From Training to Incident Response: Resilient XR and Digital Twin Support in Firefighting

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Abstract

Extended Reality (XR) technologies are increasingly proposed to support professionals operating in high-stress, high-risk environments, across contexts ranging from training exercises to real-world incident response. However, many existing solutions still assume seamless system behaviour and generic information delivery that may not hold under operational stress. In safety-critical domains such as firefighting, XR systems must instead prioritize resilience by design and situated explainability to remain effective. In this position paper, we present three interrelated firefighter use cases spanning mixed-reality (MR) training, high-fidelity virtual reality (VR) location familiarization, and real-time digital twin (DT) supported field operations that integrate geospatial, sensor, and predictive data streams. Drawing on deployments in realistic contexts, we discuss design implications for building XR systems that foster skill evolution and teaming, deliver embodied / role-relevant information at a glance, and ensure graceful failure.

Keywords

Extended Reality, XR, Firefighter training, Digital Twins, Operational Support

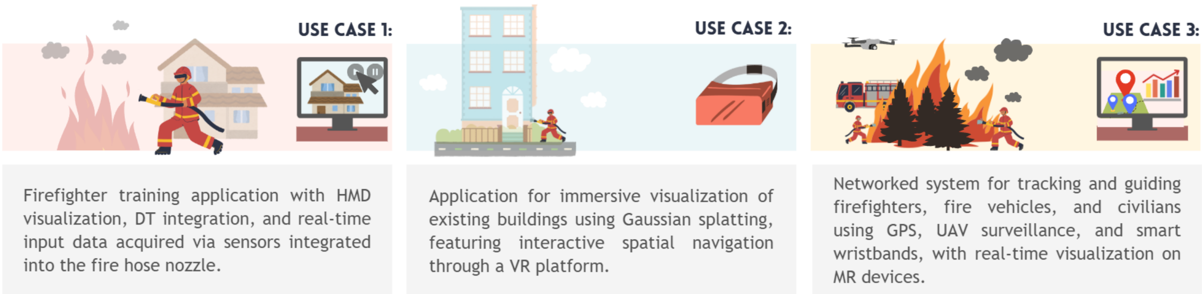

Figure 1: Illustration of three proposed conceptual use cases

1. Introduction and background

Firefighting is a dangerous, high-stress profession that exposes individuals to life-threatening conditions such as extreme heat, structural collapse, and hazardous substances [1]. Extended reality (XR) has emerged as a cost-effective alternative to traditional training, immersing trainees in virtual reality (VR) or integrating virtual elements with the real world through mixed reality (MR) [2]. Digital twins (DTs), as integrated, synchronized, data-driven virtual representations of real-world entities and processes [3], can be combined with XR to further enhance immersive training and real-time simulation.

Use of XR and DTs in firefighting has been widely studied. XR-based training systems provide realistic and controlled environments for experiential learning [4, 5, 6, 7, 8]. Commonly cited benefits include high interactivity, multiple perspectives, and context-relevant scenarios, while maintaining

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safety and cost-effectiveness [9, 10, 5, 11, 12]. To enhance realism and environmental familiarity, DTs of real-world objects (such as firefighting equipment [13]), and real-world spaces (buildings, terrain) may be integrated into immersive applications [14] for firefighter training [15, 16, 17].

Different flavours of XR have been applied in different contexts. A relatively recent literature review [18] shows the prevalence of VR for fire-training, whereas MR solutions have also been explored for operational use. The operational use of MR is based on the idea that capturing real-time environmental data (e.g., temperature, RGB, and depth imagery [19]), and presenting it through visual overlays or other modalities could enhance safety, navigation, team communication and collaboration [20]. Since VR is well suited for immersive simulation and MR can be applied directly in real-world environments, integrating both into firefighter training and operations presents a clear opportunity.

While user experience evaluation in VR firefighter training has received considerable attention [4], user interface (UI) design in MR adds further complexity. Challenges include information placement within the user's field of view, visual element design, and the lack of standardized interaction guidelines [21, 22, 23]. Information overload can reduce effectiveness, especially in crisis situations where rapid identification of critical information is essential [24]. Situated visualization places data within its physical context, linking it to relevant real-world referents [25]. In AR/MR, it supports in-situ tasks (e.g., situational awareness and training) [26], but must minimize overload, clutter, and occlusion to remain usable alongside physical referents [27]. The literature also calls for stronger engagement with target users and more in-situ, ecologically valid methods grounded in the target audience and context of use [25].

