

Executive Summary

We addressed the challenge of training first responders in hazardous and unpredictable environments where traditional methods are costly and unsafe. This project presents an immersive training approach using Extended Reality (XR) and digital twin technology to simulate indoor emergency scenarios for drone operations. We created a realistic building environment and integrated it into a physics-based XR system where participants performed tasks such as human identification and hazard identification. We found that XR-based training provides a safe, scalable, and effective method for improving situational awareness, decision-making, and operational readiness.

Background

Did you know?

Every year in the United States there are

16,500 office and store fires.



Figure 1. USFA data [1]

- These office and store fires cause over \$932M in direct property damage [1].
- The National Fire Protection Association (NFPA) estimates around 26,000 firefighter injuries per year, primarily due to hazardous exposure and overexertion during training [2].

- Drones enable responders to remotely assess hazardous environments reducing direct risk.
- However, real-world drone training is limited by safety risks, high costs, and logistical constraints so we propose XR-based systems as to provide repeatable, and scalable training environments [3]
- Prior research shows XR technologies improve task accuracy, safety, and situational awareness in dynamic environment [3-4].



Figure 2. Scenes from the Experiment



Figure 3. Experiment - Mission Layout

Experiment

Experiment Plan: Participants completed a structured three-phase experiment:

Phase 1

- PRE-EXPERIMENT
- Consent, demographic survey and Floor plan review

Phase 2

- XR-SIMULATION
- Reminders and objective

Phase 3

- POST-EXPERIMENT
- Identify objective on map and survey

Participants:
n=8
Ages: 21-37



Figure 4. Human subject

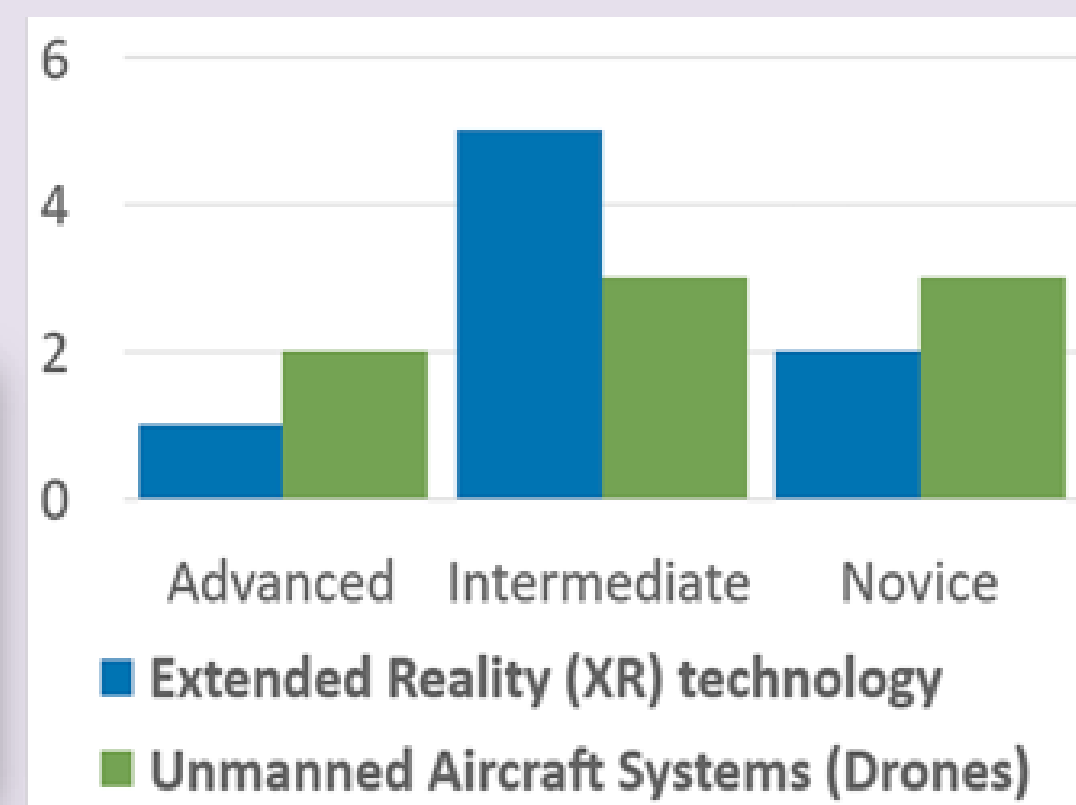


Figure 5. Pre-experiment survey

The mission was to Identify number/location of human humans and find fire origin. The mission was timed and stopped after 5 collisions. Participants completed hazard identification & performed smooth flight. Time & success, accuracy (fire + humans), navigation efficiency, collisions, user confidence.

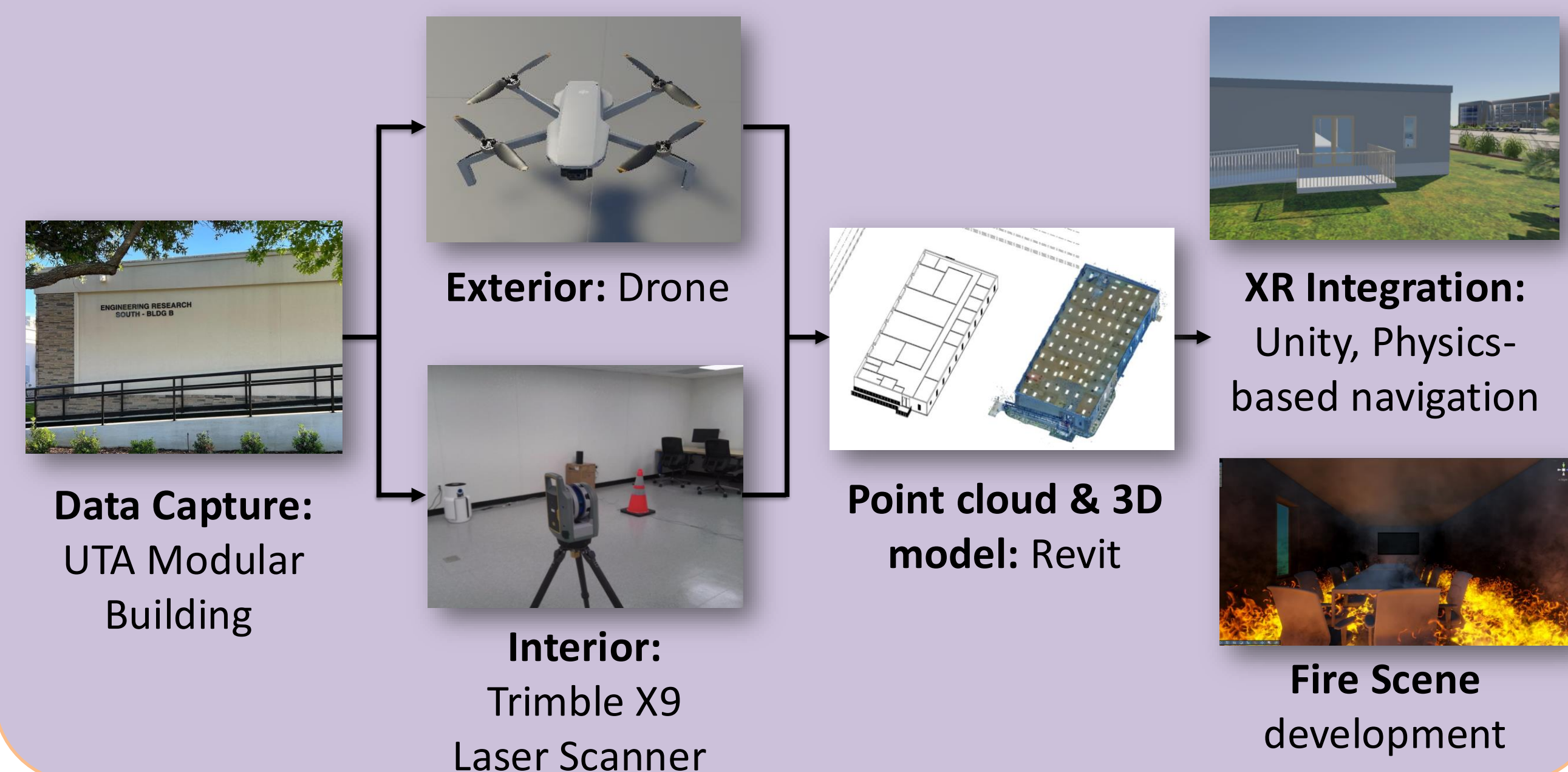
Digital Twin Development: We used a Trimble X9 Laser Scanner and a drone to capture images of the building and generate point clouds, which were then converted into a 3D model in Autodesk Revit and exported to Unity to build the simulated environment [5]. After importing the descriptive digital twin into Unity, we created interactive layouts of rooms, equipment, and pathways. This allowed us to maneuver the drone in a realistic simulation.

