User Focused Fire Evacuation Simulation for HoloLens

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Abstract

Augmented Reality (AR) possesses significant potential to transform pedagogical methodologies and enhance learning outcomes. Despite these advantages, AR remains underutilized in emergency evacuation training. This paper presents a flexible AR-based fire evacuation simulator developed for the Microsoft HoloLens 2, designed to bridge the gap between traditional procedural drills and adaptive decision-making in real-world emergencies. While conventional training methods are often non-interactive or environment specific, this application developed as a joint initiative between a German and a Japanese university integrates specific design requirements for both contexts. This should enable its users to create and execute customized crisis scenarios across diverse physical environments. The authors address the limitations of static, pre-modeled simulations by implementing a dynamic "setup mode" that allows instructors to place fifteen distinct interactive objects–including smoke, fire, and localized fire alarms-directly into the user's real-world space. Leveraging the HoloLens 2's spatial awareness capabilities, the application facilitates immersive multiplayer training scenarios that provide immediate feedback and collect behavioral data while maintaining participant safety. The system's effectiveness and user-friendliness were evaluated through expert interviews. Due to the limited amount of participants, more in depth research is needed.

Keywords

Extended reality, XR, Augmented Reality, AR, Safety Training, Fire Evacuation, Crisis Training

1 INTRODUCTION

Augmented Reality (AR) facilitates a previously unattainable convergence of the digital and physical worlds. At present, no other modern technology rivals its capacity for integrating digital data into physical reality while providing six degrees of freedom (6DoF), a high degree of immersion, and a sense of presence beyond the reach of conventional display technologies [1]. Despite this, the full potential of AR remains underutilized, even as scholarly interest continues to grow steadily [2, 3]. In educational contexts, AR has shown significant promise, though further empirical research into its effectiveness is required [1, 3, 4]. The objective of this work was to develop a flexible and user-friendly AR application for fire evacuation training, as research shows that adaptable systems are not investigated nor used. By leveraging the Microsoft HoloLens 2, the application provides instructors with a technology to generate diverse training scenarios in various environments, thereby enhancing training for the general public. This collaborative project was carried out as a master thesis between the German Furtwangen and Japanese Kanagawa university, trying to combine design choices tailored to both the German and Japanese markets. The application is designed to heighten user awareness through interactive, immersive simulations of fire emergencies.

While fire evacuation drills in Japan and Germany share the fundamental goal of life safety, they differ in emphasis and implementation. In Japan, drills are systematically conducted in schools and workplaces under the Fire Service Act. These exercises are typically scheduled, highly structured, and follow predefined protocols. A core feature is the standardized behavioral mnemonic "O-Ha-Shi-Mo" (Do not push, Do not run, Do not speak, Do not return), which fosters orderly collective evacuation. This approach prioritizes discipline and coordination, generally omitting realistic elements such as actual flames or dense smoke.

In contrast, German drills are governed by occupational safety regulations, such as the work safety law (Arbeitsschutzgesetz) and are frequently informed by site-specific risk assessments. Realism is occasionally enhanced through unannounced scenarios and smoke simulations. Employees are encouraged to act autonomously, supported by designated fire safety assistants (Brandschutzhelfer), with systematic post-drill evaluations.

In both nations, however, recreating the sensory stress of a real emergency remains a significant challenge. The integration of AR technology can substantially enhance situational realism by simulating fire, smoke, and dynamic hazards both visually and acoustically without compromising participant safety. AR-based training bridges the gap between procedural drills and actual emergency conditions, fostering adaptive decision-making and psychological preparedness.

2 RELATED WORK

2.1 Theoretical Foundation

AR makes it possible to visualize digital information in the real world, melting both worlds together [5]. Instead of creating a new reality, as is known from virtual reality (VR), AR enhances the reality by adding virtual computer-generated information. Due to availability, the HoloLens 2 was chosen as the AR device. It is an AR-headset by Microsoft, containing displays, input devices, tracking, and a computing unit in one package. As its display technology, it uses a binocular head-mounted display (HMD) with optical see-through, allowing an almost unaltered view of the real world to pass through the lens. The digital overlay is reflected in the user's eyes, merging the digital and the real world together [6]. Note that we use the term AR as synonym to Mixed Reality (MR) which is the marketing term Microsoft used to sell the HoloLens. See the review article by Speicher et al. from CHI 2019 for a deeper discussion about the terminology [7].

