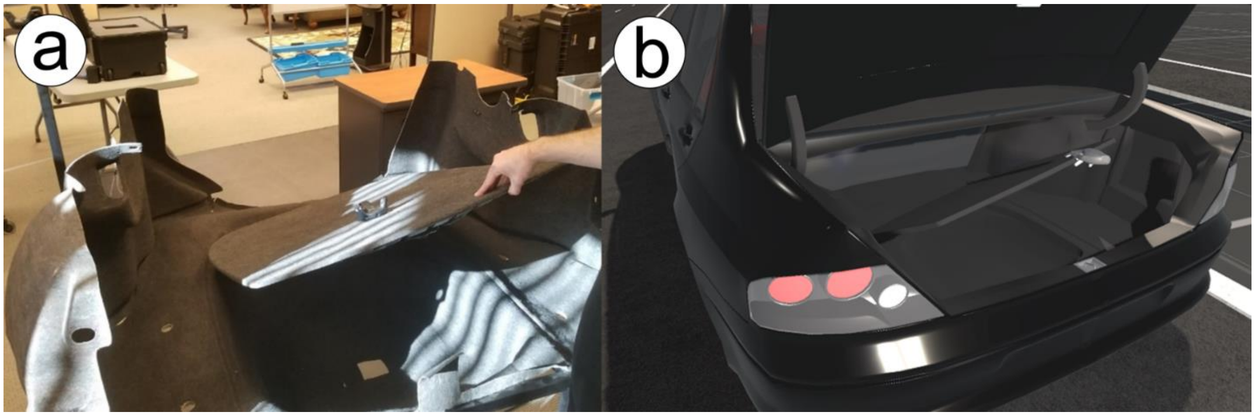

Figure 3. A Tier 1 physical trunk with a Tier 2 tracked wheel well cover (a) and the corresponding virtual view (b).

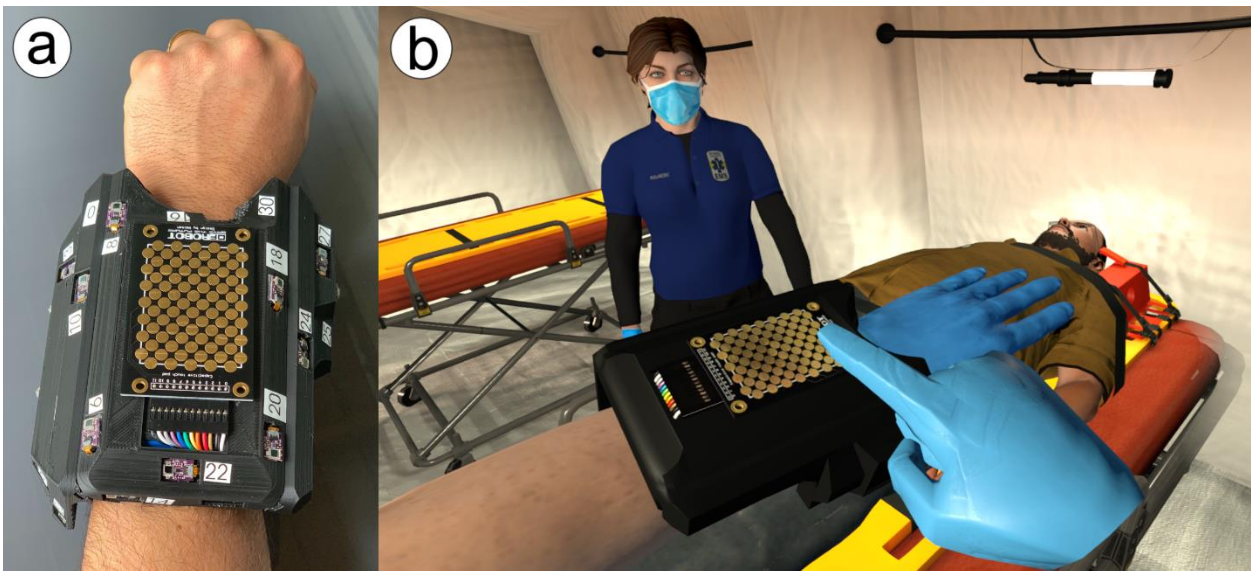

Figure 4. A Tier 5 tracked armband interface with button inputs and a trackpad (a) and the mass casualty triage scenario (b) where the participant records data on the armband.

PLANNED USER STUDY

The next stage of our research is to evaluate the effectiveness of the interfaces according to the following high-level research questions.

- *Does the addition of passive haptics to VR benefit simulation and training of first-responder scenarios and interfaces?*
- *Does the addition of passive haptics result in better matching to real-world tasks?*
- *In what cases are passive haptics beneficial?*

We are in the process of piloting the first user study, which aims to addressing the second research question above. The focus of the user study is to evaluate if the physical VR air monitoring implementation (Tier 5) matches real-world (non-VR) performance more closely than a standard VR implementation (Tier 0). We believe that the addition of passive haptics to a VR experience will result in task performance (measured by time to completion) that more closely matches the real-world.

