

Fixed-wing UAV Forest Fire Early Warning System Based on Multi-source Heterogeneous Perception and Edge Intelligence

Minxiang Liu, Qihan Chen, Yuting Zhang, Jiachang Li¹, Xiuli Guan²

^{1,2} School of Information Engineering, Changchun University, Changchun, China
Corresponding Author: Minxiang Liu

ABSTRACT: Forest fires pose a significant threat to ecological security and human life, with early detection being critical for effective suppression. Traditional forest fire monitoring methods suffer from limitations such as delayed response, low accuracy, and high operational costs. This paper presents a fixed-wing unmanned aerial vehicle (UAV) forest fire early warning system based on multi-source heterogeneous perception and edge intelligence. The proposed system integrates visible light cameras, infrared thermal imaging sensors, and environmental sensors to achieve comprehensive fire detection from optical, thermal, and environmental dimensions. A lightweight deep learning model is deployed on the on-board edge computing terminal to enable real-time fire identification without relying on public network connectivity. The fixed-wing UAV platform provides extended endurance of 2-4 hours and large-area coverage capability, significantly outperforming multi-rotor alternatives in efficiency. Experimental validation demonstrates that the system achieves 92.3% detection accuracy with a false positive rate of 4.1% under various environmental conditions. The proposed solution offers a cost-effective, efficient, and intelligent approach to forest fire prevention, with broad application prospects in forestry management and ecological protection.

Keywords: Forest Fire Early Warning; Fixed-wing UAV; Multi-source Heterogeneous Perception; Edge Intelligence; Lightweight Deep Learning; Infrared Thermal Imaging

Date of Submission: 09-10-2026

Date of acceptance: 20-10-2026

I. INTRODUCTION

Forests serve as vital ecological barriers for nations, playing an irreplaceable role in biodiversity conservation, water and soil conservation, carbon sequestration, and climate regulation. However, forest fires represent one of the most destructive natural disasters, causing severe ecological damage, economic losses, and threats to human safety each year. According to the National Forestry and Grassland Administration, China experiences thousands of forest fires annually, with the total burned area reaching hundreds of thousands of hectares. With vast forest resources and complex terrain, forest fire prevention has long been a critical task for forestry management departments at all levels.

Traditional forest fire monitoring approaches primarily rely on manual patrols, watchtower observation, and satellite remote sensing. Manual patrols are labor-intensive, inefficient, and limited by terrain constraints, making it difficult to achieve comprehensive coverage of large forest areas. Watchtower observations depend on visual inspection by personnel, which is susceptible to weather conditions and cannot operate effectively at night or in foggy environments. Satellite remote sensing, while providing broad coverage, suffers from long revisit cycles, vulnerability to cloud occlusion, low ground resolution, and difficulty in detecting hidden fire points beneath the forest canopy. These limitations result in delayed fire detection, allowing small fires to escalate into large-scale disasters before intervention becomes possible.

The rapid development of unmanned aerial vehicle (UAV) technology, artificial intelligence (AI), and edge computing has opened new avenues for addressing forest fire monitoring challenges. UAVs offer flexible deployment, high mobility, and the ability to carry various sensors, making them well-suited for forest inspection tasks. When equipped with advanced perception systems and intelligent algorithms, UAVs can autonomously detect and identify fire sources, significantly improving the timeliness and accuracy of forest fire monitoring. Recent studies have demonstrated the feasibility of UAV-based fire detection using computer vision techniques.

Despite the potential of UAV-based fire detection, existing solutions still face several limitations. Many current systems rely on single-sensor configurations, such as visible light cameras or infrared sensors alone, which suffer from high false alarm rates and limited adaptability to complex environments. Furthermore, most UAV fire detection systems depend on data transmission back to ground stations for analysis, which is problematic in forest areas with weak or no network coverage. This reliance on communication infrastructure leads to delayed warnings, increased data transmission overhead, and reduced system reliability in remote forest regions.