The experimental scenario was inspired by the NIST evaluation guidelines [6]. Participants spawned just outside the building and used the controller to pilot the drone indoors while viewing the live drone camera feed on the controller screen. Their mission was to locate fire sources and human targets inside the building, then report the overall scenario. To encourage careful operation, the drone could collide a maximum of five times before being destroyed.

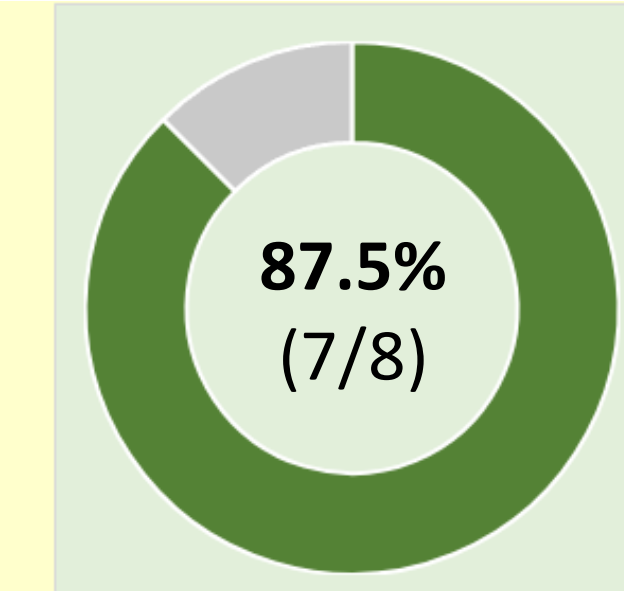
Fire origin: An electrical socket starts the fire near a window, while open doors promote smoke migration and fire spread.

Human targets: One running, one fainted, and one injured.

