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Review of Fire Emergency Training using Virtual Reality

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The severe destruction brought on by building fires is sometimes ascribed to several issues, including incomplete information and delayed decision-making, both of which can cause a situation to quickly escalate and make it more difficult to minimize the damage. Emergency evacuation exercises are essential for lessening the impacts of fires, but it's vital to remember that every building fire has a different set of challenges depending on the location, origin, and consequences of the fire. Because of this, utilizing specialized fire safety strategies and training programs may considerably boost the probability of effective mitigation and reduce the repercussions of these unforeseeable catastrophes. This essay offers a thorough analysis of cutting-edge innovations and less hazardous techniques that may be used to successfully reduce building fires. The intent is to contribute to the exploration and creation of more effective and sustainable fire safety measures and limiting the environmental impact by investigating and evaluating these cutting-edge approaches. The article will also go through conventional fire training techniques and give a thorough comparison with virtual reality (VR) fire emergency training methods, looking at the advantages and disadvantages of each strategy in terms of efficiency, expense, and accessibility.

Key Words: Virtual Reality, Building Fire, BIM, Fire Emergency Training (FET)

Introduction

Building fires have a catastrophic effect that cannot be emphasized since they not only cause major property damage but also cause a great deal of fatalities and serious injuries. These terrible occurrences have a negative emotional and financial impact on people, families, and entire communities (Alsharari, Liou, & Abudayyeh, 2019). Building fires really result in billions of dollars' worth of damage each year, thus it is crucial to prioritize fire safety measures and engage in thorough preventive and preparedness tactics to reduce the likelihood of such catastrophic occurrences. A house fire is reported every 89 seconds, and fire departments throughout the nation react to a fire every 23 seconds (Alsharari, Liou, & Abudayyeh, 2019; Bourhim & Cherkaoui, 2020). Over 1.4 million fire-related situations and 3,500 civilian fatalities and 15,200 reported wounded were the results of these accidents in 2020. Strikingly, more than one-third of these fires start on or inside of structures, making them the group most susceptible to such occurrences. These statistics highlight the critical requirement for all-encompassing fire safety measures, such as preventive, readiness, and response

plans, in order to reduce the dangers of fires and lessen their catastrophic effects on people, families, and communities (Alsharari, Liou, & Abudayyeh, 2019; Bourhim & Cherkaoui, 2020).
Although it is important to study emergency management, it is challenging to simulate disasters in real life, and exposing participants to actual risks would be immoral and unlawful. During the past 20 years, novel strategies have been created and used in emergency research to address this issue. Virtual reality (VR), augmented reality (AR), and mixed reality (MR) have emerged as particularly important among these techniques because they enable researchers to mimic situations without putting participants at risk. This is a key component of emergency management studies because it lets researchers examine intricate scenarios and assess the efficiency of various tactics in a secure and controlled setting (Zhu & Li, 2021). VR can give trainees valuable hands-on experience in a safe and controlled environment by creating immersive, simulated environments that mimic real-world scenarios. This is demonstrated in fire safety training programs, where VR can provide a useful and efficient solution to help people get ready to handle emergencies (Wang, Wu, Wang, Chi, & Wang, 2018). The goal of (AR) is to provide users the ability to perceive the real world while including virtual features that are overlaid or composed with actual items (Abotaleb et al., 2023; Placencio-Hidalgo, Álvarez-Marín, Castillo-Vergara, & Sukno, 2022; Samarasinghe & Piri, 2022; Zhu & Li, 2021). Since it enhances the actual real-world environment rather than creating a virtual one from scratch, augmented reality (AR) is more like the real world than VR (Abotaleb et al., 2023; Placencio-Hidalgo, Álvarez-Marín, Castillo-Vergara, & Sukno, 2022; Samarasinghe & Piri, 2022; Zhu & Li, 2021). In the realm of MR, the integration of reality and virtuality is reciprocal. Because there hasn't been much study on MR applications in emergency management, this analysis focuses mostly on VR and AR applications (Zhu & Li, 2021).
Three essential components made up the multifaceted research technique used to accomplish this study's goals. Initially, thorough literature research was done to compile pertinent data on the issue. Second, the study's top two questions were determined, and in-depth responses were sought to give a clear grasp of the subject. Finally, the advantages of contemporary emergency response training approaches were assessed. This included virtual reality-based training, which is increasingly recognized as a valuable tool for enhancing the efficacy of training programs and enabling people to respond to emergencies with greater competence and confidence.

