Direct Communication between Drone Operators and Field Responders through Augmented Reality

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Abstract

Head-worn Augmented Reality (AR) enhances human performance in high-stakes environments by enabling rapid, hands-free spatial reasoning and action under stress. Designing such systems is challenging, when operations involve both ground personnel and airborne actors such as drones. We present an AR system that enables direct communication between drone operators and field teams, transforming live aerial observations into actionable guidance. Operators stream real-time video and issue geo-referenced alerts when detecting hazards or people needing assistance. Alerts appear in responders' augmented view as spatially anchored markers, to orient, prioritize tasks, and make informed decisions without relying solely on verbal instructions or map co-ordination. We describe the interaction workflow and field evaluation, highlighting operator and responder roles, and demonstrate how AR communication enhances situational awareness, reduces coordination friction, and preserves responder agency in dynamic, high-pressure scenarios.

Keywords

Augmented Reality, Drone Operators, First Responders

1. Introduction

Head-mounted augmented reality (AR) can support user movement of first responders in challenging environments for efficient navigation and way finding. When firefighters are moving, AR interface design must account for divided attention, spatial updating, and safety constraints. These challenges are particularly pronounced in disaster response [1], flood emergencies [2] and firefighting [3], where responders operate under time pressure and environmental uncertainty. Although Virtual Reality (VR) has proven valuable for immersive rescue training and simulation-based preparedness [4], [5], its fully immersive nature, however, makes it unsuitable for real-world deployment [6]. AR supports in-situ

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decision-making while preserving awareness of immediate hazards [7], [8].

Earlier mobile AR for coastal erosion and sea-level rise relied on static datasets tied to fixed geographic locations [9, 10]. Useful for public engagement, these systems did not handle changing hydrodynamic conditions and depended on handheld devices [11, 12], limiting responders' hands' usage, critical in operation. Head-worn AR, instead, enhances firefighting through thermal imaging and real-time personnel tracking [3], and improves spatial awareness and navigation for responders in flood emergencies [13]. One such prototype provided real-time flood management, dynamically displaying current and forecasted water levels, flow speed, and direction, independent of fixed locations [14]. Horizon-aligned Points-of-Interest (POIs) used color cues to indicate urgent intervention points, helping responders prioritize and navigate. Evaluations with firefighters suggested that gaze-enabled AR supports situational awareness and tactical decision-making in live flood operations [14]. Despite these advances, integrating real-time flood forecasting, responder localization, and context-aware POI visualization into head-worn AR remains challenging, particularly when both ground personnel and airborne actors, such as first responders coordinating with drones, are involved.

AR enhances human-drone interaction, situational awareness, and operational efficiency. The FlightAR system integrated multiple UAV camera feeds with head-mounted displays to provide immersive, real-time visualizations of the environment and detected objects [15, 16]. Safety-focused AR heads-up displays support inspection tasks by reducing split-attention demands and cognitive load [17]. Collaborative search-and-rescue operations propose natural AR interfaces for semi-autonomous drones [18, 19]. Past systems are evaluated in controlled or simulated environments rather than complex real-world scenarios. AR overlays introduce visual clutter increasing cognitive load, while accurate tracking and registration under dynamic conditions remain challenging. Hardware constraints—including weight, battery life, and small FOV hinder use. Gaze or gesture controls suffer from errors under stress, and real-time system performance depends on reliable sensor data and connectivity, in operations. Accurate registration under motion on the ground and air, low-latency data fusion, and perceptually efficient information presentation are critical. Excessive or poorly structured overlays creating visual overload impair performance. Adaptive filtering, prioritization strategies, and gaze-aware interaction paradigms, therefore, represent important directions for research [20].

This work addresses the challenges of airborne drones supporting first responders that work in dynamic and dangerous environments with limited visibility and fragmented situational awareness in emergency situations like flood response and wildfire operations. As remote scouts, airborne drones can provide vital real-time information about changing hazards and difficult to reach regions. However, communicating this information to field personnel effectively is can be a major challenge because traditional communication methods can be confusing and mentally taxing when time is of the essence. In order to address this, we use Augmented Reality (AR) to facilitate direct, spatially contextualized communication between the drone operator and first responders. While responders can see the drone's current position, navigate to reported locations, and access sensor data , the operator can send alerts, mark points of interest and share detected hazards, facilitating enhances situational awareness and quicker and more informed decision-making in safety-critical situations.

2. Methodology

The Microsoft HoloLens 2 was selected based on its technical capabilities and feedback from domain experts. Its untethered design, unlike alternatives such as Magic Leap 2, enhances mobility and reduces encumbrance in field operations. Additionally, the articulated visor enables seamless switching between augmented and direct real-world views without removing the device.

