A Multimodality VR Training System for Future Electrical Vehicle Emergency Responses

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ABSTRACT

The human society's mobility tool is shifting the paradigm from combustion engine vehicles to electric vehicles (EV). The wide adoption of EVs will benefit the sustainability of society by improving fuel efficiency, lowering fuel and maintenance costs, and reducing carbon emissions. However, the rise of EVs also brings challenges, particularly in EV emergency responses, in which EV fires burn hotter and longer than traditional vehicle fires, and most first responders are not well prepared. This paper introduces a multimodality virtual reality (VR) training system designed to help firefighters understand EV fires. The proposed VR system allows the user to visualize different phases of the thermal runaway process during EV fires. The proposed system has four modules to enhance the fidelity and improve the presence for the user to understand the EV emergency response scenarios. The results from the preliminary evaluation case confirmed the usability and feasibility of the proposed system.

INTRODUCTION

Human society's mobility tool is shifting the paradigm from combustion engine vehicles to electric vehicles (EV). According to the EV world sales database (Irle 2023), the EV market is rapidly expanding, with global sales reaching 10.5 million in 2022, a 55% increase from 2021. The International Energy Agency (IEA) envisions that there will be 55 to 72 million EVs on the road by 2025 (IEA 2021), which means 1 in 10 cars are expected to be EVs. The widespread adoption of EVs promises significant economic and environmental benefits for society by improving fuel efficiency, lowering fuel and maintenance costs, and reducing carbon emissions. However, the high penetration of EVs will also bring unprecedented challenges to society, especially EV-related emergency responses. The lithium-ion batteries in EVs are extremely volatile and flammable when operating at high temperatures (Kalhoff et al. 2015). The EV fires burn hotter, longer, and take more resources to extinguish compared to traditional vehicle fires. For example, in January 2023, firefighters in Sacramento, California, spent approximately 10 hours and used 6,000 gallons of water to put out a Tesla Model S vehicle fire (Smith 2023). This highlights the unique challenges that first responders face in EV emergency situations. The EV-related emergency responses will bring unique challenges and threats to society, but most first responders are not well prepared. The National Transportation Safety Board (NTSB) survey found that nearly 71% of fire departments identified EV emergency response as a significant challenge, and most first responders' work standards, training protocols, and training methods related to EV emergency responses are dangerously outdated (DHS 2016). Therefore, there is an urgent need to improve first responders' training methods for future EV emergency responses.

In recent years, several federal agencies have started to be aware and warn of the potential risks of EV-induced incidents for public safety agencies and worked with EV manufacturers to develop in-person or online EV emergency response training programs for first responders, such as NFPA EV training program (NFPA 2022), NVFC training program (NVFC 2023), and GM EV training program (GM 2023). However, it has become clear that the effective and scalable ways of training first responders for future EV emergency responses are still not well explored. There are two main issues related to existing training methods: On the one hand, it is not effective and economical to in-person EV emergency response training because of resource-expensive. Since the EV is still in the early stage, only a few EVs have been scrapped, making it expensive and risky for fire training agencies to burn a real EV for hands-on experience. On the other hand, the existing online training in EV emergency response is not immersive. EV emergency responses require an egocentric cognitive awareness of motor planning, execution, and situational awareness about the surrounding working environment. Existing online training methods struggle to provide the embodied experience necessary for first responders to understand EV emergency response requirements. To narrow these knowledge gaps, a new multimodality Virtual Reality (VR) training system is proposed to help first responders to better understand EV emergency response scenarios. The proposed VR training system allows the users to interact with the virtual EV and the surrounding emergency response environment, such as fire and smoke with immersive visual and audio feedback in the immersive virtual environment. The novel fire simulator module in the VR system allows the fire and smoke not only to propagate within the vehicle but also to propagate to the surrounding built environment. The generated haptic feedback allows the users to intuitively understand the severity of the EV fire by following the progress of the thermal runway and the intensity of the fire. The results of this study have demonstrated that our proposed multimodality VR training system is a reliable and efficient platform that is able to help users understand EV emergency response scenarios. Our proposed VR training system has the potential to be utilized in the real world for training first responders to mitigate EV-related emergency response.

