Navigating Partial Automation in Firefighting with Drones: Trust, Take-Over, and Human-Drone Teaming

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Abstract

In the past years, the use of drones has been increasingly introduced to firefighting operations. Drawing on concrete examples from interviews with Thai firefighting professionals and recent field trials, as well as prior research, this paper examines the challenges of integrating (partially) autonomous, AI-enhanced drones into firefighting operations. Our findings reveal that, despite the promise of automation, on-field operators still prefer communication via a dedicated drone pilot—a preference driven by unresolved trust issues and concerns over information overload. We discuss challenges such as trust in automation and adaptive take-over. These inform our proposals for design recommendations on adaptive communication, transparent take-over mechanisms, trust calibration, physical handover and mapping of multiple data sources in human-drone teaming for firefighting.

Keywords

Safety-critical system, Human-Drone Interaction, Hybrid Human–AI Teams, Context-Aware Collaboration

1. Introduction

In recent years, the incorporation of drones into firefighting activities has significantly increased, such as utilizing their on-board cameras for area mapping [1]. Moreover, Human-Drone Interaction research is increasingly applied to emergency contexts, including firefighting [2]. An exploratory study by Khan and Neustaedter [3] highlighted the benefits of drones in assisting firefighters during emergency situations, particularly in navigating dangerous environments and assessing the spread of fires. In another study by Peschel *et al.* [4], a small UAV has been used to enable untrained responders to directly control drone payloads and coordinate with pilots in emergency contexts. Beachly et al. [5] used a UAV for a fire-aware planner that generates safe trajectories with effective ignitions for prescribed fires. In field tests, the UAV was able to safely and effectively plan ignition lines while dynamically adjusting to environmental changes. Roldán-Gómez *et al.* [6] explore the application of drone swarms in forest firefighting. Their drones are used as remote sensors, bringing information in real-time to the firefighters.

Prior work has also focused on the direct interaction between firefighters and drones. Alon *et al.* [7] applied a co-design process with firefighters to define gestural input for communication between firefighters and a drone. Li *et al.* [8] showed that a light beam projected from a drone could be used to indicate victims to firefighters. Moreover, the use of expressive lights mounted directly on drones has been explored to support communication between drones and victims [9].

While these applications show innovative drone uses in firefighting, they have not necessarily been integrated into real-world operational conditions. Agrawal *et al.* [10] discuss the co-design of emergency response systems with firefighters involved in the design process to design drone functionalities that respond to real-world needs.

Prior work has highlighted challenges and limitations of drone-use in firefighting operations. Li *et al.* [8] observed that drones are highly valued for providing real-time situational awareness [11], but concerns about trust and ease of interaction remain. Our prior study on drone-assisted firefighting

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in Thailand [12] reveals that firefighters frequently prefer to receive updates through a dedicated drone pilot rather than relying solely on information from an autonomous drone. This preference underscores a trust gap that must be addressed through transparent take-over mechanisms and adaptive communication systems, which are central issues in contemporary Human-Computer Interaction (HCI) research.

2. Firefighting as a Concrete Use Case

Firefighting operations offer a rich context for examining the interplay between automation and human expertise. The observations reported below are based on existing literature, our interviews with Thai firefighters as reported in [12] and current ongoing focus groups and field studies.

2.1. Multiple data sources and sensors

Firefighters integrate multiple data sources, including live thermal imaging and digital maps, to build a comprehensive operational overview. Drones can be a valuable addition, as they can be used as remote sensors [6]. Furthermore, their use can serve to confirm or elaborate on the information received from citizens prior to their entry into the firefighting operation. However, as we observed in our previous interviews [12], one coordinator from Thailand explained that while drones process sensor data autonomously, the resulting alerts can sometimes be ambiguous. In these cases, the team relies on direct confirmation from a human pilot to verify and clarify the data before taking action..

2.2. Communication Under Pressure

In high-stakes emergencies, even small delays or unclear signals can jeopardize safety. Li *et al.* [8] noted that audio-based instructions from autonomous drones can overwhelm operators in fast-paced scenarios. During our field trials, several firefighters noted that while visual signals, such as drone lighting, were generally effective and easy to interpret, audio messages often contributed to information overload and ambiguity. One firefighter remarked, “I’d rather get a direct call from a human operator than rely on an automated audio alert that might omit crucial context.” This finding underscores the need to carefully design drone communication systems to support adaptive, context-sensitive interventions during emergency operations [13].

2.3. Trust and Decision Making

A persistent theme in human-automation teaming is the challenge of trust. Despite advances in autonomous decision making, many firefighters remain skeptical of fully automated systems. Our interviews reveal a strong preference for human-mediated communication [12]. Firefighters believe that they would feel more secure when a dedicated drone pilot interprets complex data and provides context-rich updates. This is in line with the findings of Li *et al.* [8]. More generally, this aligns with models proposed by Lee and See [14] and is further supported by studies on human-autonomy teaming [15]. Their findings suggest that transparent, context-sensitive interfaces are essential to calibrate trust in automation.