Drone Integration and Alert System. To extend the operational range and situational awareness of the response team, the AR system integrates a real-time drone telemetry and visualization module. This system serves two distinct operational roles: *Drone Visualization* for first responders, providing eyes-on-target capability in hazardous zones, data from drone scouting, visualization of detected alerts by the

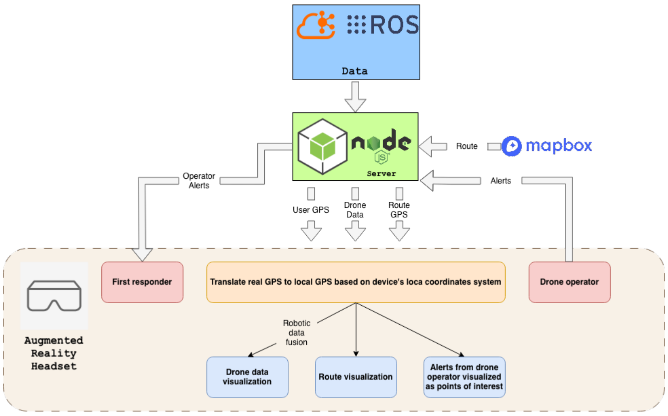

Figure 1: System Architecture

drone, routing options for safe navigation and *Operator Control Panel* for command-level coordination and hazard designation.

Data Architecture and ROS 2 Integration. The backbone of this module is a bridge between the drone's Robot Operating System (ROS 2) environment and the HoloLens 2 application. Telemetry data, including odometry (`/odom`), GNSS coordinates, and sensor readings are streamed via a TCP/WebSocket connector. A transformation matrix is used to map incoming odometry messages to the AR world space: This ensures that the digital twin of the drone moves in synchronization with the physical unit relative to the user's position.

Sensor Data and Uncertainty Estimation. To achieve localization, the system implements a sensor fusion algorithm that combines high-frequency relative odometry data with absolute GNSS positioning. The final position P_{final} is calculated using a weighted interpolation method that accounts for the accuracy and "staleness" of the GNSS signal. This logic dynamically adjusts the influence of the GNSS data (W_{gnss}) based on the horizontal (Acc_h) and vertical (Acc_v) accuracy metrics provided by the sensor's covariance matrix:

$$W_{horizontal} = W_{base} \times \left(\frac{1}{1 + |1 - Acc_h|} \right), \qquad W_{vertical} = W_{base} \times \left(\frac{1}{1 + |1 - Acc_v|} \right)$$

Furthermore, a time-decay factor is applied to the weights if the GNSS data becomes stale (i.e., exceeds a defined age threshold T_{stale}), ensuring that the system gracefully degrades to rely more on odometry during signal interruptions:

$$W_{final} = W_{calculated} \times \left(1 - \frac{Age_{gnss} - T_{stale}}{T_{max\_stale} - T_{stale}} \right)$$

The final 3D space world position is then derived by linearly interpolating between the odometry-derived offset position (P_{odom}) and the converted GNSS world position (P_{gnss}):

$$P_{final}.x = \text{Lerp}(P_{odom}.x, P_{gnss}.x, W_{hor}), \quad P_{final}.y = \text{Lerp}(P_{odom}.y, P_{gnss}.y, W_{ver}),$$

$$P_{final}.z = \text{Lerp}(P_{odom}.z, P_{gnss}.z, W_{hor})$$

First Responder Interface. For the field agent, the interface prioritizes situational awareness without cognitive overload (Figure 2b). **3D Spatial Visualization:** The drone is rendered as a 3D avatar within the AR space, accompanied by a trajectory trail that visualizes the recent flight path, aiding spatial orientation; **Live Video Feed Optimization:** A module handles the real-time video stream. To maintain high frame rates on the HoloLens 2, raw image decoding (e.g., `bgr8` to `RGB24` conversion) is offloaded to a background worker thread and both raw and compressed image transport is supported; **Sensor Telemetry:** Critical flight data: battery status, altitude, wind speed, air quality (CO levels), etc is displayed in a floating holographic panel, allowing responders to remotely assess environmental safety.

Operator Panel and Alert System. The drone operator panel extends the visualization capabilities of the first responder panel with active command functions (Figure 2c). The operator identifies hazards or critical points of interest and instantly communicates to the team via the additional colored buttons in the middle of the panel (2c).

