XR Training in Challenging Environments: The Wind Turbines Case*

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Abstract

Training professionals for challenging environments requires more than immersive simulation. Safety-critical contexts combine environmental unpredictability, spatial constraints, physiological load, and collaborative complexity in ways that fundamentally shape learning and performance. Using wind turbine maintenance as a representative case, this position paper explores how Extended Reality (XR) systems can support training and operational preparedness in such environments. We argue that integrating XR with digital twins, physiological sensing, and adaptive scenario control enables controlled risk exposure and context-aware feedback while supporting collaborative coordination. Building on this use case, we outline design directions for smart XR environments that dynamically adapt to user state and environmental conditions. We further position these environments as experimental platforms for investigating key challenges in mission-critical XR systems, including trust calibration under stress, resilience by design in volatile contexts, and situated explainability through embodied feedback. These directions contribute toward a research agenda for trustworthy XR systems in challenging environments.

Keywords

eXtended Reality, training, challenging environments, wind turbines, digital twins

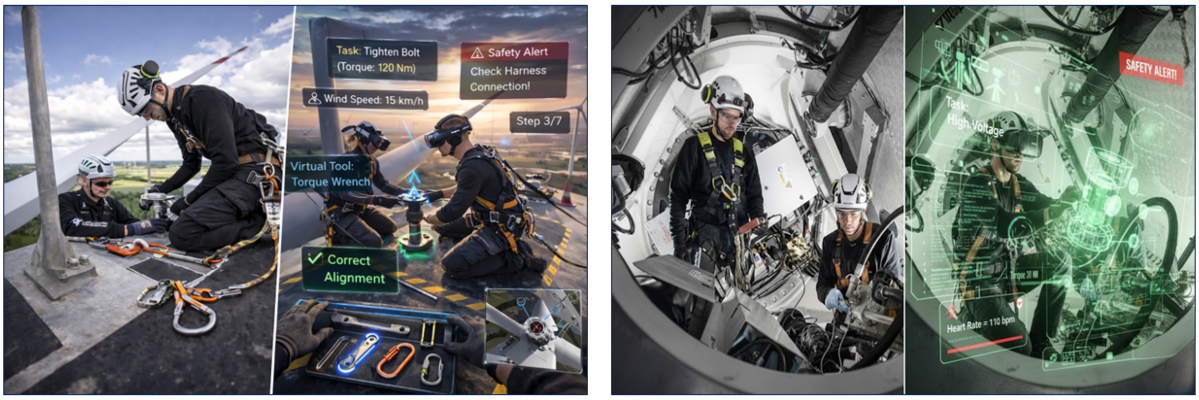

Figure 1: Wind turbine maintenance as a multi-dimensional challenging environment. High-altitude rotor work exposes technicians to environmental variability and physical risk (left), while confined nacelle operations require precision and teamwork (right). XR training can simulate both contexts with adaptive guidance and safety feedback.

1. Introduction & Motivation

Challenging environments are characterized as non-traditional settings that are rapidly changing, difficult to control, and often unpredictable [1]. In addition to these characteristics, we argue that such environments are defined by an explicit element of criticality or danger. This danger may vary widely across contexts, from outdoor settings at high altitudes to indoor emergency rooms, but it shares a

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common feature: *the potential to harm one or more individuals if actions are performed incorrectly or under adverse conditions.* Accordingly, challenging environments span a wide range of application domains, including firefighting, intensive care units, advanced industrial manufacturing, and other high-risk professional settings. While the nature and severity of the danger element differ across these scenarios, each imposes distinct requirements on how training situations should be simulated and supported.

Recent research in Extended Reality (XR) has begun to explore how immersive technologies can support professionals operating in such environments[2, 3]. However, mission-critical work introduces additional requirements beyond realism and immersion. In contexts where mistakes can have severe consequences, XR systems must support appropriate human reliance, remain functional under volatile conditions, and provide feedback that can be understood quickly under pressure[4, 5]. These challenges point to the need for XR systems that are trustworthy, resilient, and capable of providing situated explanations directly within the workspace.

