Drones in Firefighting Emergencies: Advanced Applications and Emerging Innovations

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***Abstract*—The increasing frequency and severity of fires have driven the adoption of drones (Unmanned Aerial Vehicles, UAVs) in firefighting operations. UAVs are now instrumental in the detection of wildfires, aerial suppression, victim location, and real-time situational awareness. This paper reviews recent technological advances in drone systems, including thermal imaging, autonomous navigation, payload delivery, and integration with incident command systems. Field trials demonstrate the operational potential of UAVs, but challenges remain in usability, regulation, and human-drone interaction. The study concludes by highlighting future research directions to improve drone effectiveness in emergency firefighting scenarios.**

***Index Terms*—UAVs, emergency situations, fires**

I. Introduction

Modern firefighting operations face increasing complexity due to urban expansion, climate-induced wildfires, and industrial hazards. UAVs offer enhanced aerial perspectives, faster deployment, and reduced risk to personnel. Their ability to access hazardous or obstructed zones makes them an ideal asset in both wildfire and structural fire emergencies. The integration of thermal cameras, AI-based navigation, and cooperative drone systems has pushed the boundaries of what is possible in emergency response..

II. Firefighting UAV Applications

A. Wildfire Detection and Monitoring

UAVs are widely used for early wildfire detection using thermal infrared (IR), multispectral, and optical cameras. Studies demonstrate the use of deep learning models such as YOLOv5 and LSTM to detect fire regions and smoke propagation in real-time, even under poor visibility conditions [1]. These systems help identify ignition points, monitor fire spread, and assess containment efforts.

Advanced UAVs using sensor fusion (thermal, gas, and visual) can analyze terrain, wind, and heat to model fire dynamics. Their mobility makes them suitable for mountainous or forested regions inaccessible to ground teams [2].

B. Structural Fire Response

In urban environments, UAVs equipped with high-resolution cameras and thermal imaging provide firefighters with a bird's-eye view of building conditions. Lagkas et al. [3] evaluated semi-autonomous drones in live structural fire drills, noting improvements in search-and-rescue timing and safety. The drones identified hot zones, escape routes, and even trapped individuals with a high degree of accuracy.

However, the study also noted that responders faced cognitive overload when interfacing with complex UAV controls, highlighting the need for user-friendly systems integrated with command structures.

III. Aerial Fire Suppression and Payload Delivery

A. Heavy-Lift Drones

Define abbreviations and acronyms the first time they are used in the text, even after they have been defined in the abstract. Abbreviations such as IEEE, SI, MKS, CGS, ac, dc, and rms do not have to be defined. Do not use abbreviations in the title or heads unless they are unavoidable.

B. High-Rise Suppression

Zhou and Li [5] introduced a UAV-based system for fighting fires in high-rise buildings. Their drone platform can navigate complex urban terrains and discharge suppressant agents at specific structural zones, significantly reducing response times compared to traditional ladder-based suppression.

IV. Aerial Fire Suppression and Payload Delivery

UAVs are increasingly being designed to function as part of multi-agent systems that include other drones and ground-based robots. The TRIFFID platform, introduced by Elwin et al. [6], coordinates teams of UAVs and unmanned ground vehicles (UGVs) using semantic scene understanding and shared mapping. This enables effective victim location and hazard mapping in dynamic, low-visibility environments such as collapsed or burning buildings.

These coordinated systems use AI onboard for obstacle avoidance, SLAM (simultaneous location and mapping) and survivor detection, substantially reducing the need for manual drone piloting.

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V. Integration with Incident Command Systems

For UAVs to be effective in real-world operations, integration with fire departments' Incident Command Systems (ICS) is crucial. Tan et al. [7] demonstrated a GIS-based platform that streams real-time UAV data, including fire perimeters, wind data, and responder locations, directly into ICS dashboards. This allows incident commanders to make informed decisions based on live aerial intelligence.

Despite technical feasibility, interagency differences in drone protocols, data formats, and training continue to limit full-scale deployment.

VI. Field Studies and Operational Challenges

Field evaluations conducted by Lagkas et al. [3] found that firefighters benefited from drone data in terms of decision making and hazard identification. However, the complexity of the interface and the demands for multitasking led to a high cognitive load. The study emphasized the need for: - simplified user interfaces

- modular control devices
- augmented audio-visual cues
- These design elements are vital to reduce operator fatigue and improve response efficiency.

VII. Ethical, Legal, and Environmental Constraints

A. Airspace Management

The deployment of drones during wildfires must be coordinated with manned aircraft. Regulatory frameworks, such as Beyond Visual Line of Sight (BVLOS) exemptions, are still evolving in many countries [8].

B. Privacy and Public Perception

Thermal surveillance in residential areas can raise privacy concerns. Transparent policies and public education are necessary to ensure civilian trust in drone deployments during emergencies.

C. Environmental Resilience

Extreme heat, wind, and smoke can interfere with drone operations. Recent work by Hamdy et al. [9] applied metaheuristic optimization to UAV control systems, improving flight stability and response time in dynamic environments.

VIII. Future Research Directions

Thermal-Resistant Components: Development of heat-resistant materials and sensors to withstand high-temperature environments. Swarm Autonomy: Research into cooperative algorithms for large-scale UAV swarms with decentralized control.

Edge AI Processing: Integrating AI onboard for real-time fire modeling and decision-making without ground control.

Interoperable Communication Standards: Standardization across emergency services to support seamless integration of UAV data.

Simulation-Based Training: Creating realistic training environments for drone operators to improve skills under stress.

IX. Conclusion

Drones are revolutionizing emergency firefighting by offering rapid, precise, and safe situational awareness and suppression capabilities. While advances in autonomy, imaging, and payload delivery are promising, full integration into firefighting operations requires addressing challenges in usability, regulation, and interoperability. Continued research, policy development, and cross-disciplinary collaboration will be essential to realize the full potential of UAVs in firefighting.

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