Fire training in this work describes the process of repetitive evacuation and behavioral training in case of a fire. These are available for multiple user groups, for example, fire service instructors, firefighters, and normal citizens [8]. The fire safety training created in this application is the evacuation of ordinary citizens, as it is one crucial aspect of safety strategies in buildings [9].

Gamification was defined by Huotari and Hamari as a process of enhancing a service with affordances for gameful experiences in order to support user' overall value creation [10]. In short, it attempts to create the same psychological effect that games have on people by augmenting experiences with game components [11]. But it must be added that gamification is a loose construct that can be defined in many ways, depending on the perspective of the researcher [12, 13]. Using its benefits, the implementation of gamification could increase user satisfaction. However, as the concept seems to need more research, it was decided to implement game elements into the here proposed application and call it gamification. Although this is a superficial approach, it is considered sufficient for development.

The interaction represents the exchange between the AR-system and its user. This interaction can occur using different systems, like gaze and pinch, direct touch and grab, and worlds-in-miniature [14]. The interface is the component of the application in which the user can operate the interactive parts of a system.

2.2 AR training

AR as part of XR is applicable in general as an innovative learning technology. Kaplan et al. showed in their meta-analysis the effect of XR on enhancing training methods [15]. This work concludes that XR training can achieve comparable results as traditional training, highlighting the potential for improvement while also showcasing drawbacks. Fast technological advancements quickly make tech and software obsolete. Also, the choice of used technology highly impacts the perceived quality. In conclusion, AR research is still a convoluted mess, but insights are gained that are highly valuable for the development of this simulator. It has the potential to reduce time- and costs of training while also improving the effectiveness [3, 15]. But to be able to create an effective trainer, the definition of objectives and expectations of the application need to be properly researched and laid out, allowing the right choice of technology and software.

2.3 Crisis Situation Training

In order to develop a fire evacuation trainer, it is important to understand what kind of practices are currently in use and what their strengths and weaknesses are. Understanding current fire drill methods would be beneficial as it would enable realistic guidelines. Regular training enables smooth operations in an emergency and reduces panic, misconduct and unsafe situations. To allow a more streamlined training process, an evacuation flowchart (see Figure 1) is proposed based on official German emergency training material [16]. It is important to understand the principle of current training and evacuation procedures to develop the simulator.

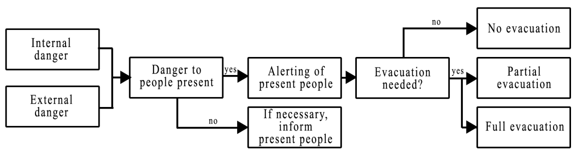

Figure 1: Evacuation flow chart

Menzemer et al. conducted a scoping review and bibliometric analysis of methods for fire evacuation training in buildings [9]. Highlighted are the differences between traditional training methods and modern training methods. Not always specified, traditional training methods include analog safety training approaches, such as poster-, slide- and audiovisual-based training, workshops, mental rehearsal, and walkthroughs. These methods have multiple drawbacks, being described as not interactive, motivating, or effective. The paper also addresses the issue of transfer and retention of skills and shows that AR and modern training methods can achieve good results in both aspects [9, 17]. While being able to overcome most of the drawbacks of traditional methods, it is clear that modern techniques are not a replacement but rather an addition to successful training strategies. Still, modern technologies are rarely used [17]. It is important to anchor the user in the virtual environment, conveying a sense of presence. The user's acceptance of the digital additions in AR therefore plays a crucial role. Cagampan et al. [2] give a good understanding of the usage of AR technology in current trainings while also proposing a study concept. When applied, it can determine how AR could affect participants' firefighting training seminars, highlighting the high potential of AR training applications, seemingly enhancing decision-making, problem-solving and situational awareness of trainees.