2.4. Handover of Physical Objects

Firefighters are confronted with complex situations under time pressure for which drones can be of invaluable help by supporting manual tasks, e.g., helping lift a load or bringing medical supplies [7]. The handover process is a collaborative joint action in which a giver delivers an object to a receiver (who are each either humans or robots) [16]. Research on adaptive handovers with robots [13] demonstrates that incorporating social cues (e.g., verbal signals or spatial gestures) can smoothen the transition between autonomous and human control. More specific design considerations for human-drone handover have been proposed regarding the drone design, drove movement, robotic arm and the object [17] .

2.5. Take-Over Mechanisms

Automated systems may detect anomalies—such as a sudden temperature spikes—but often fail to provide clear signals when manual control should be taken back. In firefighting, such ambiguity can delay critical interventions. Recent work has shown that effective takeover mechanisms benefit from multimodal feedback and adaptive cues that reduce ambiguity during control transitions [18, 19]. For example, integrating visual, auditory, and haptic signals can provide redundant and complementary information, ensuring that the need for manual intervention is communicated unambiguously even under high cognitive load [19]. Additionally, adaptive takeover strategies that dynamically adjust the urgency and presentation of cues based on real-time conditions and system confidence have been found to enhance operator response times and reduce errors [20]. Recently, physiological computing has been used to estimate drone operators' future performances and consequently launch adaptive visual alerts [21]. In the firefighting context, where every second counts, designing clear, context-sensitive takeover cues is essential to ensure that human operators can promptly and reliably assume control when necessary.

3. Design recommendations for Enhanced Human-Drone Teaming

Based on our empirical findings and the literature, we propose the following design recommendations:

3.1. Adaptive Communication and Data Integration

Develop systems that dynamically adjust communication channels (visual, auditory, haptic) based on real-time conditions. For instance, in environments with high noise or poor visibility, the system might switch from detailed audio instructions to concise, prioritized alerts or other sensory modalities (e.g., haptic). Moreover, integrating digital sensor data with analog inputs (e.g., hand-drawn maps, local expertise) enhances decision making in resource-constrained settings where conventional mapping may be incomplete. Additionally, recent multi-drone search and rescue research [22] shows that carefully crafted user interface designs can foster trust while reducing cognitive workload, and explicit alerts help guide operator focus in supervisory settings [23].

3.2. Transparent Take-Over and Trust Calibration

Design control systems that enable seamless switching between autonomous and human-led operations by providing explicit, real-time feedback on system status. A visual dashboard can display dynamic indicators, for example the "trust meter" from Lee and See [14] which reflects system confidence in sensor data and decision making. In addition, incorporating countdown timers and adaptive feedback loops helps operators determine when manual intervention is necessary. This level of transparency reduces ambiguity and builds operator confidence, reinforcing findings from human–autonomy teaming [15] and mitigating cognitive biases highlighted by He *et al.* [24].

3.3. Supporting Physical Handover

When designing for handover tasks, base your design on existing design considerations. Incorporating social cues (e.g., verbal signals or spatial gestures) to clearly demarcate handover events, as demonstrated in adaptive handover studies [13], can enhance coordination and ensure that control transitions are smooth and intuitive. Considerations for drone design, drove movement, robotic arm and the object itself have been proposed in prior work [17].

4. Discussion and Future Directions

Our study underscores that while autonomous, AI-integrated drones hold promise for enhancing situational awareness in firefighting, unresolved trust issues and ambiguous take-over cues continue to hinder full reliance on automation. The strong preference for a dedicated drone pilot—as observed in our interviews [12]—indicates that human-drone teaming remains a critical area for exploration. Future work should include longitudinal studies to assess how adaptive interfaces impact trust over time, field trials comparing fully automated versus hybrid handover scenarios, and cross-domain studies in other high-stakes environments such as emergency medical services. Furthermore, as drones become more closely integrated with wearable personal protective equipment, considerations around sustainability in product development also become increasingly pertinent [25].

5. Conclusion

Partial automation in high-stakes environments like firefighting presents both significant opportunities and challenges. Although automation can enhance situational awareness and decision support, ambiguous take-over cues and unresolved trust deficits often lead operators to favor human-mediated communication. In this position paper we propose design recommendations to develop drone systems that better support firefighters in critical situations. These systems will not only improve operational efficiency and safety but also advance our understanding of human-AI teaming in the HCI field.

Declaration on Generative AI

During the preparation of this work, the authors used Generative AI (Gemini) in order to: Grammar and spelling check, Improve readability, Paraphrase and reword. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the publication's content.

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