The user study is being conducted under the following narrative.

You are a firefighter investigating reported gas leakage in a house where the owner believes the gas is coming through a vent. You must take gas measurements with a hand-held device at the vent. The device takes approximately 30 seconds to obtain a reading. Your task is to hold the device for 30 seconds at the vent location to determine if there is gas there. Your device may or may not result in a change in gas level as shown on the device. At the conclusion of the experiment, you will be asked if there was gas present or not.

In the study, we are measuring time to completion for various tasks. We minimize confounding factors by closely matching all conditions other than what we are testing for. For example, the real world, standard VR (Tier 0), and passive haptics (Tier 5) conditions will look similar and have equivalent interactions (Figure 5).

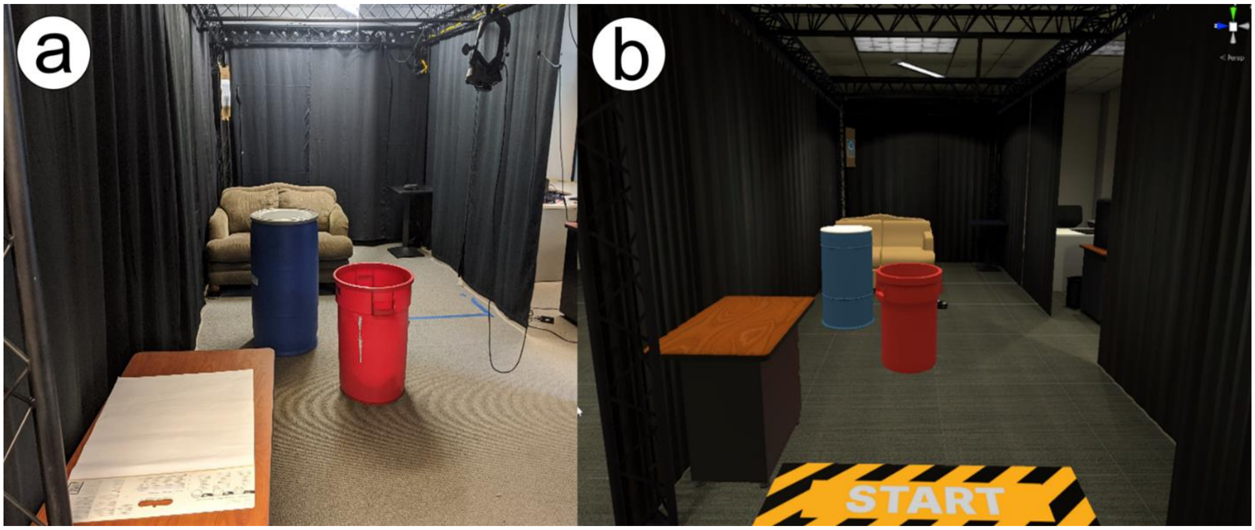

Figure 5. The real world space (a) and the corresponding virtual space (b). We match the virtual conditions to the real world conditions in order to compare real world performance to VR performance.

DISCUSSION

We have established various levels of haptic implementation and discussed their tradeoffs. In addition, we have integrated VR-enabled physical equipment into scenarios aimed at improving training transfer to the real world.

Physical props can be instrumental, especially where the physical manipulation of equipment needs to be mastered. We believe the best use cases for integrating physical equipment is where there is need to practice for high-risk low-frequency incidents. Unfortunately, workers rarely have an opportunity to use their equipment in such situations—full competency of using physical devices in the context of dangerous, distracting, and chaotic environments only comes with years of experience. VR provides for simulation and training 24 hours a day even when resources are unavailable. Even when resources are available (e.g., live-action training), some things are difficult, impossible, or unsafe to do using traditional means (e.g., usage of toxic gases to trigger gas monitors). Although our current work focuses on public safety, we believe this work could significantly benefit other domains—specifically the military, astronaut operations, the nuclear industry, and the oil & gas industry.

Even with physical equipment integrated into VR, we do not believe VR will ever completely replace traditional training. We do believe it can provide enhanced benefits if used where appropriate and in addition to existing methods that are already known to work well. Multimodal experiences can bridge the gap between theory and practice by enabling trainees to apply cognitive know-how to practice of using that knowledge outside of the classroom. Likewise, practice of physically using equipment will reinforce their cognitive understanding of what would otherwise be unapplied abstract concepts.

Although we have prototyped all of physical-prop tiers described in this paper, more research is necessary to quantify the benefits of haptics in real-world training simulations. Ultimately, we need to scientifically expose the trade-offs across the benefits of realistic and complex tiers versus the easier to develop lower-level tiers. We believe each tier has its own advantages and disadvantages, and a more thorough analysis of the tiers will result in being able to select the most appropriate tier based on specific use case needs.

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