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Leveraging Interactive Mixed Reality for Dynamic Situational Information Updating in Fire Evacuation

Shengkai Wang [a,*], Qianhe Zhang [a], Nianhua Liu [a], Yu Feng [a], Liqiu Meng [a]

[a] *Chair of Cartography and Visual Analytics, Technical University of Munich, Germany, shengkai.wang@tum.de, ge84get@mytum.de, nianhua.liu@tum.de, y.feng@tum.de, liqiu.meng@tum.de*

* Corresponding author

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Abstract:

Building fires in multi-story structures pose significant challenges for safe evacuation due to the rapid spread of fire and smoke, reduced visibility, and unpredictable changes in escape routes. Traditional static evacuation aids, such as indicator signs and floor maps, often fall short in addressing these dynamic emergencies. Mobile navigation systems and augmented reality (AR)-based applications on smartphones provide improved guidance with real-time positioning and route planning, yet they face significant limitations in adapting to obstacles caused by fires or explosions. These limitations stem from the high cost of real-time sensors and the difficulty in accurately detecting and representing fire locations and spread.

Manually updating situational information within navigation apps on mobile phones offers a potential solution. However, this approach also introduces limitations and risks during navigation. Small screen sizes of smartphones reduce users' effectiveness and efficiency of interaction during operating the navigation systems (Raptis et al. 2013). Continuous reliance on visualized navigation routes also necessitates frequent shifts in attention between the screen and the environment (Brügger, Richter, and Fabrikant 2019), which compromises users' situation awareness (Leshed et al. 2008) and navigation safety (Lin et al. 2017). These challenges are exacerbated during emergencies (Ozel 2001), where stress and time pressure heighten individuals' cognitive load. To address these issues, head-mounted mixed reality (MR) technology emerges as a promising alternative, offering intuitive visualization and flexible interaction methods.

Mixed reality excels in spatial information visualization, navigation guidance, and dynamic interaction, making it an immersive and effective platform for emergency scenarios. Its ability to seamlessly integrate digital content with the physical environment enables users to visually perceive fire situations in real time and interact with 3D building models or directly with fire locations in the physical world. Through modalities such as gestures and eye tracking, users can dynamically update fire conditions and navigate escape routes with minimal cognitive load. For instance, MR allows users to manipulate layout models rendered in front of them or interact with fire locations in their surroundings, reducing reliance on small screens and enhancing situational awareness. These capabilities highlight the potential of MR for enabling manual and dynamic updates of fire scenarios, supporting safer and more efficient evacuations.

This ongoing work aims to investigate how interactive navigation systems can be designed and optimized for emergency fire scenarios. Two mixed reality interaction conditions will be tested, which are demonstrated in Figure 1: (1) MR visualization with layout visualization, allowing users to interact with the models to update fire situations (Figure 1b); and (2) MR visualization enabling direct interaction with real-world fire locations for dynamic updates (Figure 1c). Key research questions include:

- How do different interaction modalities affect evacuation efficiency and safety?
- How do different interaction modalities influence users' behaviour and cognitive processes?

To address the research questions, a minimum of thirty participants will complete both MR interaction conditions using a within-subjects, counter-balanced experimental design to control individual differences and potential learning effects. Each condition includes two main tasks: an evacuation task and a remote interaction task.

The evacuation task is conducted in a four-storey building with two staircases and two main exits, each floor covers approximately 880 m². (Figure 2). Participants will navigate from a predetermined starting location to the closest exit. Throughout this task, participants will encounter three distinct fire scenarios: fire directly ahead in clear view, fire suddenly emerging from around a corner, and fire progressively approaching the participant. Participants mark blocked routes by clicking as soon as flames are visually detected. The system subsequently updates evacuation paths and provides updated navigational instructions.

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Considering the need for users to mark distant fire locations in expansive structures, the remote interaction task occurs in a separate scenario involving an approximately 80-meter corridor (Figure 3). Participants will remain stationary at a predetermined position and sequentially interact with fires emerging at four distinct locations along the corridor, marking each blocked route accordingly.

Quantitative data collected will include the number of interactions, movement speed, evacuation and interaction-completion times, and gaze behaviours, all recorded through synchronized eye-tracking and system logs. Subjective workload is assessed after each trial using the NASA-TLX questionnaire. Distance-related performance will also be evaluated by comparing interaction-completion time and positional errors between participant-placed fire markers and ground-truth fire locations.

This study seeks to advance the design of MR-based fire evacuation systems and contribute to future innovations in emergency response technologies.

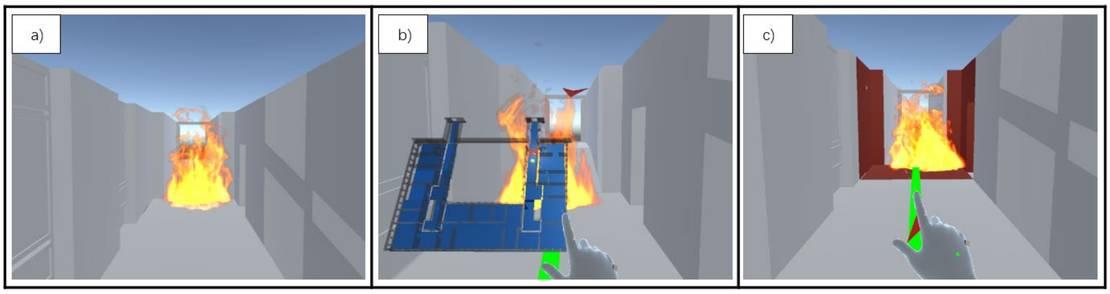

Figure 1. Interfaces of the MR-based interactive fire evacuation system. (a) original scene; (b) System with layout visualization and interaction; (c) System with in-situ visualization and interaction.