To train experts for work in such environments, immersive Extended Reality (XR) technologies offer a particularly promising approach. XR enables the controlled simulation of hazardous conditions, allowing learners to experience and respond to dangerous situations without real-world consequences [6]. Importantly, the level, timing, and nature of the danger can be manipulated, repeated, or escalated in ways that would be impractical or unsafe in physical training environments. Similar , dynamic inputs and environments, where the primary focus lies on acquiring and refining task-specific skills, training in challenging environments requires careful consideration of learning progress, accuracy, and performance. These factors must also be examined in relation to the presence of danger and its cognitive, physical, and emotional implications for learning and decision-making.

Beyond skill acquisition, such training environments also offer an opportunity to investigate how professionals interact with XR assistance under stress[7]. Controlled training scenarios make it possible to study how trust in system guidance evolves as task difficulty increases, how systems respond to uncertainty or failure, and how explanations can be delivered through embodied cues integrated directly into the working environment. As such, XR-based training environments can serve as experimental platforms for exploring key design challenges of mission-critical XR systems.

In this context, we define a smart environment as one that not only meets the requirements for realism and immersion but also adapts to the non-traditional, high-risk nature of the simulated setting. Such adaptation may arise from diverse and dynamic inputs, as well as from both expected and unforeseen changes in system behavior and user performance. More specifically, we define a smart XR environment as an adaptive system that integrates environmental simulation, physiological sensing, and collaborative interaction data to dynamically regulate scenario difficulty, feedback, and risk exposure[8, 9].

As a concrete example, we consider *XR-based training for wind turbine maintenance and operation.* Building on this use case, we outline a path toward a standardized framework for smart XR environments that support training in challenging, safety-critical contexts. Using this case, we highlight how XR training environments can contribute to a broader research agenda on trustworthy XR systems in challenging environments, particularly with respect to calibrated trust under stress, resilience by design in volatile contexts, and situated explainability in embodied work settings.

2. XR for Wind Turbine Training in Safety-Critical Contexts

Wind turbine maintenance[1], while not a novel technological domain, represents a rapidly evolving industrial field. Advances in turbine size, offshore deployment, digital monitoring, and maintenance procedures continuously reshape the competencies required of technicians. As turbines grow taller and more technologically complex, maintenance work demands high levels of precision, physical endurance, and safety-critical awareness.

[1]This work is conducted in collaboration with experts from Deutsche Windtechnik AG, an independent service provider for wind turbine maintenance.

Training individuals to operate in this domain is, therefore, inherently challenging. The work environment combines technical tasks with exposure to height, environmental variability, confined indoor spaces, and coordinated teamwork. These demands do not arise from a single factor but from the interaction of outdoor, indoor, and collaborative constraints that together define the training context. To support such environments, XR systems can be combined with digital twin infrastructures that mirror the structure and operational state of real turbine systems. Digital twins enable realistic scenario generation based on maintenance procedures, component configurations, and potential system faults[10]. When integrated with XR environments, they allow training scenarios to dynamically reproduce operational challenges such as environmental disturbances, equipment failures, or coordination dependencies between technicians. This integration enables more realistic and adaptive training conditions while providing a foundation for studying how XR systems support decision-making and coordination in safety-critical contexts[11]. Together, these dimensions illustrate how challenging environments emerge from the interaction of environmental volatility, spatial constraints, physiological stress, and collaborative complexity.

2.1. Outdoor Conditions: Altitude and Environmental Volatility

A defining characteristic of wind turbine maintenance is the requirement to operate at high altitudes. Technicians must perform precise mechanical tasks while suspended hundreds of meters above ground or sea level. Adapting to height exposure takes time, both physically and psychologically. Gradual, stepwise exposure is therefore essential in training.

Extended Reality environments provide opportunities to scaffold altitude adaptation progressively [12]. Physiological sensing, such as heart rate monitoring, gaze tracking, or stress indicators, can support adaptive exposure by identifying when trainees experience overload or loss of focus. This enables a controlled escalation of difficulty while maintaining safety and learning effectiveness. In addition, gamification elements, such as structured progression levels, performance feedback, and challenge-based milestones, can reinforce motivation and encourage gradual acclimatization to height-related stress [13]. When carefully designed, these mechanisms support engagement without trivializing the safety-critical nature of the task. Moreover, weather conditions introduce an additional layer of complexity. Although training often occurs under stable, favorable conditions, real-world maintenance is often conducted in volatile environments, particularly offshore. High winds, heavy rain, thunder, and sudden environmental shifts can drastically alter task demands. Beyond simulating adverse weather, XR systems must account for unpredictability and rapid environmental transitions, which are critical elements of real-world risk.

