Reactive AR Safety Guidance for Operators on the Move: Lessons from AI-Driven Industrial Evacuation

George E. Raptis
graptis@humanopsis.com
Human Opsis
Patras, Greece

Eleni Chrysopoulou
echrysopoulou@humanopsis.com
Human Opsis
Patras, Greece

Christina Katsini
ckatsini@humanopsis.com
Human Opsis
Patras, Greece

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1 Introduction

Augmented reality (AR) systems operate in mobile and safety-critical environments. Industrial settings present a demanding case. Operators move across production floors, interact with machinery, and respond to dynamic hazards. These environments shift due to machine activity, human presence, and environmental conditions. AR on-the-move must support locomotion while preserving situational awareness. Visual overlays compete with physical hazards for attention. Alerts must interrupt when necessary but avoid overwhelming the user. Guidance systems must adapt when exits become blocked or hazard zones expand. These requirements challenge static overlays and conventional notification design, in practice.

We address this problem through SENSE-XR, a safety notification system developed for XR manufacturing environments. The system delivers three spatial notification types: informational panels, volumetric danger zones, and AI-generated evacuation routes. It integrates real-time sensor input and dynamic pathfinding to support hazard response while users move through the environment. We designed and evaluated SENSE-XR through two user studies with industrial stakeholders. The formative phase revealed issues related to color semantics, spatial rendering, and environmental immersion. The summative evaluation showed improved usability, reduced workload, and higher task success rates after targeted refinements.

In this position paper, we reflect on lessons learned from deploying reactive AR guidance in a dynamic industrial setting. We identify key challenges for AR on the move and outline directions for adaptive, safety-critical AR systems.

2 SENSE-XR: System overview in motion

SENSE-XR supports operators who move through industrial environments while responding to emerging hazards. The system combines spatial notifications, real-time data integration, and AI-driven path planning. We designed it to function during continuous locomotion rather than stationary interaction.

2.1 Industrial AR context

Manufacturing environments contain moving machinery, restricted areas, heat sources, and potential gas leaks. Operators walk between workstations, inspect equipment, and react to alerts. Hazards may appear or change while the operator is in motion. SENSE-XR connects to backend services that stream contextual data from sensors and simulation modules. The system processes hazard states and triggers notifications based on severity. The XR client renders these notifications directly in the operator's field of view while preserving spatial alignment with the environment. This setting introduces constraints. The user cannot stop inspecting detailed menus. The system must communicate risk, proximity, and direction with minimal interaction. It must also remain responsive when environmental conditions change.

2.2 Severity-based spatial notification design

We structured the notification system into three levels: informational, warning, and critical. Each level corresponds to a different hazard severity and user response requirement. This escalation model allows the system to adjust visual intensity based on hazard severity. It reduces desensitization to low-priority alerts and highlights immediate threats that require movement.

- **Informational notifications** provide contextual guidance. The system renders them as 3D floating panels anchored relative to the user's head position. The panel includes a title, an icon, a short description, and an optional image. Users dismiss the panel through a simple gesture or controller input. We position the panel at eye level to support readability without obstructing navigation.
- **Warning notifications** indicate proximity to potential hazards. The system renders them as volumetric danger zones anchored to world objects, such as machines or restricted areas. These zones remain fixed in the environment and do not follow the user. When the operator approaches the boundary, the system increases visual salience and displays contextual information. The zones are non-disruptive to maintain spatial awareness.
- **Critical notifications** trigger evacuation behavior. The system renders an animated path composed of directional arrows anchored to world coordinates. The arrows guide the operator toward a safe exit. The path remains visible until the user reaches the destination or the alert is cancelled.