LITERATURE REVIEW

Electric Vehicle Emergency Response

Vehicle emergency response is not a new concept for first responders. For example, in 2022 alone, there were 212,500 highway vehicle fires that accounted for 15% of the 1.4 million fires in the United States (US), which resulted in 3261 fatalities, 1500 injuries, and $1.6 Billion in economic losses (Ahrens 2020). But it is a different story when an EV catches on fire. Compared to traditional vehicle fires that can be put out with water or foam and usually don't reignite once the fires are extinguished, EV battery fires always happen in the compartments that are isolated by the battery shields (Plungis 2018). This existing manufacturing design makes the EV fires extremely challenging to extinguish. The current practice to put out EV fires is to cool down the battery shields' temperature to a certain point where the chemicals stop burning (Plungis 2018). But this firefighting technique requires lots of water, resources, and experience. A recent report from NTSB indicated that firefighters need to use at least 2000 to 3000 gallons of water to extinguish EV fires (NTSB 2020). They also need to continuously monitor the temperature of the batteries even after the fire is out since the fire in the compartments may reignite within the next 24 hours. By considering all the mentioned challenges in the EV emergency responses, there is a pressing need to design a training method that provides intuitive training instructions for first responders to understand the EV-related emergency response scenarios.

VR Applications for Fire Emergency Response Training

With the development of technology, VR has been widely implemented to investigate fire-related emergency response behaviors in recent years since VR can provide a high-fidelity virtual environment to evoke participants' mental and behavioral responses to emergency response scenarios. Compared to traditional fire training may expose participants to hazards, such as toxic gas emissions and uncontrolled fires, potentially resulting in fatalities. In contrast, VR-based training platforms offer a controlled, cost-effective, and secure training environment, mitigating the risks associated with conventional training methods (Xu et al. 2014). For example, Lin et al. (2020) conducted a VR-based experimental study to explore how the completeness of spatial knowledge influences the evacuation behavior of passengers in metro stations. They found that the completeness of spatial knowledge significantly affected participants' evacuation performance, and the pattern of the crowd flow significantly impacted participants' evacuation behaviors. Shi et al. (2021) also conducted a VR-based experiment with 40 firefighters to understand the impact of spatial information on firefighters' wayfinding performance. The results indicated that the route and survey spatial information was more efficient in facilitating firefighters to memorize the layout, leading to better wayfinding performance. Lovreglio et al. (2020) compared the effectiveness of fire extinguisher training between the use of VR and traditional video training. They found that VR trainees scored better than video trainees in terms of knowledge acquisition. Zhu et al. (2019) proposed a participatory and evolutionary fire simulation framework that is grounded in the domain experts' comprehensive understanding of fire events. This approach endeavors to balance the accuracy and fidelity of the simulation with its usability and to offer a robust and efficient instrument for practitioners. However, by comprehensively reviewing the existing literature on implementing VR technology in fire-related emergency response training, there are very limited studies that utilized VR techniques to explore vehicle fire emergency response scenarios, especially the EV emergency response scenarios. This proposed study aims to fill the knowledge gap in this research area.

METHODOLOGY

Overview of the multimodality VR training system

In this paper, we proposed a multimodality VR training system specifically designed for EV-related emergency response scenarios. This proposed system is capable of replicating the EV-related emergency response process without causing any harm to the user and the physical environment. We developed the proposed VR system in Unity3D with version 2019.4.30f1, and our system consisted of a wireless head-mounted display (HMD) (HTC VIVE Pro Eye) with two hand controllers, haptic accessories, thermal cloth, and a VR-ready desktop (Nvidia 3090Ti, i9-11900k, RAM 64GB) as illustrated in 1. The virtual environment was designed where an EV catches fire while it is located close to a residential house. This virtual environment has the potential to escalate into a larger conflagration that can affect the entire house and potentially extend to the surrounding neighborhood if not addressed promptly and effectively. In this simulation, participants assume the role of firefighters, utilizing fire hoses to extinguish the EV-related fire. The primary aim is to increase awareness about the potential severity and hazards of EV fires and to provide valuable training for firefighters who may not have extensive experience handling such situations. The virtual fire hose is attached to the virtual hand, enabling intuitive interaction with the VR environment. Triggering the hose discharges water, simulating the extinguishing of the fire. We designed the VR locomotion function with safety considerations in mind. The user can swing both controllers while holding the triggers, which provides not only clear directional cues, reducing potential disorientation but also minimizes real-world movement, mitigating tripping hazards and physical obstructions. The proposed multimodality VR system has four modules, which are visual/audio module, a haptic-thermal controller module, and an eye-tracking module. The following paragraphs will introduce more details about each module.

