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A Mixed Reality Application for Multi-Floor Building Evacuation Drills using Real-Time Pathfinding and Dynamic 3D Modeling

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Abstract

In modern high-rise buildings, complex layouts and frequent structural changes often hinder emergency evacuation. Traditional evacuation plans, usually 2D diagrams, do not provide real-time guidance and are difficult for occupants to interpret. We propose a Mixed Reality (MR) application to address these challenges in real-time evacuation in multi-floor buildings. This application was developed on Meta Quest 3, chosen for its status as one of the best low-cost eXtended Reality (XR) headsets and a popular standalone Head-Mounted Display (HMD). Our system allows users to rapidly rescan and update building models, ensuring that evacuation guidance is always up-to-date. The proposed approach overcomes the Meta Quest 3 API's limitation of scanning only 15 rooms. It extends its capability by saving room data externally and using spatial anchors to maintain accurate alignment with the physical environment. Additionally, the application integrates Dijkstra's algorithm to dynamically calculate optimal escape routes based on the user's real-time location. A preliminary evaluation study demonstrates the application's effectiveness in enhancing situational awareness and enabling users to stay mentally sharp, highlighting its potential to improve decision-making and emergency response in dynamic building environments significantly.

CCS Concepts

• ***Human-centered computing*** → ***Mixed / augmented reality;*** • ***Software and its engineering*** → ***Virtual worlds training simulations;***

1. Introduction

In recent decades, how people interact with built environments has significantly evolved. Today, individuals spend 80–90% of their time inside large and complex modern buildings [JCCS20]. As more people occupy these spaces, navigating them, particularly in high-rise structures, has become increasingly challenging [HLJ12]. The rapid increase in high-rise buildings has also escalated the potential risks associated with indoor emergencies, such as fires and gas leaks, posing significant threats to life and property.

Evacuation drills play a crucial role in preparing building occupants for emergencies. However, these drills often rely on traditional evacuation plans, typically presented as two-dimensional (2D) diagrams that aim to indicate unsafe areas and suggest evacuation routes. However, many building occupants struggle to quickly interpret these drawings, locate themselves within the building, or identify the most efficient evacuation path during an emergency [KJT23].

To address these limitations, recent advancements in Virtual Reality (VR) [DZC*24] and Augmented Reality (AR) [KJT23, WRK22] technologies have been explored for evacuation drills. These technologies use pose estimation techniques to simulate emergency scenarios, allowing users to practice evacuations in a virtual environment. However, these VR and AR methods are usually based on pre-loaded 3D models of the building, which quickly become outdated due to frequent changes in room layouts from renovations or repurposing. This static nature limits the effectiveness of VR and AR drills in preparing occupants for real-life emergencies.

Although AR and MR are often used in applications based on outdoor geolocation [CAE16, CLK*24, Ker22], it is essential to note that Indoor localization systems offer various approaches for providing indoor positioning. These systems rely on fiducial markers, near-field communication, Bluetooth Low Energy, and WiFi [KCU*22]. However, they require substantial infrastructure and can be limited by signal interference, maintenance needs, and the necessity for pre-installed markers or access points.

We propose an MR application to overcome these challenges in real-time indoor emergency evacuation drills. Our system utilizes the Meta Quest 3, which is recognized as the top-budget XR headset. Our system brings inside-out tracking beyond traditional room-scale limitations, allowing users to generate a 3D model of an entire building encompassing multiple rooms and floors. This feature enables users to quickly re-scan rooms and refresh the 3D model, ensuring evacuation drills reflect the most up-to-date layout. Consequently, our method addresses the limitation of the Meta Quest 3 API, which can only scan 15 rooms, by enhancing its

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capabilities to externally store room data and utilizing spatial anchors to ensure precise alignment with the physical environment. Furthermore, our system uses the Visual-Inertial Simultaneous Localization and Mapping (SLAM) capabilities of the Meta Quest 3 to track the user's position in real-time without needing external systems like WiFi, markers, or Bluetooth. This approach enables the creation of dynamic 3D models and provides accurate positional tracking even in environments where traditional localization methods may fail. In addition, MR technologies, when combined with our dynamic 3D modeling approach, can significantly enhance evacuation drills by overlaying digital information directly onto the physical environment. This may improve situational awareness and navigation capabilities.

Our application uses Dijkstra's algorithm [Dij22] to calculate the shortest evacuation routes, considering critical features such as door positions to ensure precise and efficient real-time pathfinding. This approach may significantly enhance decision-making during drills, helping building occupants evacuate swiftly and safely and reducing the potential for injuries or fatalities.

To evaluate the usability and effectiveness of our proposed application, we conducted an evaluation study with a diverse group of participants engaged in a simulated emergency scenario. The study offered valuable insights into the system's usability and sentiment, demonstrating the potential of MR-based guidance to enhance emergency preparedness in real-world settings.

The contributions of this research are:

- development of an MR-based evacuation tool that integrates an algorithm for real-time computation of shortest evacuation routes;
- integration of features for dynamic 3D modeling of multi-floor buildings;
- conduction of a preliminary evaluation study on the usability and sentiment of the application.

