Mixed Reality for Remote Supervision and Risk Assessment of Unstable Terrains

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Abstract. Introduction*: Operating drones in unstable terrains poses safety and logistical challenges. This Serious Game leverages Mixed Reality (MR) to simulate hazardous environments using Virtual Reality (VR) for training and Augmented Reality (AR) for collaborative analysis.* ***Objective****: This work develops an MR-based training simulation where players explore unstable environments, evaluate pre-planned drone trajectories, and predict terrain changes to improve flight strategy and risk assessment.* ***Methodology****: Players use VR to safely explore hazardous terrains, analyze drone data, and rehearse flight paths before real missions. The system gradually trains operators to transition to real drone use. A future AI prediction module is intended to enhance terrain analysis by anticipating environmental changes. AR supports strategic collaboration by enabling shared visualization and discussion of unstable environments.* ***Expected Results****: The game aims to enhance spatial awareness, improve flight planning, and support safer decision-making. It offers a risk-free environment to evaluate terrain evolution and drone strategies without field exposure.*
Keywords *Mixed Reality, Training, Prediction, Visualization, Drone*

1. Introduction

Operating Unmanned Aerial Vehicles (UAVs) in unstable terrains is risky due to uneven ground, sudden collapses, poor visibility, and unpredictable structures [Khan et al. 2022]. These conditions complicate navigation, compromise safety, and make real-world training impractical.

Mixed Reality (MR), combining Virtual Reality (VR) and Augmented Reality (AR), offers a safe, immersive environment for UAV training and planning [Perera et al. 2024]. It allows operators to rehearse missions, assess terrain, and build decision-making skills without field exposure.

Existing simulators like VRpilot [Thomas Ph D et al. 2023], Loft Dynamics [Zintl et al. 2024], and military platforms [Marron MS et al. 2024] improve flight control but focus on repetition, lacking dynamic terrain or evolving challenges. Their gameplay is often static and procedural.

Tools such as AirSim [Sousa et al. 2010], Vermeer [Butler et al. 2011], and AirSkill [AirSkill 2024] support planning but don't simulate terrain evolution or collaborative strategy. Forecasting tools like Google Earth Engine [Mutanga e Kumar 2019] and Terragen [Tegel e Mengotti 2005] model terrain but lack immersion. AR platforms [Sivanesan et al. 2021, Nalamothu et al. 2024] aid planning, yet are rarely integrated into serious games.

This work proposes an MR-based serious game combining VR, AR, and AI to train UAV operators in unstable environments. It bridges simulation and real-world tasks, offering an interactive tool for mission planning, risk assessment, and terrain forecasting.

2. Methodology

This MR serious game combines VR training, AI terrain prediction, and AR mission planning using real UAV data and evolving scenarios to build practical skills and enhance strategic decision-making in unstable environments.

2.1. Training Pilots

Players begin in VR-based training missions, where they develop fundamental drone piloting skills, including manual flight control, sensor utilization, and terrain navigation. The game introduces progressive difficulty levels, adding environmental hazards such as wind turbulence, limited visibility, and sudden terrain shifts.

To enhance learning, the system provides real-time feedback, tracking flight precision, reaction time, and decision-making. Adaptive AI adjusts the complexity of training based on player performance, ensuring gradual skill improvement. Emergency scenarios, including partial drone failures and unexpected terrain shifts, force players to think critically and react under pressure, improving risk assessment and flight stability.

The training module also incorporates a scenario-based progression system, where players complete objectives such as safe landings, data collection, and emergency maneuvers. This encourages active problem-solving and practical skill application, reinforcing drone operational expertise before moving to more complex missions.

2.2. Inspect Trajectories and Terrains

The trajectory evaluation system allows players to plan, test, and refine flight paths dynamically before real-world deployment. Paths can be created manually, imported from drone logs, or optimized by AI. In a VR environment, players adjust parameters like altitude, camera angles, and speed to enhance data collection.

A recording and playback feature enables comparison between planned and executed trajectories, highlighting deviations and inefficiencies. AI-driven suggestions recommend flight adjustments based on mission goals and environmental factors.