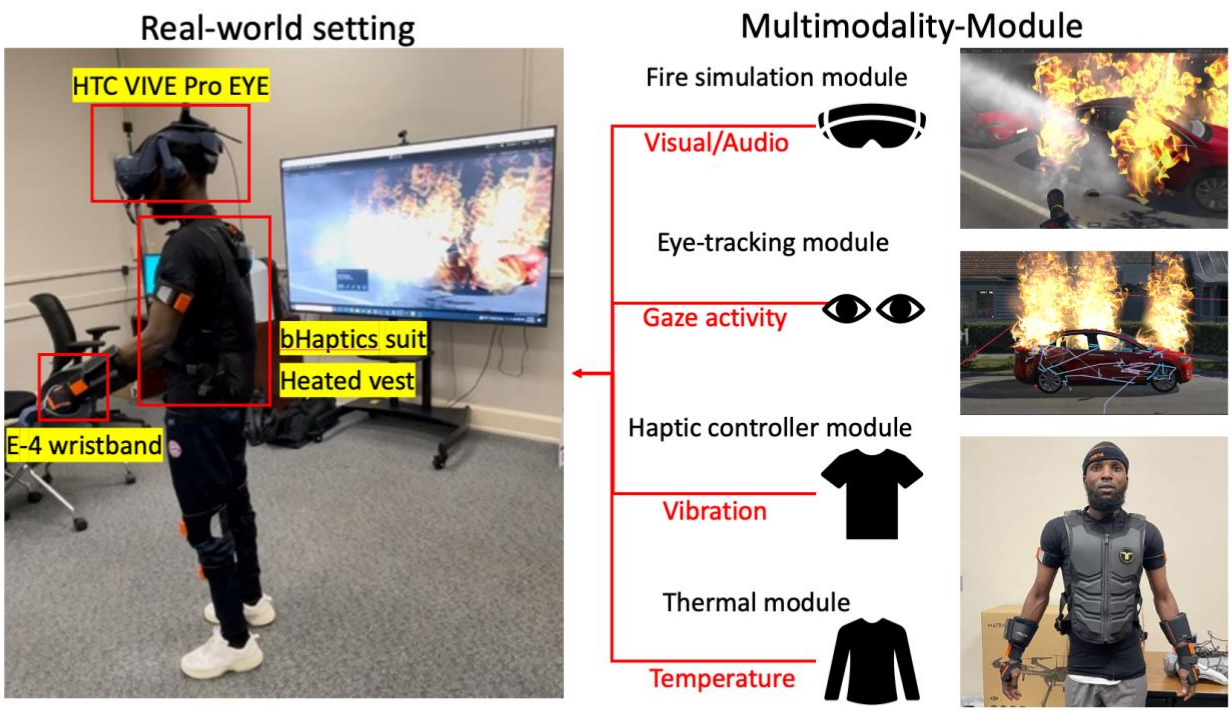

Figure 1. Overview of the proposed VR system with multiple modules.