Background and Literature Review

The most recent technological advancements employed by authors to generate virtual fire situations for teaching and study are summarized in this section. The emphasis is on cutting-edge virtual reality headsets and simulation software, among other technologies and methods, that are revolutionizing how fire-related events are practiced for and prepared for. Readers may learn in-depth details about the cutting-edge technology used in immersive virtual fire situations, frequently used for teaching and research reasons. Figure 1 provides an account of the use of technology. It is seen that VR is the most commonly used technology for training and educational purposes. Whereas Unity 3D software technology is commonly used to generate the stimulation output.
Virtual reality (VR) is a technology that duplicates viewers' realistic physical presence in an all-encompassing virtual setting. It is an affordable proactive learning strategy, especially in fields where real practice is unfeasible due to cost or safety concerns. VR is presently being used in training programs for the military, aviation, healthcare, and fire departments (Abotaleb et al., 2023). Advanced safety and health instruction are possible in VR, where accidents do not result in harm. Since VR requires specialized gear and technological know-how, it might be challenging to integrate a VR training facility into a building project (Abotaleb et al., 2023; Cha, Han, Lee, & Choi, 2012; Jacobsen, Solberg, Golovina, & Teizer, 2022).
Augmented Reality: The indirect or direct perception of the physical surrounding to the actual surrounding that is immersed with virtual aspects to produce a mixed reality in real-time using

technological or computational equipment is known as augmented reality (Placencio-Hidalgo, Álvarez-Marín, Castillo-Vergara, & Sukno, 2022). AR makes it possible to analyze human movement in real space from a particular vantage point.

Building Information Modelling (BIM): Building Information Modeling (BIM) is a modeling technology and associated set of processes which can communicate, produce, and analyze building models used for building design, construction, and everyday usage. The building's essential details, including its geometric measurements, structural and non-structural factors, and material, are provided by this BIM model. While material information is required since it impacts how building components burn, geometric information may be utilized to describe the inside environment (Lorusso et al., 2022). Revit, AutoCAD, 3D max, Navisworks are a few common 3D modeling software's that provide detailed building data.

Gaming Technology: By recreating a physical workspace in a secure training environment utilizing gaming technology, this technology has made it feasible to alter the human cognitive system. A game that is informative and entertaining is called game technology. This simulation of a game is built on the interaction and response of various human behaviors. Users can participate in the interactive model, and their choices can affect the next stage in the model or game, rather than using set ways to detect dangers (Jacobsen, Solberg, Golovina, & Teizer, 2022; Jiang, Zhou, & Zhang, 2018). It provides a path towards the fire. Unity 3D and Unreal engine are a few game platforms where a 3D BIM model can be integrated, and gaming scenarios are generated, and data is collected.