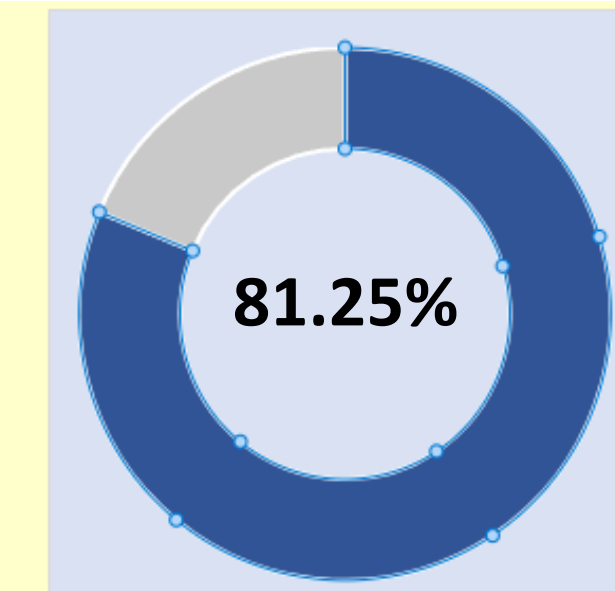
DEVELOPMENT PIPELINE



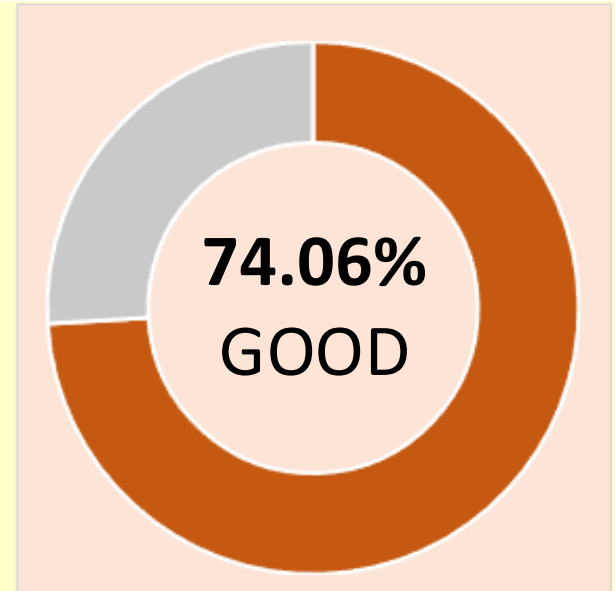
Experimental Results



Mission Completion Success



Hazard Identification Accuracy: from post experiment map identification



System Usability Scale (SUS): Threshold score=68%

- We found that **mental demand** was moderate to high, indicating that participants actively engaged in decision-making and navigation tasks.
- We observed low **physical demand**, suggesting that XR-based drone operation does not require significant physical effort and is ergonomically manageable.
- Overall, participants reported **manageable workload levels**, indicating that the XR system was challenging but not overwhelming.