In current research, multiple trainings systems were developed using different technologies such as handheld devices [18, 19, 20], AR headsets [21] or both technologies [1]. All papers focused mostly on the training of evacuation routes. In conclusion, these publications demonstrate how AR could enhance current evacuation training in an interactive, safe, and entertaining way while reducing costs. However, all proposed systems are not flexible in their usage. They were made for a specific environment, implementing handmade and/or previously scanned 3D models, fixed layouts, and fixed game processes. Changing the environment and scenario would thus need time and knowledge about the program and processes. It is therefore not possible to use them in the field, which highlights the research gap on flexible systems. To give an insight into the state of commercial XR training, a web-research was conducted. The first three company's who came up on the web were chosen and analyzed, using the google search engine. SENAR offers a course for handheld devices with four different scenarios, teaching the right usage of on work firefighting equipment as a subscription service [22]. PRO-XR offers subscription courses for VR and AR HMD's, implementing real fire extinguisher dummies [23]. XVR Simulation offers courses implementing custom-made applications adjusted to the need of its customers [24]. These applications have the same problem as as the in current research presented trainers: being restraint to one training scenario and/or one environment.

3 STUDY DESIGN

This works tries to start closing the gap of flexible training application research. There appears to be a discrepancy between research focusing on modern training methods and actual evacuation training, where mostly traditional methods are used [17]. Furthermore, as can be seen in current research, the applications are usually tailored to a certain scenario and, more importantly, for a specific environment. Unfortunately, this does not allow the application to be quickly adapted for other environments. The systems are therefore static, and a certain amount of rework is required for use in other surroundings and circumstances. However, as the implementation of AR and its potential increase with new and more advanced technologies, it should be considered more for actual evacuation training. This leads to the research presented in this paper, which attempts to answer the following questions:

- Is AR suitable for evacuation training?
- Is it possible to create a flexible training system that can be used in different environments without much preparation?
- Would this flexible system be usable in current training sessions?

To answer these questions, literature research was conducted and an AR application for evacuation training was conceptualized and developed. Expert interviews were conducted on a small scale to validate the simulator. The aim of this work is to evaluate the effectiveness of XR as a training technology, and to provide insights into the design process of virtual and real life training exercises and programs. It is anticipated that this work could influence the design of new flexible systems that, when implemented, will increase the learning effect and thus the safety of the general public.

4 FIRE EVACUATION TRAINING SIMULATOR

4.1 Preproduction

The goal of this application was not to create a fire evacuation trainer which implements realistic fire simulations, as realism does not appear to increase the level of learning [3]. Instead, the focus was laid on creating a program that can be used in different environments. It should be easy to operate, implementing an simple-to-understand interface, allowing its users to set up a fire scenario and train said scenario on the same device, increasing accessibility. The goal is to close the currently existing discrepancy between research and practice [17]. Training should help end-users to learn how to act in a fire scenario and build up knowledge of where rescue equipment and exits are. In short, the simulator aims to increase the awareness of fire scenarios in users by using AR, implementing the concept of gamification and providing direct feedback [3, 11, 15]. This learning effect utilizes the first stage of the experiential learning theory: concrete learning, undergoing a new experience, or reinterpreting an experience [3, 25]. This should improve evacuation behavior, and thus have a positive effect on the users' outcome in the event of fire disasters [17]. The learning effect should be boosted by a multi-user functionality, and thus a multiplayer is needed [9]. A trainer like the proposed system would allow for more realistic and repetitive but secure training while keeping costs low [9, 15]. Indeed, a properly set up traditional evacuation drill, for example using real fires, hands on extinguisher use and so on, would have a better learning effect. But this kind of training is not feasible for most institutions, due to high costs, required planning and time [9]. The presented application would allow the implementation of such training scenarios in a flexible and cheap way, closing the gap. The generated data can be used to analyze behavior and give more in-depth recommendations to users. Expanding on the planned functionality, these data can also be used to improve fire safety design in buildings by showcasing weak spots in the design, for example bad extinguisher placement. We hypothesize that the problem of skill transfer from the simulator to the real world does not apply here due to the applications' implementation of training, as current fire training is effective [15]. The virtual training is not intended to replace current practical fire drills. Rather, the aim is to enhance them by facilitating planning and execution through the insertion of digital objects into the real world without compromising the traditional concept of training. The application should therefore implement two aspects favored by the participants, namely the use of the real physical space and the possibility of training various training scenarios [17]. This plan and research led to six target points:

- User-friendly interface
- Directly applicable in different environments
- Running completely on the headset
- Multiplayer capabilities
- Save & Load system for scenarios
- Data collection during usage

To achieve this goal, the target use case and group were identified. Research and interviews showed that a lot of current fire training systems are tailored towards experts, such as firefighters and other personnel. Those systems support the teaching of a firefighter's role and duties as well as other actors during a fire scenario. These training tools do not consider the training of evacuation for citizens. Our application aims to enhance current fire training drills, known from schools or the workplace, by including AR technology. The design is simple and user-friendly. The interface allows the instructor to quickly create training scenarios. The proposed game loop visualizes the planned usage-flow of the application, making development easier (see Figure 2).

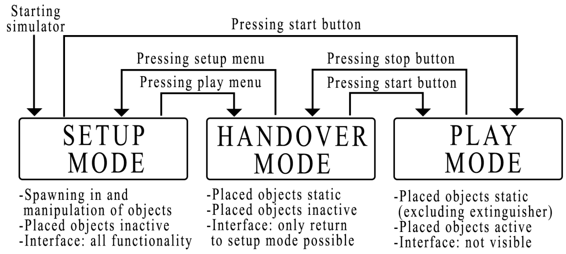

Figure 2: Game loop, showing the three states of the simulator and their activation flow

4.2 Development

The application was built for the HoloLens 2 headgear, going through multiple development phases. The concepts previously described in the preproduction section 4.1 were implemented into the system. Even though HMD AR simulations performed the worst in the research by Howard et al. [3], we think HMD are the only device that allows the user to interact with their surroundings naturally. Other technologies would require its users to hold a device blocking one hand or limiting the experience to a small space.

This version of the simulator was build using Unity version 2022.3.48f1 and the mixed reality toolkit version 2.8.3.0. To allow the functionality of multiplayer, Photon Pun 2 was used. The previously conceptualized game loop (see Figure 2) was implemented, allowing the creation, saving and execution of training scenarios. Hand gestures and head gaze were implemented, as recommended by Kang et al. [14] and respectively by Hertel et al. [26]. The use of complicated gestures has been actively avoided, as these could be difficult to learn, especially for inexperienced users [27]. A simple user interface for the instructor was implemented, taking the shape of a pad, using buttons with unique and recognizable icons to carry out different commands. These buttons allow for the spawning and deletion of placeable objects, saving and loading a scene, accessing the spatial awareness system, and entering the training and setup mode of the simulator. To make navigation easier, these were grouped into three submenus. To allow the interaction of digital objects with the real environment, a spatial awareness system was implemented with the option to stop updates to save computing power. The visibility of the created world mesh could be toggled on and off. In total, fifteen different object can be used by the instructor to create a training scenario.

- Utility
  - Exit sign: a sign to show the user the way out. Made to be placed on the floor. It has English and Japanese labeling, and uses a common exit sign symbol.
  - Extinguisher: a working fire extinguisher. It can be grabbed and activated. To activate it, both hands must be closed. When activated, a particle

system that resembles spray foam, a spray sound effect, and a handle animation is activated. It can extinguish fires placed in the simulation. Its texture shows an English and Japanese user manual, explaining the use of the fire extinguisher.

- Start & Stop button
  - Start button: starts simulation by pressing.
  - Stop button: ends simulation by pressing.
- Smoke
  - Smoke (static): static volume of smoke.
  - Smoke (trigger): expanding volume of smoke, activated by the player.
- Debris
  - Debris (static): static debris.
  - Debris (trigger): Debris falling from the ceiling activated by the player. Uses an animation and a sound effect.
- Fire alarm
  - Fire alarm, German (Wall): German-style fire alarm made to be placed on walls. When pressed, audio (German fire alarm sound) and flashing lights are activated.
  - Fire alarm, German (Pillar): German-style fire alarm mounted on a digital pillar, allowing easy reach when placed on a floor. Designed for cases where no wall is available for placement. When pressed, audio (German fire alarm sound) and flashing lights are activated.
  - Fire alarm, Japanese (Wall): Japanese-style fire alarm made to be placed on walls. When pressed, audio (Japanese fire alarm sound) and flashing lights are activated.
  - Fire alarm, Japanese (Pillar): Japanese-style fire alarm mounted on a digital pillar, allowing easy reach when placed on a floor. Designed for cases where no wall is available for placement. When pressed, audio (Japanese fire alarm sound) and flashing lights are activated.
- Fire
  - Fire (small): Small version of fire. It uses a sound effect and particle system. Extinguishable.
  - Fire (big): Big version of fire. It uses a sound effect and particle system. Extinguishable.
  - Fire (trigger): Small version of fire, activated by the player. It uses a sound effect and particle system. Extinguishable.