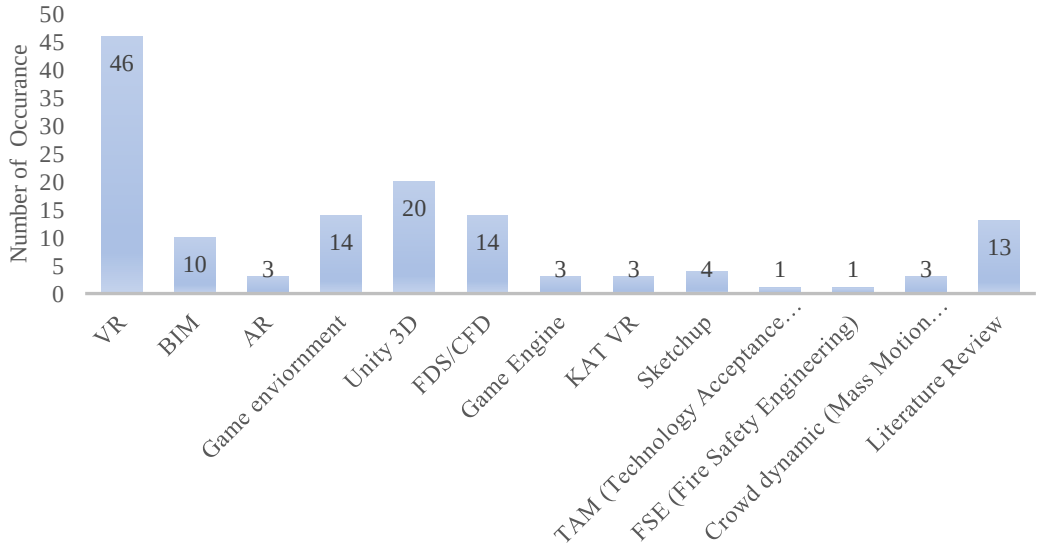

Figure 1: Frequency of technology usage in emergency training

Methodology

With the use of cutting-edge tools like virtual reality, augmented reality, and building information modeling (BIM), this study aims to give a thorough evaluation of the most recent developments in fire mitigation and fire emergency training. The review concentrated on articles that discussed technology utilization, traditional and modern firefighting techniques, and comparisons of old and new approaches. It also examined the advantages of current technologies, with experimental studies examining the effectiveness of newer technologies receiving the greatest attention. To improve the security and efficiency of fire prevention and response initiatives, this paper intends to offer helpful

advice for academics, practitioners, and policymakers by combining the lessons from these many sources.

A two-pronged search method, employing Scopus and Kennesaw State University's online library, to compile an extensive collection of pertinent publications was used. Several term combinations, such as virtual reality, fire, building fire, BIM, augmented reality, and fire emergency, made up our search criteria. Search resulted in a massive 900 papers on the subject, spanning the years from 1994 to 2023, using Scopus' Title/Abstract/Keywords search option and the keywords "virtual reality" + "fire." However, not all these papers focused specifically on building fires. To refine the search, we conducted a modified search with the keywords "virtual reality" + "building fire," which resulted in only 28 papers, of which we selected the most relevant. Similarly, we conducted a search with the keywords "augmented reality" + "building fire," which yielded 6 papers, and "augmented reality" + "fire," which resulted in 191 documents. We also employed the use of Computational Fluid Dynamics (CFD), a software tool used to analyze the flow of fire and smoke in materials and spaces, as a keyword in combination with "virtual reality," which led to the discovery of 573 documents. Furthermore, after searching with the keywords "virtual reality" + "fire" + "BIM," which resulted in only 28 relevant papers. After thoroughly reviewing all the papers gathered from these searches, only 65 of the most appropriate papers are studied in this research. By employing this robust search strategy, it is believed that data collection for a comprehensive and relevant collection of papers is ready.

Figure 2 provides a brief description of steps involved in reviewing the relevant 65 papers for this study. Beginning with categorizing the papers into two categories: fire emergency readiness and virtual reality for training. For the analysis, each paper was evaluated to find answers to two questions. The questions and their answers will be discussed in the paper. Second, the technologies used to create experimental fire emergency training were studied. After reviewing these papers for the subjects, results for the best technology and methodology are stated. Conclusions regarding current trends, optimal methodology, benefits, and drawbacks of modern technology in fire mitigation are also listed. Future direction and scope of this research are also discussed.