The remainder of this paper is structured as follows: Section 2 provides an overview of related work; Section 3 describes the technologies used and provides details on the design and architecture of the proposed MR application, including the dynamic 3D modeling and the evacuation guidance tools; Section 4 presents the results from our experimental evaluations; and Section 5 discusses the potential impact, the limitations, and future directions of this research.

2. Related Work

XR systems have already investigated serious games for emergency evacuation drills [AYA24, FGM*23, KMS16]. However, most are mainly focused on VR applications, indeed in the last years, a plethora of systematic reviews were presented [FGA*18, ZL21, GBQ*23]. Some of them consider the simulation of emergencies, also trying to examine the skills training of involved people [ACJ*23], while others focus on safety training studies, evaluating the effectiveness of such approaches [SMH23]. As reported in this section, although practical applications of AR and VR have been proposed, our work specifically focused on using MR for evacuation drills. Additionally, the proposed approach aims to surpass existing commercial MR applications, such as those based on Meta Quest 3, by overcoming hardware limitations to effectively track large, complex buildings with multiple rooms and expansive, intricate environments.

2.1. Virtual Reality Approaches

VR-based approaches like the one proposed by Liu *et al.* [LCY*22] introduce a Markov Chain Monte Carlo-based method to automate VR fire evacuation drills, exploring the participants' remote collaboration behavior. A user study shows that varying drill difficulty levels enhance teamwork, helping users prepare for real-life scenarios. In addition, in [LZLBG20], the key concept is collaboration behavior. Indeed, the authors examine how crowd flow affects behavior during fire evacuation using VR simulations in major cities' metro stations. The proposed results indicate that participants tended to follow the majority under stress, with similar behavior across cultures. The study underscores the role of crowd flow in evacuation decisions and the value of VR in studying emergency responses. Lu *et al.* [LYXX20] developed a simulation framework for indoor post-earthquake fire rescue, combining the Building Information Model (BIM) and VR to model the complex environment caused by seismic damage, fire spread, and fallen debris, creating an immersive training scene for firefighters. The earthquake emergency training scenarios inspired several studies [LLQ*17, ZXY*21]. In a couple of papers, Feng *et al.* [FGA*20, FGM*20] explored the application of Immersive Virtual Reality (IVR) and serious games for earthquake emergency training. The first one investigates the effectiveness of IVR serious game designed to improve earthquake behavioral responses and post-earthquake evacuation preparation. The second paper explores how IVR serious games can be customized to meet different learning goals. It introduces a framework that allows for adjustments to virtual environments, storylines, and teaching methods, making the training more relevant and effective for different users.

2.2. Augmented and Mixed Reality Approaches

The effectiveness and usefulness of AR for emergency evacuation training have already been explored by Paes *et al.* [PFK*24]. They evaluate an AR-based training system for fire safety, comparing it to traditional video-based methods. Through a controlled experiment, the AR system matched traditional methods in knowledge retention while significantly increasing motivation and self-efficacy, making it a promising tool for enhancing fire safety training. Gan *et al.* [GLLC22] presents an indoor evacuation guidance system that employs an AR virtual agent on smartphones to provide real-time, voice-guided directions to the nearest exits during emergencies in large, complex buildings. Tested in a museum, the system demonstrated good usability, effectively helping users in safe and efficient evacuations even in unfamiliar environments. Similarly, Catal *et al.* [CAT*20] introduces an AR-based evacuation training game designed for academic people, utilizing architectural plans and 3D models to simulate realistic emergency scenarios. The system guides users to the nearest exits and includes educational animations on various emergencies. A user study demonstrated high satisfaction and effectiveness in enhancing evacuation preparation, suggesting AR as a viable alternative to traditional training methods.

MR Zhen et al. [XYZF23] focused on a method for conducting indoor earthquake safety drills, specifically addressing the risks posed by nonstructural components such as furniture and ceilings. Utilizing the HoloLens, the approach reconstructs detailed 3D models of indoor environments and simulates seismic damage using a physics engine. The study highlights the effectiveness of this mixed reality drill in improving participants' ability to navigate to safe zones during an earthquake.

3. Methodology

3.1. Technologies Used

This study utilizes several advanced technologies to develop an MR application for real-time emergency evacuation in multi-floor buildings. Key components include the Meta Quest 3 headset, the Unity game engine, and the Meta All-In-One SDK. The Meta Quest 3 is one of the best low-cost next-generation XR headset featuring high-resolution visuals, powerful processing, and advanced inside-out tracking, enabling environment mapping without needing external sensors. Its standalone design eliminates the need for additional hardware, making it a convenient off-the-shelf solution for deploying an MR application that needs to operate in multi-floor buildings. Meta Quest 3 capabilities are essential for our application thanks to the feature that enables rapid scanning and updating of 3D models of buildings and allows users to ensure accurate and current evacuation guidance in dynamic environments. Our system was developed through Unity [Uni], a cross-platform game engine that provides robust tools for creating immersive experiences. We used Unity to build the 3D environments, interactive elements, and user interface, integrating virtual and physical worlds to enhance emergency evacuation strategies.