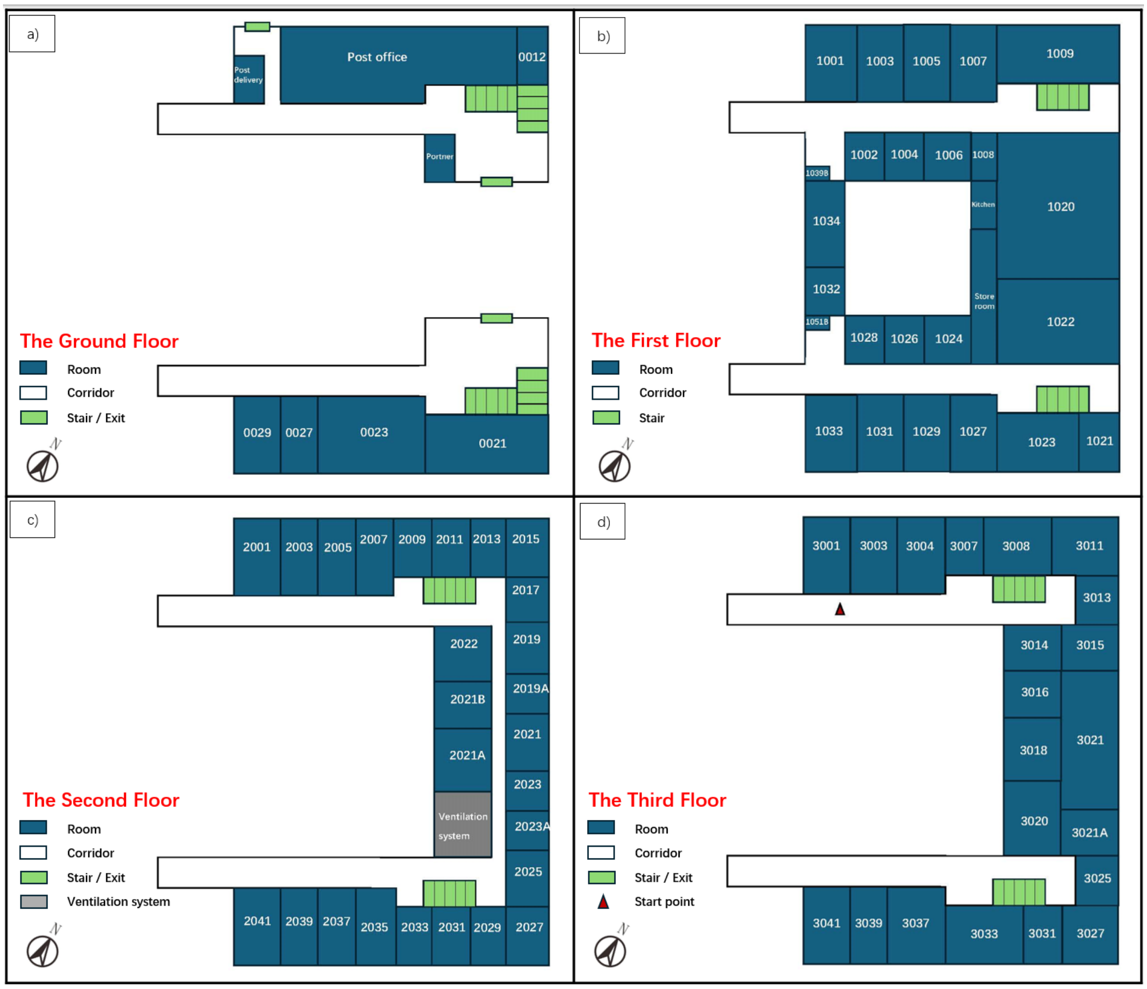

Figure 2. Floor plans of the experimental building used in the evacuation task, covering (a) the ground floor, (b) the first floor, (c) the second floor, and (d) the third floor.

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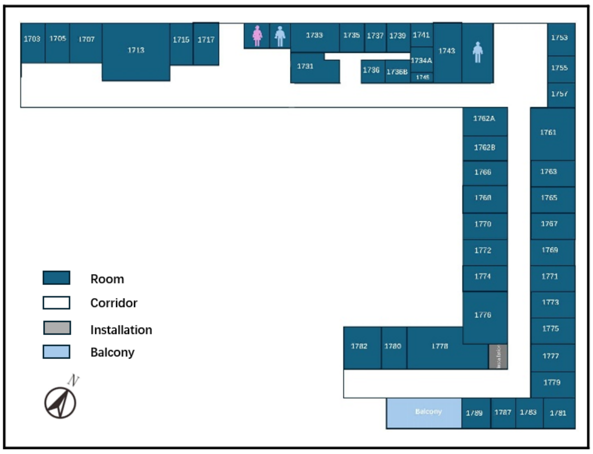

Figure 3. Floor plan of the experimental site used in the remote interaction task.

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