2.2. Indoor Constraints: Confined and Elevated Spaces

Despite the visibility of the external height factor, a significant portion of maintenance work takes place inside the turbine nacelle. While structurally secure, this space is confined, elevated, and physically demanding. Technicians often remain at the top of the turbine for extended periods, requiring careful planning of timing, coordination, and maneuvering within limited space. Training must therefore address not only technical execution but also spatial awareness, fatigue management, and decision-making under constrained conditions. These aspects are difficult to reproduce consistently in traditional training settings, where space limitations, elevation, and prolonged exposure are often abstracted or simplified.

XR environments can emulate the spatial constraints and ergonomic demands of nacelle operations with high fidelity, allowing trainees to rehearse maneuvering, tool handling, and coordination within realistically confined layouts [14, 15]. Integrated physiological sensing can further support the detection of fatigue or cognitive overload during prolonged tasks, enabling adaptive scenario pacing. Additionally, structured gamification elements, such as timed task sequences, collaborative role-based challenges, and performance-based feedback, can simulate operational pressure while maintaining engagement. When carefully designed, these mechanisms reinforce procedural learning and coordination without diminishing the environment's safety-critical nature.

2.3. Multi-User and Collaborative Demands

Wind turbine maintenance is rarely a single-person task. It requires coordinated collaboration between multiple technicians, often distributed across different physical locations within the turbine structure. Training one individual is complex; training teams introduces additional challenges related to communication, timing, shared situational awareness, and distributed responsibility.

Simulating multi-user collaboration in safety-critical contexts is itself a demanding design challenge. Effective training requires synchronization of actions, precise role distribution, and dynamic adaptation of the scenario to team behavior. Even in XR environments, achieving collaborative fidelity is not trivial. Latency, limited embodiment cues, misaligned perspectives, or incomplete awareness of others' actions can distort coordination dynamics and reduce training validity. Furthermore, in real-world operations, individual errors can cascade across the team, amplifying risk. XR systems must therefore model not only individual performance but also interdependencies between users, communication breakdowns, and collective recovery strategies to meaningfully replicate collaborative risk.

Beyond individual training, collaborative XR environments also provide opportunities to investigate team-level dynamics in safety-critical work. Errors made by one technician may propagate through the team, requiring rapid coordination and recovery strategies. Designing XR systems that support shared situational awareness, role clarity, and communication resilience is therefore essential for realistically simulating collaborative risk. Such environments may also support remote collaboration scenarios, where experts provide guidance or assistance from outside the turbine, further expanding the potential role of XR in operational contexts.

3. Conclusion

In summary, training in challenging environments demands adaptive and safety-aware systems rather than immersive simulation alone. Using wind turbine maintenance as a case study, we highlight how XR, digital twins, and human-centered augmentation can form the foundation of smart training environments for safety-critical domains.

Beyond training, such environments also offer a controlled setting for investigating how XR systems should be designed for mission-critical work. In contexts characterized by environmental volatility, physical risk, and collaborative complexity, XR systems must support appropriate human reliance, remain robust under uncertainty, and provide feedback that can be interpreted rapidly under pressure. The wind turbine maintenance use case illustrates how XR environments can support controlled risk exposure, team-based coordination, and adaptive feedback mechanisms. These characteristics make such environments particularly valuable for exploring broader design questions related to trustworthy XR systems in challenging environments. Future research should therefore investigate how XR systems can support calibrated trust under stress, how resilient interaction design can enable systems to degrade gracefully in volatile conditions, and how situated explanations can be embedded directly into the physical workspace through embodied feedback mechanisms. By framing XR training environments as experimental platforms for studying these challenges, we hope to contribute to a broader research agenda on trustworthy, resilient, and explainable XR systems for professionals operating in challenging environments.

Declaration on Generative AI

During the preparation of this work, the author(s) used GPT-5.3 Grammar and spelling check. Further, the author(s) used Google Gemini to generate Figure 1. After using these tools, the author reviewed and edited the content as needed and took full responsibility for the publication's content.

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