Essentially, the use of the Meta Quest 3 and Unity is almost a necessary choice, as the Meta All-In-One SDK [Meta] is specifically designed for Unity. It consists of several Unity-compatible packages that provide essential tools for developing applications on the Meta Quest 3 headset, including three main components: (*i*) Meta XR Core SDK [Metb], which provides essential functionality for VR and MR applications, such as camera rigs, hand tracking, compositor layers, passthrough capabilities, spatial anchors, and scene management; (*ii*) Meta XR Interaction SDK [Metc], which adds modular interaction capabilities, including ray, poke, locomotion, and grab for controllers and hands, as well as hand-specific interactions like gesture detection. These features support intuitive and natural user interactions in the virtual environment; (*iii*) Meta XR Mixed Reality Utility Kit [Metd], which offers tools for building spatially-aware applications, aiding in tasks like aligning virtual content with the physical world and managing spatial anchors. This kit simplifies the development of dynamic, context-aware MR experiences.

3.2. System Architecture

The proposed MR application is designed to operate in two distinct modalities: scanning and updating the layout of the building and the other for guiding real-time indoor evacuation. Figure 1 shows the framework of the proposed system.

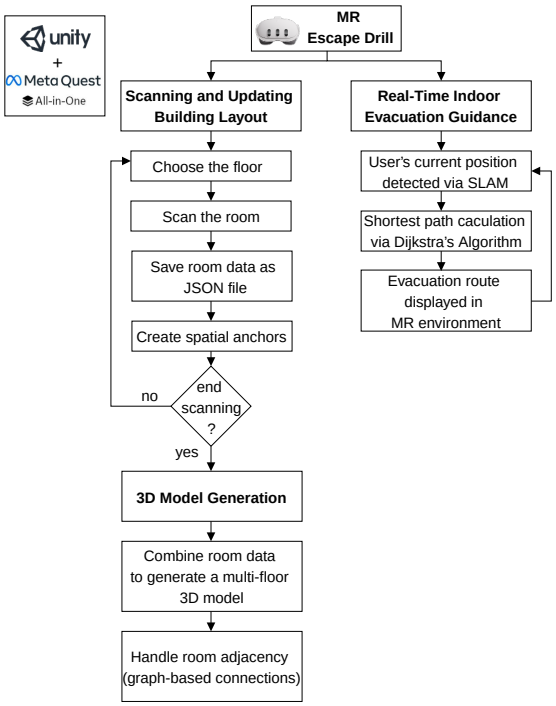
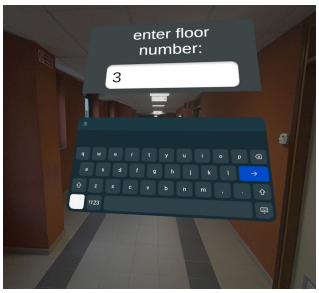


Figure 1: *Proposed system framework. The flowchart shows the two modalities of the proposed application (MR Escape Drill): the scanning and updating building layout modality and the real-time indoor evacuation guidance modality.*

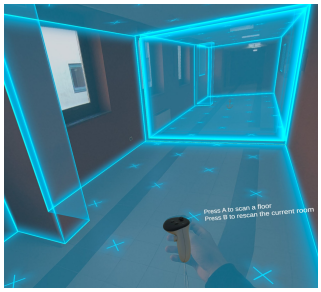
3.3. Scanning and Updating Building Layout Modality

The first modality of the application focuses on scanning and updating the 3D model of the multi-floor building. This process allows the system to capture the rooms' current layout and structural features, such as walls, floors, and doors, ensuring that evacuation guidance is based on the most up-to-date building information.

The Meta Quest 3 offers built-in functionality to scan and save 3D models of rooms and their structural features directly into the device's storage space. However, it can only store a maximum of 15 rooms, which limits its ability to handle larger buildings. To overcome this limitation, we utilized the capabilities of the Mixed Reality Utility Kit (see Section 3.1) to store the room data externally. The scanning information, including room geometry and structural features, is saved in a JSON format. This allows the application to store and manage unlimited rooms by loading them from their respective JSON files, bypassing the Quest 3's memory constraint. One challenge of saving room data externally is the misalignment when reloading these rooms, as they are not stored in the device's internal memory. To address this issue, we leveraged the spatial anchors [Mete] provided by the Meta XR Core SDK (see Section 3.1). A spatial anchor is a world-locked frame of reference in the real world that provides position and orientation to a virtual object. It enables the object's position to be saved and located across different sessions, and it can be shared with other users in real-time or later. A spatial anchor is created for each scanned room, ensuring



(a) *Floor selection*



(b) *Scanned rooms*

(c) *Room's spatial anchor*

Figure 2: *Floor scanning process*

that when a room's 3D model is reloaded, it is accurately aligned with the real-world environment.