This paper presents three use cases showing how XR and DT technologies can support different firefighting stages, from training to operational use. The use cases were developed in close collaboration with the firefighting unit and training school in Zagreb. This work is the first phase of an iterative design and testing process involving continuous quality assurance and systematic user experience evaluation, focusing on workload, usability, performance, trust, and learning outcomes. Professional firefighters serve as consultants and primary evaluators to ensure alignment with operational requirements.

In our XR and DT based approach, MR enables immersive training in real environments, while VR provides high-fidelity building visualizations for training and pre-deployment familiarization. In both cases, DTs improve familiarity with environments, equipment, and conditions, strengthening confidence and readiness. For operational scenarios, we propose integrating DTs with real-time data streams and drone imagery to provide role-specific, cross-platform support. Thus we aim to improve situational awareness, support coordination, and help anticipate evolving conditions through predictive AI-based simulations. We also consider unobtrusive UI design and redundant visualization strategies for safety, robustness, and adaptability under degraded conditions.

2. Conceptual use cases

We present three use cases, introduced in Figure 1 and described next. For each use case, we developed a proof-of-concept (POC) prototype to support pilot studies and refine requirements and UI design.

2.1. Use case 1: Mixed reality firefighter training at a training ground

The first use case presents an MR-based collaborative training system for firefighters in high-stakes emergency response. A multi-user MR environment supports trainee skill development and team situational awareness, while giving instructors scenario control and performance assessment. The system is deployed in real environment, where multiple trainees in full gear interact with shared virtual elements aligned with the physical surroundings. A simplified DT models key spatial and operational features, updates dynamically based on trainee movements and interactions, while instructors monitor and adjust scenarios through a control UI. Similar to the XR simulator in [2], the system combines immersive simulation with instructor control to deliver safe, repeatable, context-specific training. Our design preserves existing full-gear training routines, and enables safe, repeatable scenarios without live-fire exposure. The POC includes an MR trainee application (Figure 2, left) and a PC-based instructor application (Figure 2, right). While commercial VR tools such as FireFighterVR[1] are widely available, AR/MR systems for firefighter training are limited. Existing options such as PROXR FAST XR[2] and irvino Fire AR[3] focus on basic fire-safety tasks, and only FAST XR supports multiplayer. In contrast, our system is specifically aimed at multi-user training of professional firefighters.

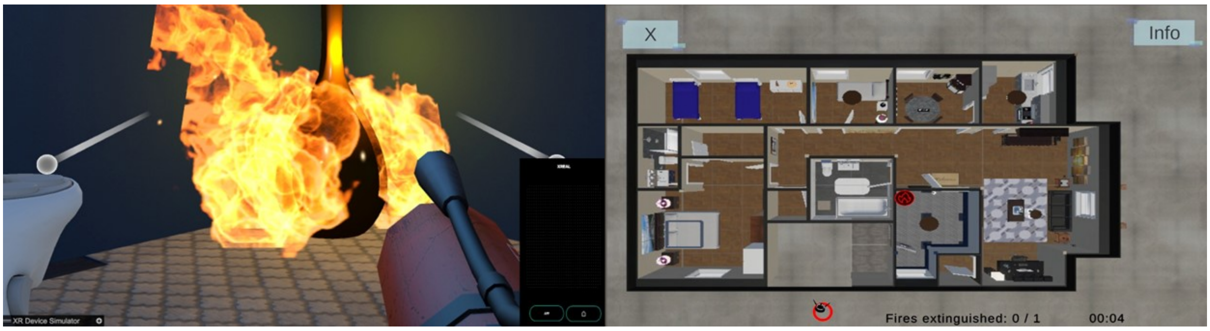

Figure 2: Developed POC applications for use case 1. Left: MR training application showing a firefighter's point of view in the virtually represented DT of a house, positioned on a physical training ground. Right: Instructor's DT interface for supervising and controlling the training simulation (e.g., initiating a virtual fire).

2.2. Use case 2: Virtual reality firefighter training and en-rout tool for location familiarization

The second use case focuses on a VR firefighter training and operational use system based on detailed 3D reconstructions of real-world spaces. Techniques such as Gaussian splatting and photogrammetry are used to create realistic DTs of buildings or industrial facilities. The goal is to enhance situational awareness by helping firefighters familiarize themselves with potential incident locations in advance. This supports both emergency interventions, such as fire suppression, and routine tasks, such as false-alarm inspections. The system enables flexible, repeatable, and measurable training, especially for large or complex environments. Compared to commercial VR systems, our approach not only enables training, but also supports pre-incident preparation through en-route familiarization, improving orientation, efficiency, and safety. Futhermore, it employs DTs and Gaussian Splatting to generate detailed real-world replicas and turns them into interactive 3D environments. In general, commercial systems mainly use predefined virtual spaces, with the exception of Structurus STRX-3D[4] that offers custom 3D replicas. This scenario also points to a role for fire-protection authorities in commissioning 3D reconstructions of important public spaces to support preparedness and public safety. We developed a VR POC prototype using a 3D model of a faculty building with an integrated fire alarm system (Figure 3, right). The prototype allows free navigation and guides users in locating and deactivating the alarm. Its design was informed by firefighter interviews, which highlighted frequent false alarms and difficulties locating and operating different alarm units.