Eye-tracking Module

An eye-tracking function was integrated into the proposed multimodality VR system, facilitating the acquisition of eye-tracking data related to fixations, gaze points, and pupillary changes. This data provided insights into areas of interest, dwell time, fixation sequences, and revisits. Utilizing these eye-tracking measurements, it becomes feasible to evaluate users' psychological responses during the training, thereby enabling a comprehensive evaluation of their training performance in the virtual environment. This proposed eye-tracking function was additionally developed based on our previous research works (Shi and Du 2022; Shi et al. 2020; Shi et al. 2020). This eye-tracking feature came with advanced recording and visualization options. The system autonomously generated a comma-separated values (CSV) file containing raw data after each recording. By utilizing the recording ID associated with each user, the system facilitated data visualization through the loading of the respective CSV file. In order to accomplish this visualization, the system employed Universal Render Pipeline (URP) techniques within the virtual environment, which was achieved by updating the positions of the built-in game engine's camera. Subsequently, the eye movement trajectories were rendered through the connection of gaze points, as gathered by the system, in accordance with their temporal sequence. To achieve these functionalities, several C# scripts were developed based on the Tobii Pro software developer's kit (SDK) and the corresponding application programming interface (API) in Unity.

Fire Simulation Module

To generate realistic fire and smoke effects in the virtual environment, we implemented the particle system technique in our proposed multimodality system. This approach allows users to dynamically modify the particle simulations by modifying a set of parameters in the virtual environment. The particle systems consist of a multitude of individual elements that can be manipulated and controlled through a series of C# script-driven parameters, including but not limited to emission rate, particle size, color, and lifetime. Particles within a particle system are not static entities, and they have a three-phase lifecycle, which is generation, dynamics, and termination. During the dynamics phase, the attributes of the particle system can be extensively manipulated to emulate the desired phenomenon, such as achieving a realistic representation of a flame in the present scenario. In the fire simulation module, the visual representation of fire and smoke is developed based on the particle systems. This approach facilitates emulating physical phenomena, including rising and spreading. Furthermore, the particle system allows for customizing various attributes, such as size, color, and intensity. The simulated fire can also be affected by an external force like wind or be extinguished by other methods like foam and water. By assigning flammable function to different virtual objects, the virtual fire can be propagated through the virtual environment. This function defines how the object burns, such as burn duration, fire spreading, and burnout behavior. To facilitate fire propagation, a physic dynamic function was added to the objects involved. The notion of spreading fire relies on detecting particle collisions between objects. In essence, the physic dynamic function is employed to ascertain the proximity between objects and the fire. When a flammable object's collider enters or remains within the fire's collider region, the object is ignited and subsequently acquires the ability to transmit the fire to neighboring objects, as illustrated in Figure 2. The process of extinguishing flames follows a similar approach, initially enabling collision between the objects and the fire-extinguishing agent. Subsequently, the extinguishing radius and efficacy are defined to customize the extinguishing effect according to specific requirements. The proposed system possesses the capacity to emulate various stages in a typical EV fire incident by manipulating the parameters associated with distinct fire characteristics, including shape, height, and color. For instance, the system demonstrates versatility in not only simulating the eruptive, incendiary flames characteristic of fire accidents, but also replicating the white-grey smoke indicative of the early stages of thermal runaway by modifying attributes such as color, length, density, and emission rate. A thermal runaway typically exhibits higher temperatures compared to normal fires, depending on the battery chemistry and specific condition. Consequently, the system possesses the capability to emulate the dissemination of fire at varying velocity rates contingent upon the materials involved. For instance, the rate of fire advancement exhibits a greater rapidity in a thermal runaway scenario compared to that observed in a standard combustion situation. Lastly, the burnout rate of an object exposed to combustion is influenced by a confluence of factors, encompassing material properties, prevailing environmental conditions, and fire attributes, such as heat release rate and flame dimensions. The proposed system is designed to account for and simulate these pertinent variables, thereby enhancing its applicability and accuracy.

Figure 2. Different situations of purposed electric vehicle (EV) fire training system: (a) White smoke emission; (b) Black smoke emission; (c) Fully engulfed fire; (d) Environmental involvement.