3.3.1. First Scanning Pipeline

The user begins by selecting the floor to be scanned (see Figure 2a), with floors labeled numerically (e.g., "0" for the ground floor, "1" for the first floor, etc.). This step ensures that data for each floor is organized and distinguishes between different building levels in the final 3D model. After selecting a floor, the user scans the first room using the Meta Quest 3 headset, capturing its structural features such as walls, doors, and floors (see Figure 2b). Each scan is saved as a JSON file, and a spatial anchor (see Figure 2c) is created for future alignment between the virtual model and the physical room. The user then moves through doors to adjacent rooms, scanning each one in turn. As each room is scanned, its structural data is stored in a separate JSON file, with a spatial anchor ensuring accurate positioning within the building. This process is repeated for all rooms on the current floor, and the user then proceeds to scan additional floors following the same process, systematically capturing the layout of each room on every level of the building. Following the principles of structured modeling [IYF15], after scanning all rooms across each floor, the system generates a comprehensive adjacency graph that represents the layout of the entire building. In this graph, each node corresponds to a room, while edges between nodes represent connections between adjacent rooms. The weight of each edge is calculated based on the distance between the doors of connected rooms. Rooms adjacent to staircases are also connected to corresponding rooms on other floors, allowing the graph to span multiple levels of the building. The resulting adjacency graph serves as the foundation for the dynamic 3D model of the building, with nodes representing rooms and edges representing connections between them. This model, shown in Figure 3, will be used during real-time evacuation guidance to ensure accurate and up-to-date routing based on the building's current layout.

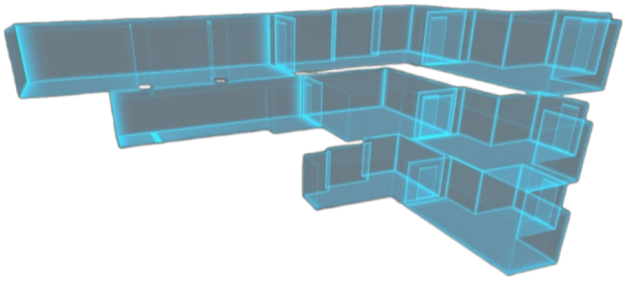


Figure 3: *A 3D model of a multi-floor building created using the scanning and updating building layout feature of the proposed application.*

3.3.2. Room Updating Pipeline

After selecting the room that requires updating from the building's existing 3D model, the user initiates the rescan process using the Meta Quest 3 headset. The previous room scan, JSON file, and spatial anchor are replaced with the new data, reflecting the room's current structure. The application updates the graph's adjacency list to reflect any changes in room connections. If the room's doors or connections to adjacent rooms have changed, the corresponding edges in the graph are modified. The distances between adjacent rooms are recalculated to reflect the updated layout.

3.4. Real-Time Indoor Evacuation Guidance

Once the building has been fully scanned and the adjacency graph generated, the second modality of the system – real-time indoor evacuation guidance – can be activated. This feature leverages the Meta Quest 3's real-time tracking capabilities and the pre-scanned 3D model to guide users to safety during evacuation drills.

The application starts by detecting the user's current location within the building using the Meta Quest 3's SLAM technology. This allows the application to accurately track the user's position without relying on external systems like WiFi, Bluetooth, or markers. Furthermore, the Meta Quest 3 uses a combination of other technologies, such as depth and IMU sensors, machine learning techniques, and boundary detection, to minimize the impact of incorrect initial placement. The Meta Quest 3 orientation system continually updates the user's position in real-time as they move through the building, ensuring precise location tracking. Once the user's location is established, the system dynamically calculates the shortest evacuation route to the nearest exit using Dijkstra's algorithm [Dij22] on the adjacency graph created during the scanning phase. As the user moves through the building, the system continuously recalculates the optimal route, ensuring that guidance is always based on the user's current location and real-time conditions within the building. The evacuation guidance is displayed through

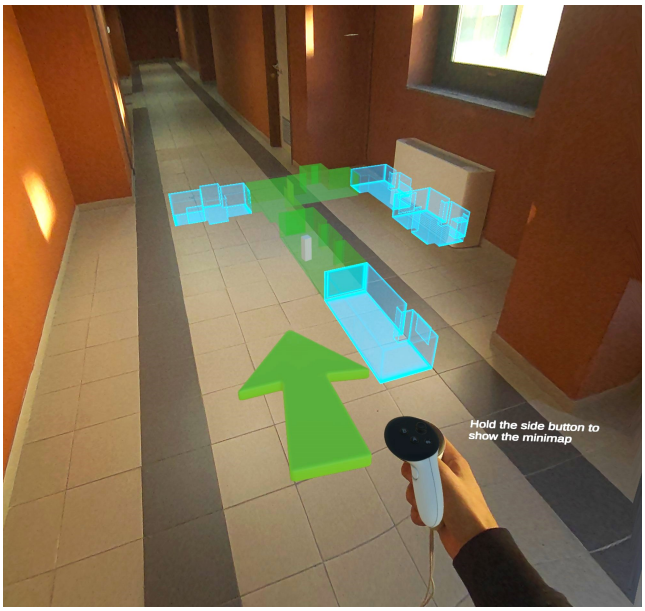


Figure 4: *Evacuation guidance with digital evacuation cues: a green arrow that shows the direction to follow and a minimap that shows the best route and the user's current position*