2.3. Use case 3: Real-time operational support using digital twin visualization

The third use case focuses on real-time operational support through multi-modal feedback during incidents. Its main objective is to improve shared situational awareness by locating firefighters in impaired visibility, tracking ground and aerial assets, supporting tactical adjustments, and enabling safe navigation in remote areas. A terrain-level DT integrates geospatial data (GIS), drone imagery, meteorological information, and real-time tracking of personnel and vehicles into a coherent operational overview for fast-changing, high-risk environments. Information is delivered via MR headsets, tablets,

[1]https://firefightervrmobile.de
[2]https://pro-xr.com/en/fast-xr-fire-training-simulator-ar-vr/
[3]https://www.irwino.com/en/the-fire-ar-augmented-reality-simulator/
[4]https:https://structurus.com/en/strx

or laptops and tailored to operational roles, enabling incident commanders and field teams to maintain shared situational awareness. By combining live positioning, environmental data, and predictive AI-based simulations, the system anticipates evolving conditions, supports structured documentation, and improves team coordination while preserving hands-free interaction in hazardous environments. This approach aligns with prior work showing that MR with positioning and wildfire spread simulations improves situational awareness and tactical decision-making [20]. To foster appropriate trust, the UI will display clear indicators of information reliability, such as confidence levels or uncertainty markers. The commanding officer retains full authority and can correct any UI element when necessary, ensuring human oversight. Service robustness is a core design requirement. If the system fails, firefighters must still be able to operate normally, which limits feasible solutions to optical see-through MR devices. These may require adaptation to fit under standard protective gear, which remains an open challenge. To improve robustness, the architecture will follow low-bandwidth multiplayer game models. If connectivity is lost, the system will either display the last known state with a clear update-loss warning or disable visualization and revert to standard radio communication. Redundant visualization methods will further ensure access to essential information. Following situated visualization principles, the UI displays only task-relevant information anchored to the physical environment and entities, while remaining simple and unobtrusive even in system failure so it does not interfere with the firefighter's primary task. The visual layer can be disabled when needed, with information conveyed through audio. To reduce cognitive load, only essential, context-dependent cues are shown and adapted to each role. Additional information is available on demand, and the commanding officer can control what is displayed to others. As an initial step, we developed a POC PC-based video game that simulates the MR UI from a first-person perspective (Figure 3, left). We chose video game environments to explore initial design requirements, support early refinements, and help firefighters with limited XR experience understand the system. Features were based on firefighter-identified challenges in a forest-fire scenario.

Figure 3: Left image: Developed proof of concept PC video game for use case 3. Right image: Developed proof of concept VR application for use case 2.

3. Research challenges and summary of contributions

By grounding the use cases in feedback from professional firefighters, we identify how the real-world needs of emergency services can be addressed by the research community. The use cases contribute to the workshop's research agenda and motivate the following research challenges:

- how to measure and account for trust in the system during training and firefighting operations;
- how to design fallback modalities to ensure graceful system failure, while supporting field operations, such as using drones or thermal imaging in smoke or low visibility, or manual input when sensors or trackers fail;
- how to provide clear, relevant multimodal feedback and explanations to firefighters and incident commanders, while reducing cognitive load in critical situations.

Our expected contributions include:

- Design of scalable and flexible XR scenarios that provide realistic, safe, and controlled experiential learning environments, validated through multi-user evaluations involving firefighters in operational and instructional expert roles.
- Validated methodologies for assessing trust, learning outcomes and usability of XR technologies in training of civil protection professionals, considering operational demands and workload in high-stress environments.
- User interface design guidelines that account for field-of-view limitations, workload, ergonomic constraints, and contextual information prioritization in MR environments.

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Declaration on Generative AI

ChatGPT-5.4 and M365 Copilot GPT-5.4 were used to: assist with paraphrasing and spelling check. After using these tools/services, the authors reviewed and edited the content as needed and take full responsibility for the publication's content. All scientific content is entirely prepared by the authors.

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