This paper proposes a fixed-wing UAV forest fire early warning system based on multi-source heterogeneous perception and edge intelligence. The system integrates three types of sensors—visible light cameras, infrared thermal imagers, and environmental sensors—to achieve comprehensive fire feature extraction from multiple dimensions. A lightweight deep learning model is deployed directly on the on-board edge computing terminal, enabling real-time fire identification and decision-making on the UAV itself. The fixed-wing platform provides 2-4 hours of endurance, enabling large-area, long-duration forest patrol missions. The main contributions of this work include: (1) a multi-source heterogeneous perception fusion framework that combines optical, thermal, and environmental data to improve fire detection accuracy; (2) an edge intelligence architecture that deploys lightweight deep learning models on UAV-mounted computing terminals, achieving real-time on-board processing without network dependency; (3) a fixed-wing UAV platform optimized for forest fire patrol missions, offering extended endurance and large-area coverage capability.

II. SYSTEM OVERVIEW

The proposed fixed-wing UAV forest fire early warning system consists of three main subsystems: the multi-source heterogeneous perception subsystem, the edge intelligence processing subsystem, and the fixed-wing UAV platform subsystem. These subsystems work together to enable autonomous forest patrol, real-time fire detection, and timely warning dissemination.

2.1 Multi-source Heterogeneous Perception Subsystem

The multi-source heterogeneous perception subsystem is responsible for acquiring comprehensive environmental data during UAV flight. It comprises three types of sensors: visible light cameras, infrared thermal imaging sensors, and environmental sensors including temperature and smoke sensors. The visible light camera captures high-resolution optical images for visual fire feature extraction, including flame morphology and smoke characteristics. The infrared thermal imager detects temperature distribution and identifies heat anomalies that may indicate fire sources. The environmental sensors measure ambient temperature and smoke concentration, providing additional contextual information for fire verification. This three-modal sensing approach ensures that fire features are captured from optical, thermal, and environmental dimensions, significantly reducing the probability of missed detections and false alarms.

2.2 Edge Intelligence Processing Subsystem

The edge intelligence processing subsystem serves as the computational core of the system, performing real-time data analysis and fire identification directly on the UAV. It consists of an edge computing terminal equipped with a lightweight deep learning inference engine based on NCNN framework. The subsystem receives data from all three sensor types, processes them through the multi-sensor fusion algorithm, and executes the fire detection model. When a fire is detected with confidence above a predefined threshold, the system generates a fire warning message containing the fire location coordinates, timestamp, and confidence level. This on-board processing eliminates the need for high-bandwidth data transmission to ground stations and ensures rapid response even in areas without network coverage.

2.3 Fixed-wing UAV Platform and Ground Station

The fixed-wing UAV platform subsystem provides the flight capability for large-area forest patrol. It includes the fixed-wing airframe constructed from lightweight composite materials, propulsion system, flight controller with GPS/IMU navigation, power supply system, and long-range data transmission radio. The platform is designed for extended endurance of 2-4 hours and stable flight at various altitudes and speeds. The flight controller executes pre-planned patrol routes and can adjust flight parameters based on mission requirements. The data transmission radio establishes a dedicated communication link with the ground station for transmitting fire warning messages and receiving mission commands, independent of public network infrastructure.

The ground station subsystem provides mission planning, real-time monitoring, and warning reception capabilities. Operators can plan patrol routes, set mission parameters, and monitor UAV status through the ground station interface. When fire warnings are received, the ground station displays the fire location on a digital map, stores the warning data, and can trigger further response procedures. The system architecture is designed with modularity and scalability in mind, allowing each subsystem to be independently upgraded or replaced.

III. RESEARCH METHODOLOGY

3.1 Multi-sensor Data Fusion Framework

The multi-sensor fusion framework operates at both the feature level and the decision level, leveraging the complementary strengths of each sensor modality to achieve robust and accurate fire detection. At the feature level, the system extracts relevant features from each sensor modality independently. From visible light images, features include color histograms in fire-relevant color spaces (RGB, HSV, and YCbCr), texture features using Local Binary Patterns, and shape features of suspected fire regions. From infrared thermal

images, features include temperature statistics (maximum, minimum, mean, and standard deviation in suspect regions), thermal gradient features, and temporal temperature variation patterns. From environmental sensors, features include ambient temperature readings, rate of temperature change, smoke concentration levels, and rate of smoke concentration increase.

These extracted features are then fused using a weighted feature concatenation approach. The weights for each modality are dynamically adjusted based on environmental conditions assessed during flight. For example, in clear daytime conditions, visible light features are assigned higher weights due to their high resolution and rich detail. In nighttime or foggy conditions, infrared thermal features receive increased weight because they remain effective when visible light sensing is degraded. Environmental sensor features serve as a verification modality that contributes to the final decision, particularly when the UAV passes close to a suspected fire source.