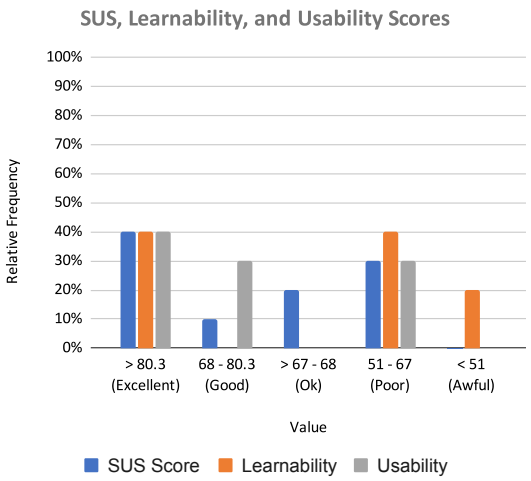


Figure 5: *SUS questionnaire results for evacuation drills using the proposed MR Application.*

the Meta Quest 3's MR interface, combining digital navigation cues with the user's real-world environment. These cues include digital arrows and a minimap (see Figure 4). The digital arrows are combined with the physical environment, guiding the user step-by-step toward the nearest exit. These arrows are updated in real-time as the user progresses along the calculated path, clearly indicating the direction they need to move. The system presents a minimap which represents the current floor. The rooms along the shortest evacuation path are highlighted in green, while the user's current position is marked as a white box. This provides users with an overview of their route and location, enhancing their situational awareness and helping them understand how to navigate the building quickly. In buildings with multiple floors, the system seamlessly integrates staircases into the evacuation routes. When a room adjacent to a staircase is reached, the system directs the user to proceed through the staircase to the floor above or below, as appropriate. The minimap updates accordingly, showing the new floor and continuing to highlight the evacuation route in green.

4. Pilot evaluation Study

To assess the usability and effectiveness of the proposed application for indoor evacuation, we conducted a preliminary evaluation study that gathered essential user feedback and focused on how well participants could learn, feel, and use the system to achieve their tasks. Given that usability and feeling are critical yet challenging parameters in determining the efficacy of MR applications, our evaluation aimed to go beyond mere data collection. Instead, it emphasized a comprehensive understanding of user satisfaction and sentiment and the extent to which the MR experience could mirror real-world conditions [BC20, RCE*19].

The study evaluated the system's usability and satisfaction through user feedback. The evaluation involved 10 participants representing diverse age groups and backgrounds [HRW00]. Each participant was asked to follow the real-time evacuation guidance provided by the MR system, which included directional arrows and the minimap described above. After completing the evacuation drill, participants were asked to fill out the System Usability Scale (SUS) [B*96] questionnaire to evaluate the usability of the MR application. The SUS is a widely used, standardized tool consisting of 10 items, each rated on a 5-point Likert scale (from "Strongly Disagree" to "Strongly Agree"). The results of the SUS questionnaire, shown in Figure 5, are divided into three categories: overall SUS score, usability, and learnability. Regarding the overall SUS score, 40% of the participants rated the MR system as "Excellent", while 30% rated it as "Good" and "OK". Only 30% rated it as "Poor". In terms of usability, most participants found the application highly usable, with 70% rating it as either "Good" or "Excellent." About learnability, 40% of the participants found it easy to learn, with scores falling in the "Excellent" category, while 60% of participants found the application difficult to learn. The results suggest that the MR application is highly usable but less easy to learn.

In addition to the System Usability Scale (SUS), the Self Assessment Manikin (SAM) [BL94] questionnaire was used to gauge the emotional responses of participants in terms of valence (pleasure), arousal (excitement), dominance (control), and liking during the evacuation process. Each participant rated the MR application on a scale from 1 to 5 for each dimension. The SAM questionnaire results shown in Figure 6 indicated that the majority of participants had a pleasant emotional experience, with 80% of valence ratings being either 1 or 2 on a scale from 1 (Pleasant) to 5 (Unpleasant). This suggests that, despite the context of an emergency drill, most users found the experience emotionally positive or at least tolerable. Only a small portion found it unpleasant. The arousal ratings show that most users experienced a neutral to moderate level of ex-