Haptic and Thermal Controller Module

The integration of haptic technology within VR systems enhances the user's immersion. A key component is the haptic controller module with an audio-to-vibrotactile system, utilizing the bHaptics TactSuit vest that comes with 40 motors, to generate precise, sensitive feedback and heighten the realism of the VR environment. Alternatively, the haptic controller can also provide tactile feedback in response to other custom events within the VR. For example, as the fire burns heavier or the user approaches closer to the burning vehicle, the more intense vibration there will be. Such a function can increase the awareness of the EV fire to the user in the virtual environment. To achieve this function, several C# scripts were developed into the haptic controller in Unity to enable the integration of haptic feedback into VR experiences. These scripts control feedback patterns, adjusting the intensity, duration, and location of vibrations on the haptic vest. This process maps virtual events to physical sensations, leveraging haptic hardware capabilities to deliver a more immersive VR experience. The flexibility of the haptic controller module allows for unique user experiences, enhancing the overall VR system.

The integration of a thermal module in the proposed VR system was designed to provide an additional layer of sensory feedback to the users, allowing them to perceive temperature variations in EV emergency response scenarios. While VR technology, traditionally dominated by auditory and visual elements, can be significantly augmented through the integration of temperature dynamics, thereby enriching the user experience and enhancing its realism. While this module can heat up to mirror the simulated scenario, it is crucial to note that the primary function of this module is to increase the degree of immersion, not to replicate the exact temperature conditions of an EV fire. Hence, the highest temperature levels should be constrained to ensure participant safety, avoiding any potential harm that could be incurred from excessive heat.

EVALUATION CASE

To test the usability and feasibility of our proposed multimodality system, we recruited five participants (3 male and 2 female) from the University of Alabama to evaluate our VR system as illustrated in Figure 3, and none of them had previously experienced EV fire scenarios. The proposed VR system was evaluated from VR sickness, immersiveness, and ease of control perspectives. The participants experienced a burning EV in the virtual neighborhood where the fire could be propagated to the virtual neighborhood. The demonstrated EV started with white smoke emission, which indicated a malfunction with the battery pack or the occurrence of a thermal runaway. Subsequently, the initial white smoke transitioned to dark smoke, which indicated the combustion of other vehicular components. This marked the escalation of the EV fire, culminating in the most critical phase, where the battery caught up on fire. The participants were instructed to suppress the EV fire while maintaining a safe distance since the EV is close to the wooden residential house. As the temperature escalated and the haptic vibrations intensified, the participants experienced heightened anxiety and stress that could be caused by EV emergency response scenarios. Following the experimental trial, we engaged each participant in a post-trial interview, during which they provided feedback on their experience. Notably, none of the participants reported experiencing any form of discomfort or sickness during or after the virtual reality (VR) simulations. As one participant eloquently remarked, "The system appears user-friendly, navigation is intuitive, and the animation depicting a fire being extinguished is strikingly lifelike." In the post-trial evaluation, a unanimous agreement was observed among the participants concerning the pedagogical value of the VR environment for understanding the core principles and concepts related to EV emergency response. The importance of the first responders' role in these simulated emergency scenarios was notably underscored by the participants. Moreover, the participants affirmed the functionality and user-friendliness of the interactions within the VR environment. The ease of use of the virtual interactions was highlighted, particularly the interaction that enabled participants to extinguish an EV fire virtually. At last, the simulated haptic and thermal feedback significantly improve the fidelity of the virtual simulations based on most participants' feedback, and one participant mentioned that haptic feedback is too strong for herself.

In summary, the evaluation test confirmed the usability and feasibility of our proposed multimodality VR system.

Figure 3. An example of participants extinguishing the EV fire in the virtual environment.

CONCLUSION

Our proposed multimodality VR training system was presented in this manuscript, and its usability and feasibility have been proved via our evaluation test by five participants. However, despite the positive evaluation outcomes of the preliminary study, several limitations still need to be addressed in our future research study. First, the current EV fire simulation module is manually modified, and its characteristics are predefined. In order to simulate more realistic EV fire scenarios, the real EV fire burning data needs to be imported into our VR system in our future research works. Second, we only simulated one EV emergency response scenario in a well-controlled environment. However, real-world EV emergency response scenarios are more complex and dynamic which involve environmental distractions such as moving traffic and other first responders. In our future study, we will integrate more environmental distractions into our virtual environment. At last, our VR system has been only evaluated by students. None of them have personal experience with an EV fire or other fire-related emergency responses. For a more comprehensive and solid evaluation, feedback and insights from first responders are needed in our future research studies.

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