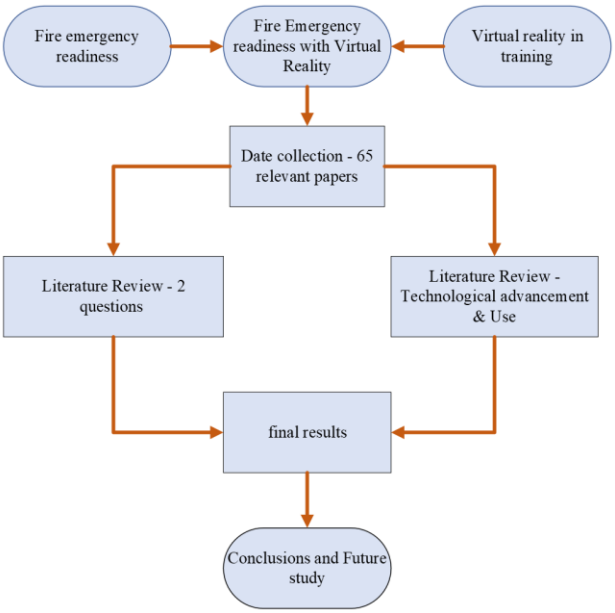

Figure 2: Proposed methodology for literature review

Qualitative Data Analysis, Results and Discussion

After reviewing 65 papers, they were classified into two distinct categories based on their similarities. These categories include virtual reality and training, emergency fire evacuation, behavior study in an emergency, augmented reality for training, and virtual fire experiments. It is important to note that not all the papers aligned with a similar objective. Therefore, the emphasis was given to the exploration of the use of technology to achieve the desired experimental results across the different categories. Figure 3 displays the number of publications related to the topic of mitigating fire with the help of virtual reality from 1999 to 2023. Initially, from 1999 to 2009, there was little to no research being done on this topic. However, there was a noticeable increase in research from 2009, with a steady growth until 2017. From 2018, there was a significant spike in research, which continued until 2021. Based on the current trend, there will be more research in this area in the future. It should be noted that the graph in Figure 3 only represents the number of publications from the 65 papers selected for the review and not the overall number of publications on the topic of mitigating fire with the help of virtual reality. However, the graph can still provide insights into the trends and patterns observed within the selected papers.

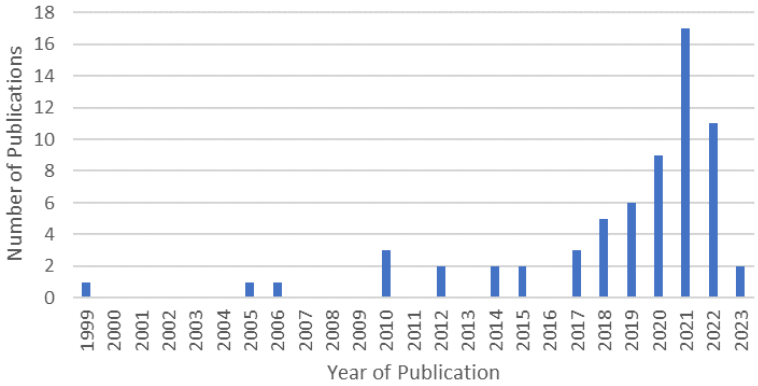

Figure 3: FET Technologies with VR Publications since 1999

This section presents the findings of a literature review based on 65 papers related to the two criteria discussed previously. The first category, "virtual reality and training," examines the use of virtual reality technology for training purposes, including fire and emergency situations. It also explores the various gadgets associated with virtual reality training. The second category, "emergency fire evacuations," analyzes current methodologies and technologies used for fire evacuations and firefighter training for emergencies. The third category, "behavior study in an emergency," aims to understand the psychology of people during a fire and its impact on decision-making. This category also investigates the behavior of candidates undergoing virtual/augmented reality training. The fourth category, "augmented reality for training," explores the use of augmented reality to train firefighters and understand the flow of fire and people's behavior during emergencies. Finally, the fifth category, "virtual fire experiment," investigates virtual fires created through CFD data, virtual reality, or augmented reality in experimental research papers, often focusing on public buildings like schools. This thorough literature review provides valuable insights into the current state of research related to virtual and augmented reality training, emergency fire evacuations, and the behavior of individuals during emergency situations.