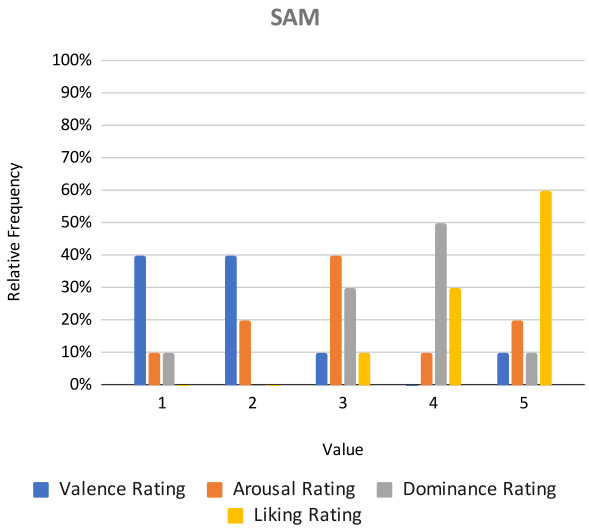


Figure 6: *SAM questionnaire results for evacuation drills using the proposed MR Application.*

citement, with a few participants feeling either significantly calm or highly stimulated by the application. Regarding dominance, most participants felt moderate in control, revealing that the app allowed for sufficient interaction but could still improve in making users feel more empowered in the experience. Furthermore, the users found the app highly enjoyable, with the majority giving very high liking ratings, confirming strong user satisfaction.

The evaluation study demonstrated the advantages of using an MR application for real-time evacuation drills. The combination of visual arrows, a minimap, and real-time location tracking allowed fast and accurate navigation. The high SUS scores and positive feedback suggest that the MR application is both usable and effective, even for users with minimal experience in MR. The SAM results indicated that the system provided a pleasant and engaging experience while maintaining a balanced level of arousal and control, suggesting that the cognitive load was well-managed during the evacuation drill. Based on our study, we noted that this application could enable users to maintain clear-headedness during the evacuation, enhancing their decision-making abilities under stress and further demonstrating the system's effectiveness.

5. Conclusions

In this work, we developed an MR application for evacuation drills in multi-floor buildings, leveraging the Meta Quest 3 headset. Our system aims to overcome the limitations of traditional 2D evacuation plans by offering an immersive, real-time experience that enhances the effectiveness of evacuation practices. Through MR technology, building occupants can practice navigating complex environments during simulated emergencies, improving their readiness for real-world scenarios. The application integrates several advanced features, including rapid 3D scanning of building layouts, spatial anchors for precise alignment of virtual models to real-world, and Dijkstra's algorithm to calculate the most efficient escape routes. Visual cues, such as directional arrows and a minimap highlighting the shortest path, guide users throughout the drills, ensuring real-time adaptation to the current building layout and the user's location. This dynamic and intuitive approach may provide more effective training than traditional static evacuation plans. Our evaluation study demonstrated that the application achieved high levels of usability, leading to strong user engagement and satisfaction. However, the system has some limitations. One significant challenge is that when the Meta Quest 3 headset overheats or has a low battery, it tends to misalign or forget the previously scanned boundaries, which results in a misalignment of the entire 3D model. This issue can affect the accuracy of evacuation guidance and the overall effectiveness of the training drill. Additionally, the built-in scanning procedure for rooms sometimes fails, forcing users to rescan the room, which can be time-consuming. One potential area for future work could involve integrating dynamic hazards such as smoke, fire, or obstacles into the simulation to make the drills more realistic and better prepare users for navigating complex emergencies.This would require the development of adaptive algorithms that integrate real-time context-sensing mechanisms to dynamically adjust the graph and reroute paths accordingly when parts of the environment become inaccessible. This enhancement will improve the robustness of the path computation process in unpredictable scenarios. Another area for development could be expanding the application to support multi-user environments, allowing for coordinated evacuation drills where multiple users navigate the building together and simulate real-world group dynamics during emergencies. Additionally, it will be important to conduct large-scale testing in diverse building environments, such as schools, hospitals, and commercial centers, to gain valuable insights into how the system performs in more complex and varied real-world scenarios. In the short term, we aim to expand our user study on a larger scale by engaging non-expert participants and simulating an evacuation emergency scenario to assess our approach's effectiveness thoroughly. We propose adding time-bound tasks to simulate pressure and enhancing the questionnaire to evaluate cognitive load, stress levels, and their influence on task performance. These additions will provide a deeper understanding of the interface's usability in high-stress scenarios.

References

[ACJ*23] ABBAS J. R., CHU M. M., JEYARAJAH C., ISBA R., PAYTON A., MCGRATH B., TOLLEY N., BRUCE I.: Virtual reality in simulation-based emergency skills training: A systematic review with a narrative synthesis. *Resuscitation Plus 16* (2023), 100484. 2

[AYA24] AHMADI M., YOUSEFI S., AHMADI A.: Exploring the most effective feedback system for training people in earthquake emergency preparedness using immersive virtual reality serious games. *International Journal of Disaster Risk Reduction 110* (2024), 104630. doi:10.1016/j.ijdrr.2024.104630. 2

[B*96] BROOKE J., ET AL.: Sus-a quick and dirty usability scale. *Usability evaluation in industry 189*, 194 (1996), 4–7. 5

[BC20] BOURHIM E. M., CHERKAOUI A.: Efficacy of virtual reality for studying people's pre-evacuation behavior under fire. *International Journal of Human-Computer Studies 142* (2020), 102484. doi:10.1016/j.ijhcs.2020.102484. 5