2.3 Reactive AI-driven evacuation guidance

SENSE-XR computes evacuation routes using a pathfinding engine integrated with real-time hazard data. The system models the environment as a navigable graph that includes static obstacles, dynamic hazard zones, and exit points. When the backend detects a critical event, it computes an evacuation path based on the operator's current position and the active hazard state. The engine reevaluates routes at short intervals to account for environmental changes, such as blocked exits or expanding danger zones. If the hazard configuration changes, the system invalidates the current path and renders a new one. The XR client receives the ordered 3D coordinates and instantiates arrow prefabs aligned with the route. Each arrow orients toward the next waypoint to support directional continuity. The path is slightly above ground level to maintain visibility while walking. This approach supports reactive guidance in the face of environmental volatility. The operator does not request route updates. The system adapts automatically while the user remains in motion.

2.4 Design for movement

Designing for locomotion required attention to spatial coherence and perceptual stability. Informational panels are anchored relative to the user to maintain readability. Warning zones anchor to world objects to preserve spatial reasoning. Evacuation paths anchor to floor coordinates to support directional flow. We also integrated multimodal cues. Warning and critical events trigger distinct auditory signals. Ambient factory sounds reinforce presence and contextual grounding. These cues support attention management without requiring constant visual focus. Together, these components create a notification framework that operates during movement, adapts to environmental change, and maintains alignment between virtual guidance and physical space.

3 Empirical insights from deployment

We evaluated SENSE-XR through a formative and a summative study with participants who had backgrounds in industrial engineering, occupational safety, and XR training. Both studies used scenario-based tasks in a simulated manufacturing environment. Participants completed hazard-handling, evacuation, notification overload, and interruption-recovery scenarios while wearing an XR headset.

3.1 Formative evaluation: identifying friction during movement

The formative evaluation examined an early version of the system. Participants achieved a task success rate of 78.5% and reported a System Usability Scale (SUS) score of 67.8. The NASA-TLX workload index averaged 56.2, indicating moderate-to-high cognitive effort. Mean system latency remained within the predefined threshold. Qualitative feedback revealed issues that directly affected locomotion and hazard interpretation. When participants entered a warning zone, the transparent volumetric sphere became difficult to perceive due to rendering behavior from the inside. Several participants reported uncertainty about whether the hazard remained active. This reduced confidence in spatial cues during movement. Participants also misinterpreted the red evacuation arrows used in the initial version. Red commonly signals prohibition or danger. Some users hesitated before following the path because they associated the color with "do not enter." In emergency scenarios, this hesitation affected reaction time. In addition, participants described the early environment as lacking contextual grounding. The absence of ambient sound reduced the sense of urgency and spatial presence. Together, these findings showed that minor perceptual inconsistencies can disrupt trust and situational awareness when users are moving.

3.2 Design refinements

We implemented targeted refinements to address these issues. First, we modified the warning zone shader to render both sides of the volumetric surface and adjusted opacity and glow parameters. This ensured visibility even when the user stood inside the zone. Second, we replaced the red evacuation arrows with green directional arrows. Participants consistently associated green with safe movement and exit behavior. We adjusted luminance to maintain visibility under varying lighting conditions. Third, we introduced ambient factory sounds and distinct auditory cues for warning and critical alerts. These additions provided redundant feedback and improved environmental grounding.

3.3 Summative evaluation: effects on usability and workload

The summative evaluation assessed the refined system. Task success increased to 91.3%, and average time-on-task decreased. The SUS score rose to 78.9, indicating good usability. The NASA-TLX workload index dropped to 43.5, reflecting reduced cognitive effort. Notification accuracy reached 96%, and latency remained within performance targets. Participants described the refined prototype as transparent and trustworthy. They interpreted the green arrows as safe guidance without hesitation. Persistent warning zones improved hazard awareness even at close range. Auditory cues supported faster orientation in complex scenes. These results demonstrate that targeted adjustments to color semantics, spatial rendering, and multimodal feedback can improve usability and reduce cognitive load in AR systems used during locomotion. The evaluation also shows that AR-on-the-move design depends on perceptual stability and semantic alignment as much as on algorithmic accuracy.