3.2 Adaptive Weighting Mechanism

To optimize fusion performance under varying environmental conditions, the system implements an adaptive weighting mechanism that dynamically adjusts the contribution of each sensor modality based on real-time assessment of operating conditions. The environmental assessment module continuously monitors several indicators: ambient light level from the visible light camera exposure settings, image clarity using sharpness metrics, atmospheric visibility estimated from image contrast degradation, and the presence of precipitation. Based on these indicators, the system classifies the current operating conditions into categories such as clear daytime, hazy daytime, nighttime, and rainy conditions.

For each condition category, the system applies predefined weight configurations that reflect the expected reliability of each sensor modality. In clear daytime conditions, visible light features receive the highest weight (0.5), infrared thermal features receive moderate weight (0.3), and environmental sensor features receive lower weight (0.2). In nighttime conditions, infrared thermal features become dominant (0.6), visible light features are significantly down-weighted (0.1), and environmental sensor features maintain moderate weight (0.3). In hazy or smoky conditions, both visible and infrared weights are adjusted to account for reduced visibility, with environmental sensors gaining relatively more importance. This adaptive weighting ensures that the fusion system always relies most heavily on the most reliable sensor modalities under current conditions.

3.3 Lightweight Deep Learning Model

The fire detection algorithm is based on a lightweight deep learning model optimized for edge deployment. The model architecture is derived from the YOLOv5 object detection framework, which is known for its high speed and good accuracy in real-time object detection tasks. However, the standard YOLO architecture is too large and computationally intensive for deployment on resource-constrained edge devices. Therefore, several optimizations are applied to create a lightweight version suitable for on-board UAV processing.

First, the backbone network is replaced with a lightweight architecture based on depthwise separable convolutions, similar to the approach used in MobileNetV2. This significantly reduces the number of parameters and computational operations compared to standard convolutions, with only a minor decrease in detection accuracy. Second, channel pruning is applied to remove redundant filters from the network, further reducing model size and computation. Third, the model is quantized to 8-bit integer precision instead of 32-bit floating point, which reduces memory usage and speeds up inference on hardware that supports integer arithmetic through the NCNN inference framework. The model is trained on a custom dataset of forest fire images collected from various sources, including public fire image datasets, UAV-captured forest imagery, and synthetic fire images generated through data augmentation.

3.4 Real-time Processing Pipeline

The on-board processing pipeline is optimized for real-time performance, ensuring that fire detection keeps pace with the UAV's flight speed and sensor data acquisition rate. The system processes visible light and infrared image streams at a frame rate of 10-15 frames per second, which is sufficient for detecting fires during cruise flight at typical patrol altitudes. Several optimization techniques are employed to achieve real-time performance within the computational constraints of the edge computing platform.

Frame sampling is used to reduce the number of frames processed per second while maintaining detection coverage. The system processes every Nth frame from the video stream, where N is dynamically adjusted based on UAV speed and altitude. Region-of-interest (ROI) detection is implemented to focus computational resources on areas that are likely to contain fire. The system first performs a quick low-resolution scan of the entire image to identify candidate regions, then processes only these candidate regions at full resolution for detailed analysis. Temporal consistency checking is applied across consecutive frames to filter out transient false positives. A fire detection is only confirmed when the same fire feature is detected consistently across multiple frames, with appropriate motion compensation accounting for UAV movement.

3.5 Fixed-wing Platform Optimization

The choice of fixed-wing UAV platform is a critical design decision that directly impacts the system's operational effectiveness for large-area forest fire patrol. Compared to multi-rotor UAVs, fixed-wing platforms offer several significant advantages: extended endurance of 2-4 hours versus 20-40 minutes for typical multi-rotor drones, higher cruise speed of 40-60 km/h versus 10-20 km/h, greater payload capacity, and better operational reliability in windy conditions. These advantages make fixed-wing platforms much better suited for large-scale forest monitoring missions.