The application is multiplayer capable, updating each of the players and objects positions and states. While running, data points of date, time, position and rotation, current number of simulation runs and the cause of simulation stops are collected. The script is easily expandable, allowing the fast introduction of more data tracking types and customization if needed.

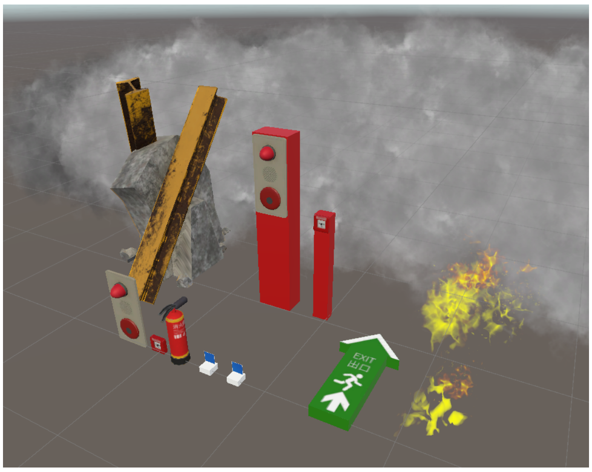

Figure 3: All spawnable objects. Trigger objects are excluded. Their triggered state is the same as that of non-trigger objects.

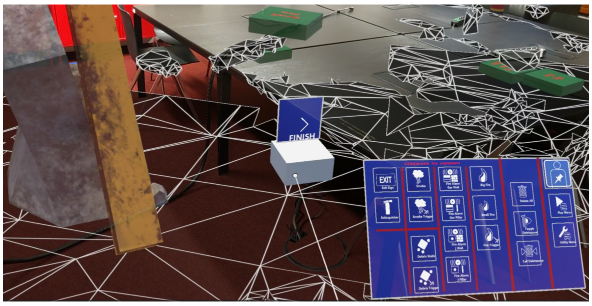

Figure 4: Instructor setting up a scene. On the bottom right is the spawn menu visible.

5 EXPERT INTERVIEWS

With the help of expert interviews, a theoretical confirmation of the program's learning functionality was given, while also suggesting many ideas for improvements and future work.

The focused interviews were semi-structured and half standardized, using a general guideline script. This script contained relevant topics and questions in thematic clusters. These include a self-introduction of interviewees, an overview of the project, fire simulation evacuation simulators in general, the use of different technologies, the proposed fire evacuation simulator and a final discussion in the end. Before the interview, each participant was given a text file containing a description of the interview process and a demo video showing all the functions and an usage example of the application. From the invited experts, four participated. Three interviews were conducted. Two were individual and one was a dyadic interview. Each interview lasted between 45 and 60 minutes and was processed anonymously and deleted afterward to protect data privacy. The participants were a safety engineer, a professor from the field of safety and security, as well as two XR-experts, whom both have professional experience in well-known companies. Two experts also work as firefighters. With these areas, both the technical aspect in relation to AR as well as the training aspect for fire evacuation were covered.

The goal of the interviews were to gather feedback on the overall experience, including the quality of the interface, evaluation of the simulator and thoughts on how AR can improve evacuation training. These interviews illustrate the current state of fire training, showing the potential but also the weaknesses of the presented simulator. Concepts and knowledge developed during the research phase were brought up by the attendees without implication, confirming the accuracy of the concepts used, such as increasing interest, commitment, learning value and reducing costs. Especially AR was highlighted for its use of the real environment compared to VR, making it more suitable for crisis situation training according to the experts. The proposed simulator was labeled as a successful prototype, with room for general comprehensive refinement.