Players interact with an immersive 3D terrain model to analyze aligned flight data, imagery, and videos using georeferenced information. This supports sensor validation, risk assessment, and mission optimization. Terrain data, such as elevation, slope, vegetation, and land use, is provided by a geology team, along with susceptibility maps that identify high-risk areas, improving situational awareness and operational safety.

2.3. Predict the Environment in the Future

The prediction mode is designed to support AI-driven terrain forecasting in future versions, introducing a dynamic environmental evolution mechanic, where players must analyze terrain changes over time. Using historical drone data, geospatial modeling, and AI-predicted simulations, the system forecasts landslides, erosion, and terrain shifts, challenging players to adapt their drone strategies accordingly.

In VR, players interact with time-lapsed terrain simulations, testing different flight strategies based on predicted terrain changes. This feature enhances long-term mission planning, requiring players to proactively adjust drone trajectories rather than react to static terrain conditions.

The forecasting system enables long-term terrain monitoring across missions, reinforcing strategic planning and environmental awareness. Terrain evolution demands strategic adaptation from players, enhancing decision-making and increasing replayability through dynamic, data-driven challenges.

2.4. AR-Presentation

The AR-based mission planning module introduces collaborative decision-making, where players visualize 3D terrain models, flight paths, and predicted environmental shifts in a shared AR space.

Teams can adjust flight paths dynamically, overlaying AI-predicted terrain changes to evaluate risks. This feature is particularly beneficial for in-game cooperative mission planning, where multiple players contribute to drone strategy development.

In a real-world application scenario, AR enables multi-user geospatial visualization, helping players analyze optimal flight routes, safe landing zones, and environmental hazards. By providing interactive, data-driven mission planning, AR enhances team coordination, situational awareness, and strategic execution.

3. The Game

The prototype was built in Unity using the Meta Quest SDK, compatible with both Quest 2 and 3, to support VR and AR modes within a single application. It uses preprocessed terrain and UAV data to enable interaction across four core modes designed to support UAV operations in unstable terrains: training, inspection, prediction, and AR visualization. Figure 1 presents the use case diagram, illustrating how users engage with each mode and how these components contribute to mission planning and terrain evaluation.

Training Mode. Players take control of a virtual drone and navigate through simulated landslide-prone environments. Environmental conditions like wind gusts, narrow paths, and low visibility are introduced to simulate real-world hazards. Instead of traditional levels, replayability is achieved by varying terrain challenges and weather parameters. The main goal is to improve motor control, spatial reasoning, and situational awareness through focused piloting tasks. An example of the training scenario is illustrated in Figure 2 (a), showing the drone's first-person view as it flies over a 3D taludes terrain.

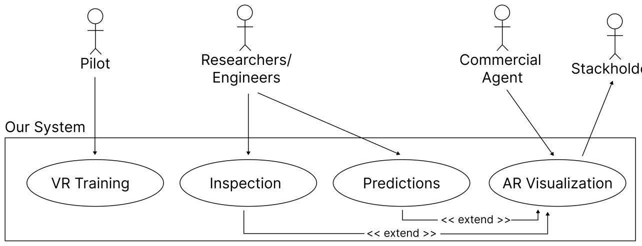
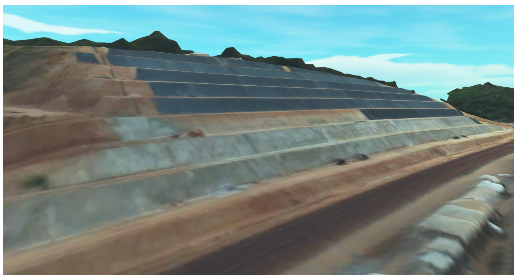


Figure 1. Use case diagram showing user interaction with each game mode



(a) Drone's first-person view flying over a simulated 3D landslide-prone terrain

(b) Visualization of the susceptibility index in the terrain

Figure 2. Game view

Inspection Mode. This mode allows players to explore a 3D reconstruction of the environment to plan and evaluate UAV paths. Trajectories can be generated by the system, imported from past missions, or manually adjusted. Players interact with the terrain to identify obstacles, evaluate coverage, and simulate data collection strategies. Players can also explore various types of terrain data, such as elevation, slope, vegetation density, and land use, and visualize susceptibility maps to identify areas at risk of hazards like landslides or erosion (Fig. 2 (b)).