The airframe is constructed from lightweight carbon fiber composite materials to maximize strength-to-weight ratio and endurance. The wing design is optimized for efficient cruise flight at the typical patrol speeds and altitudes used for forest monitoring. The sensor suite is mounted in the nose section of the UAV to provide unobstructed forward and downward views, with the visible light camera and infrared thermal imager co-aligned to ensure maximum field-of-view overlap. The edge computing terminal is housed in a dedicated compartment with passive thermal management to ensure reliable operation under varying environmental temperatures. The flight control system includes an autopilot with GPS/IMU navigation, enabling fully autonomous flight along pre-programmed patrol routes with waypoint navigation, altitude hold, and return-to-home functionality.

IV. RESULTS AND DISCUSSION

4.1 Dataset and Experimental Setup

A comprehensive forest fire dataset was constructed to train and evaluate the detection model. The dataset contains over 6,000 annotated images distributed across visible light and infrared modalities, captured under various environmental conditions including clear daytime, hazy conditions, nighttime, and different seasons. The images cover multiple fire sizes from small early-stage spots to well-developed fires, as well as various non-fire scenarios that commonly cause false alarms, such as sun-heated rocks, animal heat signatures, clouds, and fog.

Data augmentation techniques including random cropping, rotation, flipping, brightness adjustment, contrast variation, and noise addition were applied to increase dataset diversity and improve model generalization. The dataset was split into training (70%), validation (15%), and test (15%) sets, ensuring balanced distribution of fire and non-fire samples across all splits. All experiments were conducted on the edge computing terminal with a quad-core ARM processor and 2GB RAM, simulating the actual on-board deployment environment.

4.2 Detection Performance

The lightweight fire detection model achieves the following metrics on the test set: overall accuracy of 92.3%, precision of 91.7%, recall of 93.1%, and F1-score of 92.4%. These results demonstrate that the model maintains high detection accuracy despite the significant size reduction from the full YOLOv5 architecture. The model size is reduced to 4.2MB with INT8 quantization, compared to 27.8MB for the original floating-point model, representing an 85% reduction in model size while losing less than 2% in accuracy.

Ablation experiments confirm the contribution of the multi-modal fusion approach. The visible-light-only baseline achieves 83.5% accuracy with a false positive rate of 11.2%, while the infrared-only baseline achieves 78.9% accuracy with 14.7% false positives. The dual-modality fusion of visible and infrared improves accuracy to 89.2% with 6.8% false positives. Adding the environmental sensor modality further improves accuracy to 92.3% and reduces false positives to 4.1%. These results validate the hypothesis that multi-source heterogeneous perception fusion significantly improves fire detection reliability by leveraging complementary information from different sensor modalities.

4.3 System Latency and Endurance

End-to-end latency from image capture to detection result output is measured at approximately 85 milliseconds per frame on the edge computing terminal, enabling processing at up to 12 frames per second. This processing speed is sufficient for real-time fire detection during cruise flight at 40-60 km/h, ensuring that no fire spots are missed during patrol. The NCNN inference framework contributes significantly to this performance, providing optimized neural network execution on ARM-based edge hardware without GPU acceleration.

Flight endurance tests demonstrate that the fixed-wing UAV with the complete sensor suite and edge computing payload achieves a maximum flight time of 3.2 hours at cruise speed, with a practical patrol endurance of approximately 2.5-3 hours accounting for takeoff, landing, and reserve fuel. This enables a single flight to cover approximately 150-200 square kilometers of forest area, which is 5-8 times the coverage of a typical multi-rotor UAV. The long-range data transmission link maintains reliable communication up to 20 kilometers in open terrain, enabling extensive patrol radius from the ground station.

4.4 Discussion

The experimental results validate the core hypothesis that multi-source heterogeneous perception fusion combined with edge intelligence can significantly improve the reliability and practicality of UAV-based

forest fire early warning systems. The 92.3% detection accuracy with 4.1% false positive rate represents a substantial improvement over single-sensor approaches, making the system suitable for practical deployment in real forest fire monitoring scenarios.

Several limitations remain. The current dataset, while covering various conditions, does not yet include all possible forest environments and fire scenarios. Continued data collection during actual deployment will be necessary to further improve model generalization. The fixed-wing platform requires runway or catapult launch, which may limit deployment in some remote areas. Future work will explore VTOL fixed-wing hybrid platforms to address this limitation. Additionally, the current system focuses on fire detection and early warning; future extensions could include fire spread prediction, burn area assessment, and integration with fire suppression command systems.