[BL94] BRADLEY M. M., LANG P. J.: Measuring emotion: the self-

assessment manikin and the semantic differential. *Journal of behavior therapy and experimental psychiatry 25*, 1 (1994), 49–59. 5

[CAE16] CAPECE N., AGATIELLO R., ERRA U.: A Client-Server Framework for the Design of Geo-Location Based Augmented Reality Applications. In *2016 20th International Conference Information Visualisation (IV)* (2016), pp. 130–135. doi:10.1109/IV.2016.20. 1

[CAT*20] CATAL C., AKBULUT A., TUNALI B., ULUG E., OZTURK E.: Evaluation of augmented reality technology for the design of an evacuation training game. *Virtual Reality 24*, 3 (2020), 359 – 368. Cited by: 32; All Open Access, Hybrid Gold Open Access. doi:10.1007/s10055-019-00410-z. 2

[CLK*24] CHELIOTIS K., LIAROKAPIS F., KOKLA M., TOMAI E., PASTRA K., ANASTOPOULOU N., BEZERIANOU M., DARRA A., KAVOURAS M.: UnityGeoAR: A geolocation Augmented Reality package for Unity3D. *SoftwareX 27* (2024), 101774. doi:10.1016/j.softx.2024.101774. 1

[Dij22] DIJKSTRA E. W.: A note on two problems in connexion with graphs. In *Edsger Wybe Dijkstra: his life, work, and legacy*. 2022, pp. 287–290. 2, 4

[DZC*24] DANG P., ZHU J., CAO Y., WU J., LI W., HU Y., YOU J., FU L.: A method for multi-person mobile virtual reality fire evacuation drills based on pose estimation: consistency of vision and perception. *Safety science 170* (2024), 106334. 1

[FGA*18] FENG Z., GONZÁLEZ V. A., AMOR R., LOVREGLIO R., CABRERA-GUERRERO G.: Immersive virtual reality serious games for evacuation training and research: A systematic literature review. *Computers & Education 127* (2018), 252–266. doi:10.1016/j.compedu.2018.09.002. 2

[FGA*20] FENG Z., GONZÁLEZ V. A., AMOR R., SPEARPOINT M., THOMAS J., SACKS R., LOVREGLIO R., CABRERA-GUERRERO G.: An immersive virtual reality serious game to enhance earthquake behavioral responses and post-earthquake evacuation preparedness in buildings. *Advanced Engineering Informatics 45* (2020), 101118. doi:10.1016/j.aei.2020.101118. 2

[FGM*20] FENG Z., GONZÁLEZ V. A., MUTCH C., AMOR R., RAHOUTI A., BAGHOUZ A., LI N., CABRERA-GUERRERO G.: Towards a customizable immersive virtual reality serious game for earthquake emergency training. *Advanced Engineering Informatics 46* (2020), 101134. doi:10.1016/j.aei.2020.101134. 2

[FGM*23] FENG Z., GONZÁLEZ V. A., MUTCH C., AMOR R., CABRERA-GUERRERO G.: Exploring spiral narratives with immediate feedback in immersive virtual reality serious games for earthquake emergency training. *Multimedia Tools and Applications 82*, 1 (2023), 125–147. 2

[GBQ*23] GAGLIARDI E., BERNARDINI G., QUAGLIARINI E., SCHUMACHER M., CALVARESI D.: Characterization and future perspectives of virtual reality evacuation drills for safe built environments: A systematic literature review. *Safety Science 163* (2023), 106141. doi:10.1016/j.ssci.2023.106141. 2

[GLLC22] GAN Q., LIU Z., LIU T., CHAI Y.: An indoor evacuation guidance system with an ar virtual agent. *Procedia Computer Science 213* (2022), 636–642. 2022 Annual International Conference on Brain-Inspired Cognitive Architectures for Artificial Intelligence: The 13th Annual Meeting of the BICA Society. doi:10.1016/j.procs.2022.11.115. 2

[HLJ12] HAITAO C., LEILEI L., JIUZI Q.: Accident Cause Analysis and Evacuation Countermeasures on the High-rise Building Fires. *Procedia engineering 43* (2012), 23–27. 1

[HRW00] HOST M., REGNELL B., WOHLIN C.: Using students as subjects - a comparative study of students and professionals in lead-time impact assessment. *Empirical Software Engineering 5*, 3 (2000), 201 – 214. Cited by: 526. doi:10.1023/A:1026586415054. 5

[IYF15] IKEHATA S., YANG H., FURUKAWA Y.: Structured indoor modeling. In *Proceedings of the IEEE international conference on computer vision* (2015), pp. 1323–1331. 4

[JCCS20] JANG K.-H., CHO S.-B., CHO Y.-S., SON S.-N.: Development of Fire Engine Travel Time Estimation Model for Securing Golden Time. *The Journal of The Korea Institute of Intelligent Transport Systems 19*, 6 (2020), 1–13. 1