3.4 Secure-by-design considerations for safety-critical XR

Beyond perceptual and interaction challenges, our deployment also highlighted the importance of secure-by-design development practices in safety-critical AR systems. SENSE-XR relies on a heterogeneous, multi-language architecture, where vulnerabilities in individual components can affect overall system reliability during critical events. Current development practices often rely on fragmented security checks and manual reviews, providing limited visibility across the software lifecycle. In dynamic XR environments that combine real-time data streams, AI-driven decision-making, and IoT integration, this limitation becomes particularly critical. Continuous, automated security analysis integrated into development pipelines can support earlier vulnerability detection, improve runtime resilience, and enhance traceability of security and compliance requirements. Embedding such practices into XR development workflows is therefore essential to ensure that adaptive safety systems remain trustworthy, robust, and suitable for deployment in real-world industrial contexts.

4 Challenges for AR On-the-Move

4.1 Balancing visual salience and cognitive load

AR notifications must attract attention without overwhelming the user. In safety-critical contexts, alerts compete with physical hazards for perceptual resources. Excessive visual intensity increases cognitive load, while insufficient salience reduces response speed. Our formative evaluation showed that unclear rendering and ambiguous cues increased hesitation and mental effort. After refining color semantics, opacity, and auditory redundancy, we observed reduced workload and improved task success. These findings suggest that AR-on-the-move systems must calibrate visual intensity relative to hazard severity and environmental complexity. Future systems may benefit from adaptive notification scaling that considers user motion speed, gaze direction, and concurrent alerts.

4.2 Aligning visual semantics with action

Color, motion, and spatial placement encode behavioral expectations. In our early prototype, red evacuation arrows introduced hesitation because participants associated red with prohibition. Replacing red with green reduced uncertainty and improved compliance. This result highlights a broader issue: AR systems in motion cannot rely solely on visual prominence. They must align semantic conventions with expected action. Misalignment introduces delay, which carries risk in emergency contexts. Designing AR guidance therefore requires explicit mapping between visual attributes and behavioral intent. This mapping becomes critical when users must decide while moving.

4.3 Maintaining spatial trust under rendering constraints

Users rely on spatial consistency to interpret risk. When the warning zone became invisible from inside, participants questioned whether the hazard remained active. Although the underlying state did not change, the perceptual inconsistency reduced trust. AR-on-the-move systems must maintain stable spatial representations even when users cross boundaries or change perspective. Rendering artifacts, clipping issues, or occlusion errors can undermine system credibility. In safety contexts, trust depends on perceptual continuity. Developers should treat rendering behavior as part of the safety mechanism rather than as a purely technical concern.

4.4 Supporting reactive guidance in volatile environments

Dynamic environments require continuous route adaptation. Our pathfinding engine recalculated evacuation routes when hazards emerged or blocked previous paths. The XR client replaced outdated arrows with updated guidance without user intervention. While this reactive model supports adaptability, it raises open questions. Frequent re-routing may confuse users if visual transitions lack explanation. Conversely, delayed updates may expose users to risk. AR-on-the-move research should examine how to communicate route updates transparently while preserving directional clarity. Systems may need mechanisms that signal why guidance changes, especially in multi-hazard scenarios.

Participant background and experience

Dr George E. Raptis, Christina Katsini, and Eleni Chrysopoulou conduct research and development in extended reality (XR), human–computer interaction, and safety-critical systems. Their work focuses on designing, implementing, and evaluating XR applications deployed in real-world industrial and training environments. They have developed and validated XR systems for manufacturing, occupational safety, and adaptive interaction scenarios. Their projects integrate Unity-based spatial interfaces, real-time backend services, and AI-driven modules for context-aware guidance. They conduct iterative evaluations using mixed-methods approaches, including usability testing, workload assessment, and performance analysis with representative end users. In the SENSE-XR project, the team designed and evaluated an AR-based safety notification system deployed in a simulated industrial manufacturing environment. The system integrates spatial hazard visualization and real-time evacuation guidance while supporting user locomotion. Through formative and summative studies, the team examined how AR notifications affect situational awareness, cognitive load, and trust during movement. Beyond industrial XR, the authors have experience with mobile and embodied XR interaction, adaptive environments, and multimodal feedback design. Their work emphasizes human-centred development, empirical validation, and the deployment of XR systems outside controlled laboratory settings.

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