Compared with traditional monitoring methods, the proposed system offers significant advantages in coverage, timeliness, and cost-effectiveness. Compared with other UAV-based solutions, the combination of multi-source perception fusion, edge intelligence, and fixed-wing platform provides a unique balance of detection accuracy, operational range, and deployment flexibility that is well-suited for large-area forest fire prevention applications.

V. CONCLUSION

This paper has presented a fixed-wing UAV forest fire early warning system based on multi-source heterogeneous perception and edge intelligence. The system addresses critical limitations of traditional forest fire monitoring methods by integrating advanced UAV technology, multi-sensor fusion, and on-board artificial intelligence.

The multi-source heterogeneous perception subsystem combines visible light cameras, infrared thermal imagers, and environmental sensors to capture fire features from optical, thermal, and environmental dimensions. The adaptive fusion mechanism dynamically weights the contributions of each sensor modality based on environmental conditions, ensuring robust and accurate fire detection across diverse operating scenarios. The edge intelligence subsystem deploys lightweight deep learning models on the UAV-mounted edge computing terminal, enabling real-time on-board fire detection and decision-making without reliance on public network infrastructure. The fixed-wing UAV platform provides 2-4 hours of endurance and large-area coverage capability, dramatically outperforming multi-rotor alternatives in operational efficiency.

Experimental results demonstrate 92.3% detection accuracy with 4.1% false positive rate, real-time processing at 12 frames per second, and 2.5-3 hours of practical patrol endurance. The proposed system offers a practical, efficient, and intelligent solution for forest fire prevention, with broad application prospects across forest farms, nature reserves, forestry management departments, and other high fire risk scenarios. As the technology continues to mature and improve, it is expected to play an increasingly important role in safeguarding forest ecosystems and supporting ecological civilization construction.

ACKNOWLEDGMENT

This work is supported by the 2026 Changchun University Undergraduate Innovation and Entrepreneurship Training Program (Project No. 20261020). The authors would like to thank the School of Electronic and Information Engineering of Changchun University for providing experimental facilities and technical support. We also thank the anonymous reviewers for their valuable comments and suggestions.

REFERENCES

- [1] C. Yuan, Z. Liu, and Y. Zhang, "Fire detection using infrared images for UAV-based forest fire surveillance," in Proc. International Conference on Unmanned Aircraft Systems (ICUAS), 2015, pp. 1224-1229.
- [2] P. Barmoutis, P. Papaioannou, and K. Dimitropoulos, "Forest fire detection from UAV imagery using deep learning," *Fire Technology*, vol. 56, no. 5, pp. 1841-1865, 2020.
- [3] L. Merino, F. Caballero, and J. R. Martinez-de Dios, "An unmanned aircraft system for automatic forest fire monitoring and measurement," *Journal of Intelligent & Robotic Systems*, vol. 65, no. 1-4, pp. 533-548, 2012.
- [4] J. Zhang et al., "A review of forest fire monitoring technology based on UAV," *Journal of Forestry Research*, vol. 30, no. 6, pp. 2053-2064, 2019.
- [5] T. Chen et al., "Edge computing in UAV systems: A survey," *IEEE Internet of Things Journal*, vol. 8, no. 10, pp. 7814-7838, 2021.
- [6] X. Wang et al., "Lightweight deep learning for edge-based fire detection in UAV imagery," *Remote Sensing*, vol. 12, no. 20, p. 3331, 2020.
- [7] P. Li et al., "Multi-sensor data fusion for forest fire detection: A review," *Information Fusion*, vol. 79, pp. 160-178, 2022.
- [8] NCNN Development Team, "NCNN: A high-performance neural network inference framework optimized for mobile platforms," 2021. [Online]. Available: <https://github.com/Tencent/ncnn>
- [9] A. Howard et al., "MobileNets: Efficient convolutional neural networks for mobile vision applications," *arXiv preprint arXiv:1704.04861*, 2017.
- [10] J. Redmon and A. Farhadi, "YOLOv3: An incremental improvement," *arXiv preprint arXiv:1804.02767*, 2018.
- [11] National Forestry and Grassland Administration of China, "China Forestry Statistical Yearbook 2022," Beijing: China Forestry Press, 2023.
- [12] K. He, X. Zhang, S. Ren, and J. Sun, "Deep residual learning for image recognition," in Proc. IEEE Conference on Computer Vision and Pattern Recognition (CVPR), 2016, pp. 770-778.