6 RESULTS

XR seems to be a great technology to elevate the training of fire situations, but the full potential is not yet utilized. To bridge the gap, multiple findings of different fields of research, such as XR, crisis training and gamification were combined and used to create a working prototype of an adaptable fire evacuation trainer. With the proposed game loop, the simulation is divided into setup, play, and handover phases to accommodate different user roles: the instructor who sets up scenarios and trainees, for example ordinary citizens, who practice evacuation and firefighting procedures.

The small scale expert interviews gave an insight into the applicability of the proposed trainer. According to the experts, the game loop should be easy to understand and accessible for both trainer and trainee. However, it was also noted that users should be guided more during the setup phase, for example via pop-up information widgets. The interface is described as simplistic but functional and easy to use due to its similarity to mobile devices. A visual redesign and possibly additional menu structures (e.g., drop-down menus) were suggested. Features like the Save & Load function, spatial mesh system and spawnable objects are seen as sensible and beneficial. Smoke and fire should be represented more realistically, but with a careful balance to not overwhelm users or reduce credibility. Elements such as the possibility of dying and interaction with smoke can increase seriousness and learning impact. Data collection is valued mainly for research and improving fire protection systems. Multiplayer functionality is regarded as a particularly valuable extension.

7 LIMITATIONS

A general lack of methodology of this work needs to be pointed out. Due to the small sample size and scale of the interviews, only implications about the effectiveness of the simulator can be given. Also, the interviewees did not use the simulator, but were presented a video montage of its functionality. This could have an effect on the perceived quality of the simulator. Besides, no properly set up user test was conducted. In short, this work should not be seen as final research results. It aims to lay the foundation for future works by showcasing the gap in the current usage of the technology and proposes a system to integrate XR in current fire training drills in a theoretically more accessible manner.

None of the researchers working on this paper were originally experts in the field of safety training. The knowledge gained during the research phase was nonetheless deemed sufficient to create the prototype.

8 CONCLUSION

This work highlights the possible benefit of AR as an additional technology for training, especially fire evacuation. With its unique features, such as utilizing the user's real-life environment, it has the potential to create immersive, entertaining and, above all, educational experiences. However, this method cannot completely replace existing learning methods. A lack of research on flexible evacuation training simulators was identified, most proposed systems have been engineered for one specific environment and scenario.

Regarding the research questions proposed in chapter one, this leads to the following:

- AR is a possible technology that is suitable for evacuation training and overcomes the drawbacks of traditional methods. However, as this technology has its shortcomings, it should initially be treated as a supplement to traditional training and not as a replacement.
- It is possible to create a flexible training system that can be used in different environments without much preparation. Nonetheless, technical limitations need to be considered.
- The proposed system should theoretically be applicable to current training sessions. However, user testing and further refinements are needed.

In AR, the connection between the real world and the digital world allows for a wide range of applicability of the technology. It should be given greater consideration, especially for evacuation training. This work sought to explore the aspect of evacuation training in AR and demonstrated that specific design alterations could improve current systems. With the results of this research, more accessible trainer can be created to bridge the current gap between research and practice.

9 FUTURE WORK

In addition to refinement, the proposed system corrections in the section 6 and switching to a current device should be the next steps of development. As the HoloLens2 approaches the end of its life cycle, its use cases are becoming more limited. Using the device showed some general drawbacks, such as small field of view, limited computing power and having difficulties to track both hands in some situations. A switch to a more modern HMD such as the Meta Quest 3, or when released, project Swan by PICO, could improve the application by allowing more complex functionalities and having long term technical support.

Besides improvement of the simulator, the applicability needs to be investigate in much more detail. A mixed-model approach combining quantitative and qualitative methods is highly recommended, testing the usability and acceptance of the simulator, or investigating the effect of culture on gamification [28]. Conducting user studies, implementing established questionnaires, such as the simulator sickness questionnaire (SSQ) [29] or similar, or doing more expert interviews, would give a proven insight into the usefulness of the prototype or similar programs.

It would also be interesting to extend the scope of the simulator to other disaster situations, such as earthquakes. This would be particularly useful for training the Japanese population due to the higher risk of them happening. It could also be immersed in a more research focused application, as the interviews showed that the current simulator already offers needed functionality, allowing it to be used to improve safety concepts of spaces.

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