Status of VR-enabled Fire Emergency Training (FET)

This part studies all the papers using VR for fire training for firefighters, occupants, and designers. The use of technology for aligned training activities is also analyzed. It was found out that 72%, i.e., 47 papers explored VR for Fire emergency training, or used VR for training purposes. Further in this paper, an explanation for the methodology used by various researchers is explored. Table 1 below explains the potential of VR for exploring and mitigating ways to reduce fire. It also dwells on explaining the technologies used to achieve the goal. Various gadgets and software currently used are explained.

Table 1: Status of VR-enabled Fire Emergency Training (FET)

VR and related technologies like BIM and AR are being developed to improve safety training in construction, with promising results despite the time-consuming creation and classification of safety information.	(Abotaleb et al., 2023; Bakar, Sirotiak, & Sharma, 2021; Cimellaro et al., 2019; Gao, Wang, Lai, & Hung, 2022; Malagnino, Corallo, Lazoi, & Zavarise, 2022; Tzani, Besharat, Charalampous, & Stylios, 2020; Wang, Wu, Wang, Chi, & Wang, 2018; Zhu & Li, 2021)
While VR has been used in education, using a head-mounted display can cause discomfort and poor depth perception.	
Portable technologies address VR issues, and there is a research gap in VR's creation and use in education and training, where pedagogy is not always needed.	
VR/AR technologies have been utilized in hazard identification, prevention, and safety training with methods such as BIM and GIS to create more realistic simulations and develop training techniques.	
VR technology has emerged as an effective way to address limitations in conducting laboratory investigations and may be used to produce reliable findings. Creating high-detail home replicas in VR is straightforward, and concerns related to using VR apply to virtual fire and smoke simulations as well.	
Augmented reality, virtual reality, and serious games are being researched for their potential to enhance evacuation training by improving immersion, engagement, and realism while addressing issues such as cost and disruption associated with conventional drills.	
VR and AV can enhance workplace safety training by safely simulating dangerous scenarios, improving realism, and advancing data collection and analysis.	
VR platform can simulate emergency evacuation scenarios, aid in building layout planning and fire protection system design, teach users and emergency operators, and replicate multi-hazard situations.	
VR technology can provide valuable insights into improving construction regulations based on findings from virtual simulations.	
Inspect uses VR scenarios with BIM models to help build occupants identify fire safety-related amenities.	
VR technology has evolved from requiring rooms with multiple large displays to head-mounted devices such as HTC Corporation's VIVE system.	
VR can provide visualizable, reproducible, and adjustable virtual architectural sample models.	

Benefits of VR-enabled FET

After careful comparison, it was found that at the initial stages, VR-enabled FET training is most efficient and poses less risk. This section also discussed the benefits discovered by using VR on residents and students. As seen in Figure 4, 46 papers discussed the various benefits of VR training. Table 2 below explains the benefits of Virtual reality to aid in guiding occupants, firefighters, and students to evacuate building premises in fire safely.
After conducting a thorough examination, it became apparent that a mere 20 papers provided comprehensive responses to both questions that were discussed. Consequently, to delve deeper into the subject matter, we have undertaken an in-depth analysis of the objective, methodology, experiment type, and outcome in this paper. This paper hopes to provide a more distinct understanding of the topic at hand and fill in any gaps in existing research.
It is clear from reading several studies that the use of mixed reality technologies like Virtual Reality (VR) and Augmented Reality (AR) has increased significantly recently. These technologies are no longer just used for entertainment or in the gaming industry. The current study investigates integrating and applying VR and AR technologies for emergency training. A careful examination of the data demonstrates that this novel strategy has various advantages, including improved memory retention and cost-effectiveness. As a result, using VR and AR in emergency training programs has gained popularity and is an efficient way to prepare people for emergency scenarios.