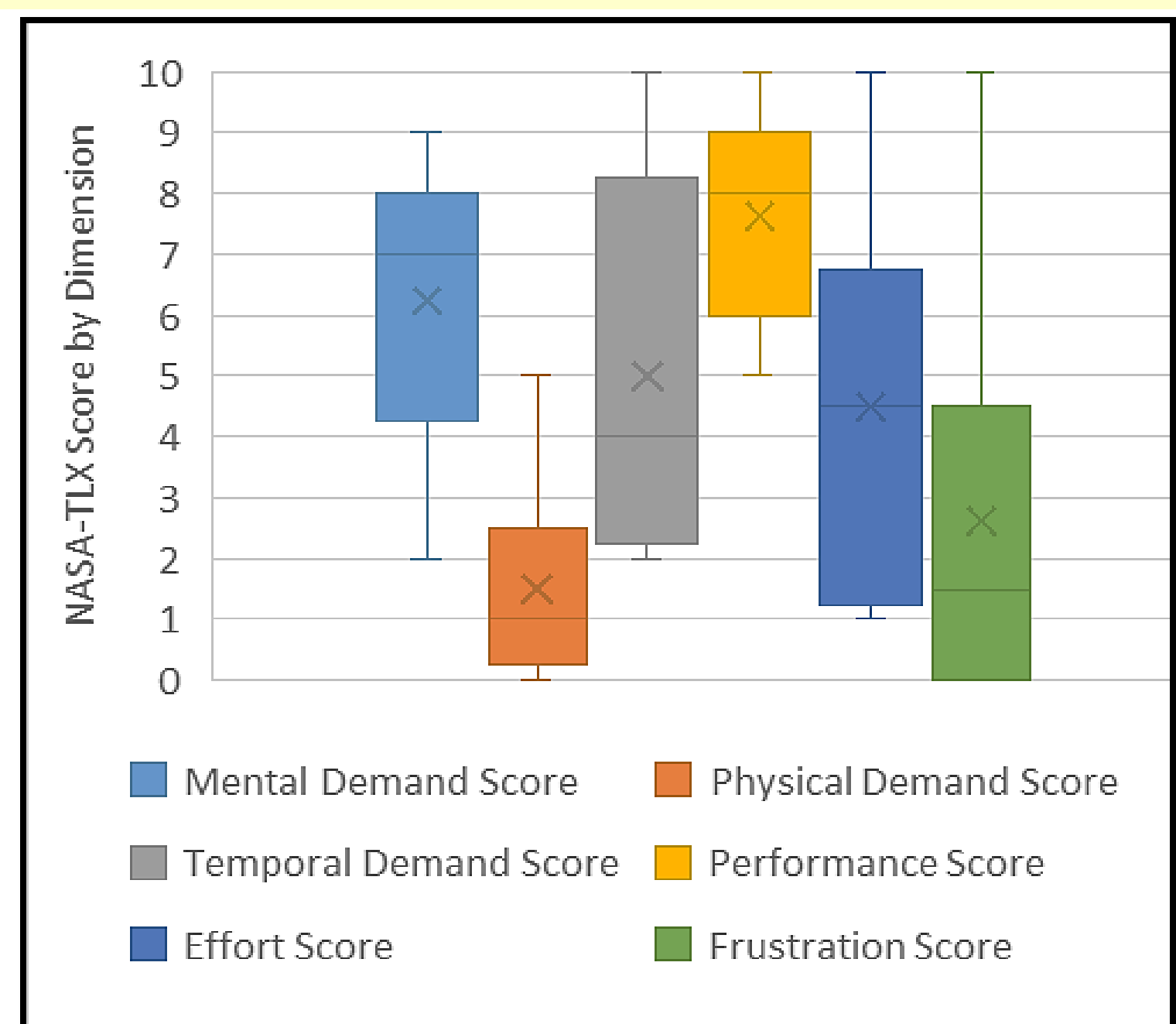


Figure 7. NASA-TLX Workload Rating Scale

Challenges: (based on post experiment survey)

- Learning curve for drone operation
- Limited realism compared to real-world environments
- Potential motion discomfort in XR

Insight:

XR training effectively supports learning while maintaining a controlled, low-risk environment.

Conclusions

XR-based digital twin training provides a safe, scalable, and effective alternative to traditional drone training methods for first responders. We found that the system improves situational awareness, supports decision-making under pressure, and reduces reliance on hazardous real-world exercises. This approach can significantly enhance first responder preparedness while minimizing risk and cost.

Future Work: Other emergency scenario generation. Multi-user collaborative training. Real-world validation with emergency agencies. Enhancing environmental realism.

References

- [1] U.S. Fire Administration, "Workplace Fire Safety," <https://www.usfa.fema.gov/prevention/workplace-fires/> (2025).
- [2] National Fire Protection Association (NFPA), "United States Firefighter Injuries," <https://www.nfpa.org/education-and-research/research/nfpa-research/fire-statistical-reports/firefighter-injuries-in-the-united-states> (2025).
- [3] M. N. Sakib, T. Chaspari, and A. H. Behzadan, "Physiological Data Models to Understand the Effectiveness of Drone Operation Training in Immersive Virtual Reality," *Journal of Computing in Civil Engineering*, 2020.
- [4] A. K. Ratul, S. Acharjee, C.-J. Liang, and M. N. Sakib, "Human-Robot Interaction in the AEC Industry: A Review of Augmented and Mixed Reality Applications," *Computing in Civil Engineering*, 2025.
- [5] S. Acharjee, A. K. Ratul, A. Aryal, and M. N. Sakib, "SfM Meets Thermal: Reconstructing 3D Thermal Profiles of Buildings Using Multimodal Drone Data," 2026.
- [6] NIST, "Tests and Scorable Scenarios for Evaluating Drone Capabilities and Remote Pilot Proficiency in Open, Obstructed, and Confined Environments (Levels 1-5)" <https://www.nist.gov/system/files/documents/2023/04/19/NIST%20Drone%20Tests%20-%20Levels%20of%20Proficiency%20Brochure%20%28v2023A%20PAGE%20SIZE%29.pdf>