[KCU*22] KHAN D., CHENG Z., UCHIYAMA H., ALI S., ASSHAD M., KIYOKAWA K.: Recent advances in vision-based indoor navigation: A systematic literature review. *Computers & Graphics 104* (2022), 24–45. 1

[Ker22] KERDVIBULVECH C.: Geo-based mixed reality gaming market analysis. *Human Behavior and Emerging Technologies 2022*, 1 (2022), 1139475. 1

[KJT23] KANANGKAEW S., JOKKAW N., TONGTHONG T.: A real-time fire evacuation system based on the integration of Building Information Modeling and Augmented Reality. *Journal of Building Engineering 67* (2023), 105883. 1

[KMS16] KAWAI J., MITSUHARA H., SHISHIBORI M.: Game-based evacuation drill using augmented reality and head-mounted display. *Interactive Technology and Smart Education 13*, 3 (2016), 186–201. 2

[LCY*22] LIU H., CHOI M., YU L., KOILIAS A., YU L.-F., MOUSAS C.: Synthesizing shared space virtual reality fire evacuation training drills. In *2022 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)* (2022), pp. 459–464. doi:10.1109/ISMAR-Adjunct57072.2022.00097. 2

[LLQ*17] LI C., LIANG W., QUIGLEY C., ZHAO Y., YU L.-F.: Earthquake Safety Training through Virtual Drills. *IEEE Transactions on Visualization and Computer Graphics 23*, 4 (2017), 1275–1284. doi:10.1109/TVCG.2017.2656958. 2

[LYXX20] LU X., YANG Z., XU Z., XIONG C.: Scenario simulation of indoor post-earthquake fire rescue based on building information model and virtual reality. *Advances in Engineering Software 143* (2020), 102792. doi:10.1016/j.advengsoft.2020.102792. 2

[LZLBG20] LIN J., ZHU R., LI N., BECERIK-GERBER B.: Do people follow the crowd in building emergency evacuation? a cross-cultural immersive virtual reality-based study. *Advanced Engineering Informatics 43* (2020), 101040. doi:10.1016/j.aei.2020.101040. 2

[Meta] META: Meta XR All-In-One SDK. https://developer.oculus.com/downloads/package/meta-xr-sdk-all-in-one-upm/, last accessed on 2024-09-02. 3

[Metb] META: Meta XR Core SDK. https://developer.oculus.com/downloads/package/meta-xr-core-sdk/, last accessed on 2024-09-02. 3

[Metc] META: Meta XR Interaction SDK. https://developer.oculus.com/downloads/package/meta-xr-interaction-sdk/, last accessed on 2024-09-02. 3

[Metd] META: Meta XR Mixed Reality Utility Kit SDK. https://developer.oculus.com/downloads/package/meta-xr-mr-utility-kit-upm/, last accessed on 2024-09-02. 3

[Mete] META: Spatial Anchors. https://developer.oculus.com/documentation/unity/unity-spatial-anchors-overview/, last accessed on 2024-09-02. 3

[PFK*24] PAES D., FENG Z., KING M., KHORRAMI SHAD H., SASIKUMAR P., PUJONI D., LOVREGLIO R.: Optical see-through augmented reality fire safety training for building occupants. *Automation in Construction 162* (2024), 105371. doi:10.1016/j.autcon.2024.105371. 2

[RCE*19] ROMANO S., CAPECE N., ERRA U., SCANNIELLO G., LANZA M.: The city metaphor in software visualization: feelings, emotions, and thinking. *Multimedia Tools and Applications 78*, 23 (2019), 33113 – 33149. Cited by: 13. doi:10.1007/s11042-019-07748-1. 5

[SMH23] STEFAN H., MORTIMER M., HORAN B.: Evaluating the effectiveness of virtual reality for safety-relevant training: a systematic review. *Virtual Reality 27*, 4 (2023), 2839–2869. 2

[Uni] UNITY: Unity Engine. https://unity.com/, last accessed on 2024-09-02. 3

[WRK22] WÄCHTER T., REXILIUS J., KÖNIG M.: Interactive evacuation in intelligent buildings assisted by mixed reality. *Journal of Smart Cities and Society 1*, 3 (2022), 179–194. 1

[XYZF23] XU Z., YANG Y., ZHU Y., FAN J.: Mixed reality drills of indoor earthquake safety considering seismic damage of nonstructural components. *Scientific Reports 13*, 1 (2023). Cited by: 0; All Open Access, Gold Open Access, Green Open Access. doi:10.1038/s41598-023-43533-9. 3

[ZL21] ZHU Y., LI N.: Virtual and augmented reality technologies for emergency management in the built environments: A state-of-the-art review. *Journal of Safety Science and Resilience 2*, 1 (2021), 1–10. doi:10.1016/j.jnlssr.2020.11.004. 2

[ZXY*21] ZHANG F., XU Z., YANG Y., QI M., ZHANG H.: Virtual reality-based evaluation of indoor earthquake safety actions for occupants. *Adv. Eng. Inform. 49*, C (aug 2021). doi:10.1016/j.aei.2021.101351. 2