Prediction Mode. In this mode, the terrain evolves over time using AI-generated simulations. Players must adapt their drone routes based on predicted future conditions such as erosion, slope collapse, or structural instability. The dynamic nature of the terrain introduces a strategic element where users must anticipate risks, reinforcing long-term planning and adaptive thinking.

AR Visualization Mode. This mode brings the terrain and planned mission paths into a shared augmented reality space. Players can manipulate the scene, visualize trajectories, and annotate risk zones in real time. Designed for collaborative use, this feature enhances communication and decision-making among multiple users in meetings or field briefings.

By combining game-based interaction with real-world UAV challenges, this system aims to bridge simulation and operational planning through an immersive and purposeful experience. The integration of VR training, AI-driven terrain forecasting, and AR-based collaboration supports strategic thinking, environmental awareness, and mission refinement. This serious game contributes to MR applications for drone-based training, offering a flexible and engaging tool for complex terrain operations.

4. Conclusion

This work presents an MR-driven serious game that supports drone pilot training, trajectory planning, terrain inspection, and environmental prediction through VR simulation and AR-assisted planning. It combines adaptive missions with realistic scenarios to bridge training and real-world UAV operations. While the current system uses preprocessed terrain and static prediction scenarios, future versions will incorporate AI-driven forecasting using an LSTM model trained on real slope data to enable dynamic terrain evolution.

References

AirSkill (2024). Airskill's vr - virtual reality flight training system. A virtual reality flight training platform designed to improve pilot skills through immersive and interactive simulations.

Butler, A., Hilliges, O., Izadi, S., Hodges, S., Molyneaux, D., Kim, D., e Kong, D. (2011). Vermeer: direct interaction with a 360 viewable 3d display. In *Proceedings of the 24th annual ACM symposium on User interface software and technology*, pages 569–576.

Khan, A., Gupta, S., e Gupta, S. K. (2022). Emerging uav technology for disaster detection, mitigation, response, and preparedness. *Journal of Field Robotics*, 39.

Marron MS, T., Captain, N., Mac Namee PhD, B., O'Hagan PhD, A. D., et al. (2024). Virtual reality & pilot training: Existing technologies, challenges & opportunities. *Journal of Aviation/Aerospace Education & Research*, 33(1):1.

Mutanga, O. e Kumar, L. (2019). Google earth engine applications.

Nalamothu, R., Sontha, P., Karravula, J., e Agrawal, A. (2024). Leveraging augmented reality for improved situational awareness during uav-driven search and rescue missions. In *2024 IEEE International Symposium on Safety Security Rescue Robotics (SSRR)*, pages 221–228. IEEE.

Perera, H., Wickramasinghe, P., Wijayawardana, P., Chathuranga, U., Akalanka, H., e Jayathilake, D. (2024). Application of vr technology and 3d reality models in enhancing community drr for landslides. *14th Annual Research Symposium*.

Sivanesan, V., Ng, Z. L., Lim, T. X., Tan, H. K., Yew, K. S., e Goh, W. W. (2021). The use of augmented reality in collaboration within the construction industry. In *Journal of Physics: Conference Series*, volume 2120, page 012032. IOP Publishing.

Sousa, P. D., Silva, D. C., e Reis, L. P. (2010). Air traffic control with microsoft flight simulator x. In *5th Iberian Conf. on Inf. Systems and Technologies*. IEEE.

Tegel, R. e Mengotti, T. (2005). Gpu, framework extensions for the distributed search engine and the terragen landscape generator.

Thomas Ph D, R. L., Albelo Ph D, J. L., Wiggins Ed D, M., et al. (2023). Enhancing pilot training through virtual reality: Recognizing and mitigating aviation visual and vestibular illusions. *International Journal of Aviation, Aeronautics, and Aerospace*, 10(3):10.

Zintl, M., Kimura, S., e Holzapfel, F. (2024). A mixed reality research flight simulator for advanced air mobility vehicles. In *AIAA AVIATION FORUM AND ASCEND 2024*, page 4651.