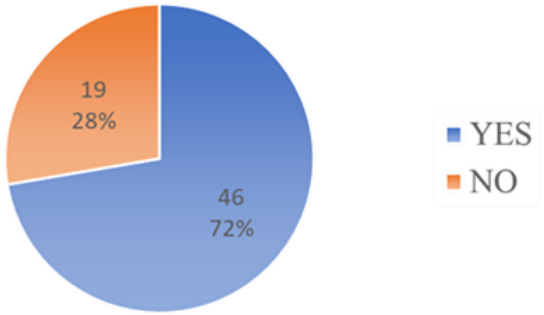

Figure 4: Benefits of VR-enabled FET.

Table 2: Explains the various benefits of VR training.

Enable interaction within the Virtual world.	(Alsharari, Liou, & Abudayyeh, 2019; Cimellaro et al., 2019; Gao, Wang, Lai, & Hung, 2022; Knapstad & Njå, 2021; Morélot, Garrigou, Dedieu, & N'Kaoua, 2021; Tzani, Besharat,
intuitive understanding of learning subjects	
Using VR's visual representation enables the integration of more freedom.	
Safe environment to train participants' cognitive abilities by simulating a dangerous scenario	
Increasing realism in simulations can improve the collection and analysis of synthetic data.	
Provide a safe and active way to experience workplace dangers with untapped potential.	
The use of VR technology in training courses improved trainees' focus and attentiveness.	
VR can be utilized to evaluate and improve building layouts, designated evacuation routes, fire protection systems, and verify existing building conditions for emergency evacuations.	

VR can also be used to train users and emergency operators on various scenarios and interventions.	Charalampous, & Stylios, 2020; Wang, Wu, Wang, Chi, & Wang, 2018)
Beneficial in understanding people's behavior in an emergency	
Influencing people to choose the correct exit path	
By providing visualizable, reproducible, and adjustable sample models, the use of this architecture can lower risks and expenses while enhancing the effectiveness of fire safety science research.	

Conclusion and Future Study

Virtual technology used in emergency scenarios is still in its infancy, and many academics are now researching this ground-breaking strategy. Although virtual technology has made significant strides, there is still much to learn about its potential uses and effectiveness in emergency situations. We can fully utilize virtual technology in emergency scenarios and create more thorough and efficient emergency response tactics via further study and investigation.

They lack any clear guidelines or standards for how to go about creating a virtual environment for emergency situations. There is no set method for constructing a virtual environment despite the wide range of technologies that are accessible and the countless combinations and permutations that may be used. Depending on the unique requirements of the experiment or simulation, the technology used may change. To create virtual environments in all emergency evacuation scenarios, a complete guidebook that explains a consistent technique is urgently needed. Emergency response teams can gain from a consistent, organized methodology with a cohesive approach that boosts the efficiency of their training and simulations. Training in virtual reality could enhance the appropriate reactions and actions to recognize fire dangers in a practical setting. Enhancing behavior skills can be aided by the sensation of presence and immersion that the virtual world creates.

In the construction sector, Building Information Modeling (BIM) has become one of the most widely utilized technologies, especially in areas like conflict detection and 3D geometry. BIM technology can quickly produce very precise and comprehensive models of the building when combined with Virtual Reality (VR) or Augmented Reality (AR). Building experts can swiftly create accurate and realistic models by employing the cutting-edge capabilities of VR and AR. This allows them to find and fix design errors before the building process even starts. As a result, the construction industry has adopted an increasingly common strategy for expediting the building process and enhancing overall project efficiency: integrating BIM with VR or AR technologies.

Understanding Virtual Reality (VR) technology's limitations and potential drawbacks is crucial as its application in emergency response scenarios continues to spread. Therefore, to increase the efficiency of VR technology in emergencies, future research in this area will concentrate on identifying and mitigating these flaws.

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