The alert system utilizes a serialized JSON messaging protocol over WebSocket. When the operator identifies a threat (e.g., an open manhole or a person in distress), they trigger a specific alert type. The system generates a unique Alert ID and broadcasts the coordinates to all connected First Responder units: **Manhole Hazard Alert:** Projects a warning manhole marker at a geospatial location in the responder's FoV; **Person Detected Alert:** Triggers a high-priority notification to calculate a navigation route to the detected person's location; **General Point Of Interest Alert:** A flexible alert type for hazards, allowing the operator to define custom POIs, then visualized in the AR environment.

Both panels can be accessed from the left hand menu that appears when the user's palm is facing towards his face as shown in Figure (2a)

(a) Hand menu from where robotic data panels are initiated

(b) First responder panel with robotic information and danger detections

(c) Drone operator panel with additional alert functions

Figure 2: Drone visualization UI, including the hand menu for initiating data panels, the first responder interface with real-time information and hazards, and the drone operator panel with alert functionalities.

3. Evaluation, Discussion and Conclusion

The AR system for robotic data visualization was evaluated through development with first responders from the Dortmund Fire Dept., one of the largest in the country. Firefighters offered early feedback in the lab where the system was tested with simulation data from a drone flight. After a brief introduction, features of the AR robotic data visualization were presented. Participants explored functionalities and rated statements on a 10-point Likert scale (1 = strongly disagree, 10 = strongly agree). Selected results included:

· "The AR visualization of the drone position provides clear and easily understandable information." – rated 9.0

· "The AR element 'drone trajectory' distracts me during usage." – rated 2.67

· "I would rely on the AR representation of the drone trajectory during an operational mission." – rated 8.0

Qualitative feedback indicated that the 3D drone visualization was too fast and difficult to locate or follow. Users suggested integrating an additional directional arrow to indicate the drone's position and movement path. The AR system underwent iterative refinement. An evaluation was conducted by fire brigade experts and emergency agencies after the main development phase in Dortmund and Innsbruck. There were 16 participants in both evaluation activities, 8 in the city of Dortmund and 8 in the city of Innsbruck. In Dortmund, was simulated a 2024 flood incident and had participants evaluate AR-supported drone missions. In Innsbruck, the AR system was tested during a large-scale alpine wildfire exercise. Drone operators used the system to locate the augmented drone within AR and set POIs and alerts to inform team members. First responders identified the drone in the AR view and communicated relevant target points or areas of interest to the drone operator.

Usability was assessed using an adjusted for head-word AR Handheld Augmented Reality Usability Scale (HARUS - 7 point Likert scale) [21] and the System Usability Scale (SUS - 10 point Likert scale) [22]. Although HARUS was formed for handheld AR, its focus on two factors (Manipulability, ease of handling the system and Comprehensibility, ease of understanding the information) was deemed relevant for head-worn AR. User perception was consistently positive. Accessing information through AR visualization was rated 8.38, confirming AR's effectiveness in information retrieval, while assessing on-site situations scored 8.25, indicating enhanced situational awareness. Trust in AR information was slightly lower at 7.38, suggesting a good level of confidence, and uncertainty visualization (7.75) showed users' appreciation for transparent data. HARUS results indicate that users experienced AR as clear, responsive, and well designed. The moderate mental effort (5.50) reflects an acceptable cognitive load, and the amount of information displayed was deemed appropriate (6.88). Readability scored well (6.00) and reading difficulty low (4.50), while system responsiveness was high (6.75). Low confusion (4.13) and flickering (3.63) point to a stable visual display, and information consistency (6.38) reinforces a well-structured interface. Usability and visual clarity were good, with minor potential to reduce workload. The AR System Usability Scale (SUS) score of 75.33 indicates above-average usability; values above 68 are considered good and those above 80 excellent.

Limitations: The proposed relies on stable Wi-Fi connectivity, which may be unreliable in harsh or remote environments, leading to delays or disconnections. Accurate spatial alignment in the Microsoft HoloLens 2 requires users to carry an additional Android device providing GPS data. Finally, the system has not yet been fully validated in real-world deployments, as testing was primarily conducted using simulated flights and recorded datasets from prior drone missions.

In conclusion, users found the AR system intuitive, well-structured, and easy to learn. The AR system demonstrated strong user satisfaction and usability. As AR glasses get smaller, this creates potential for resilient real-world deployment.

Declaration on Generative AI

During the preparation of this work, the author(s) used ChatGPT-5.2 and ChatGPT-5.3 for grammar and spelling checks, as well as for improving the clarity and readability of the text. After using these tools, the author(s) carefully reviewed and edited the content as needed and take(s) full responsibility for the publication's content.

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