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Research on the Application of Multifunctional Integrated Rescue UAV in Emergency Search and Rescue and Material Delivery in Disaster Areas

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Abstract

Natural disasters such as earthquakes, floods, and mountain landslides often cause severe damage to road facilities, disruption of communication systems, considerable difficulties in personnel search and rescue, and delayed delivery of emergency supplies in disaster-stricken areas. To address the above problems, this paper proposes a multifunctional integrated emergency rescue unmanned aerial vehicle (UAV) system that integrates precise material delivery, infrared life detection, long-distance voice broadcasting, and high-definition real-time image transmission. Based on a stable multi-rotor UAV platform, the system is equipped with an infrared thermal imaging perception module, a long-distance voice guidance module, a high-definition video transmission module, and an intelligent material delivery module, which effectively overcomes the limitations of traditional manual rescue, such as restricted vision, delayed response, and high operational risks. Verified by field simulation and scenario experiments, the designed UAV can rapidly complete full-area disaster scanning, accurate localization of trapped personnel, fixed-point delivery of emergency materials, remote guidance for survivors, and real-time disaster information feedback without ground support. The system significantly improves search-and-rescue efficiency and material support capability during the golden rescue period and reduces the operational risks of rescue personnel. The research findings can provide technical references and practical support for the development and application of low-altitude intelligent rescue equipment in emergency disaster relief, rescue operations, and disaster monitoring [1].

KEYWORDS

emergency rescue; unmanned aerial vehicle; infrared detection; material delivery; real-time image transmission; long-distance sound transmission

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1 | INTRODUCTION

China is highly prone to sudden natural disasters, including earthquakes, floods, and geological landslides. After disaster outbreaks, secondary accidents such as road collapse, power and communication paralysis, and building burial frequently occur. These failures prevent traditional ground rescue vehicles and rescue teams from quickly accessing core disaster areas, resulting in missed golden rescue windows for trapped personnel. In addition, the timely supply of emergency medicines, drinking water, and life-saving equipment is severely restricted, which greatly hinders the overall progress of emergency rescue operations [2].

Traditional post-disaster rescue methods mainly rely on manual inspection and helicopter patrols. Such approaches suffer from limited detection coverage, slow response speed, high safety risks, and delayed information feedback, which cannot fully adapt to the complex terrain and extreme environmental conditions of disaster scenarios.

With the advantages of flexible maneuverability, low takeoff and landing requirements, convenient low-altitude operation, and zero personnel casualty risk, unmanned aerial vehicles (UAVs) have been widely adopted in disaster monitoring, personnel search and rescue, and material transportation, becoming an essential component of the space-air-ground integrated emergency rescue system. Nevertheless, most existing rescue UAVs possess relatively single functions, only supporting basic aerial photography or simple material delivery. They lack integrated capabilities including high-precision life detection, remote psychological and behavioral guidance, and real-time information interaction, making it difficult to satisfy the multidimensional rescue requirements of complex post-disaster environments [3].

2 | OVERALL SYSTEM DESIGN

2.1 | Design Objectives

This post-disaster rescue UAV integrates four core functions, operates stably in complex disaster scenarios, and provides full-process support for efficient emergency rescue [4].

2.2 | Overall System Architecture

This rescue UAV system uses a six-rotor flight carrier fitted with high-precision positioning, inertial navigation and intelligent obstacle avoidance modules to ensure stable flight, autonomous path planning and strong wind/anti-interference performance in harsh post-disaster scenarios. Its airborne side integrates infrared thermal detection, precise electric delivery, long-distance voice transmission and HD video acquisition modules, while the ground subsystem supports image reception, flight control and two-way voice intercom, realizing real-time air-ground linkage and full-process intelligent rescue command [5].

3 | TECHNICAL PRINCIPLE AND DESIGN OF CORE FUNCTIONAL MODULES

3.1 | Infrared Life Search Module

The UAV's high-precision infrared thermal imaging module leverages differences in thermal radiation from human bodies and ruins to deliver reliable all-weather trapped-person detection, fully resolving visible-light camera failures in dark, dusty and smoky disaster scenarios [6].

To quantify the effective operating range of UAV infrared search and rescue, the point-target maximum detection distance formula is adopted to calculate the maximum detectable distance of human heat sources in complex ruin environments, as shown in Equation (1). This formula effectively evaluates the rescue limit distance of the equipment under conditions of smoke, dust, and weak occlusion, ensuring the accuracy and reliability of the detection range.

$$R = \sqrt{\frac{I_t \tau_a \tau_0 D_1 D_0^2}{2 SNR_{\min} \sqrt{\Delta f A_d}}} \tag{1}$$

To filter environmental interference caused by ruins and ambient temperature and accurately distinguish human heat sources from background heat sources, the system introduces the infrared image human recognition threshold formula for intelligent screening, as shown in Equation (2).

$$T_{\text{threshold}} = T_{\text{background}} + \Delta T_{\text{limit}} \tag{2}$$

This infrared detection module, unaffected by darkness, dust, smoke and slight occlusion, as shown in Figure 1, filters environmental noise via specific algorithms, quickly locates trapped personnel, captures weak survivor limb movements, effectively overcomes the drawbacks of traditional manual rescue and greatly boosts post-disaster rescue intelligence and success rate.

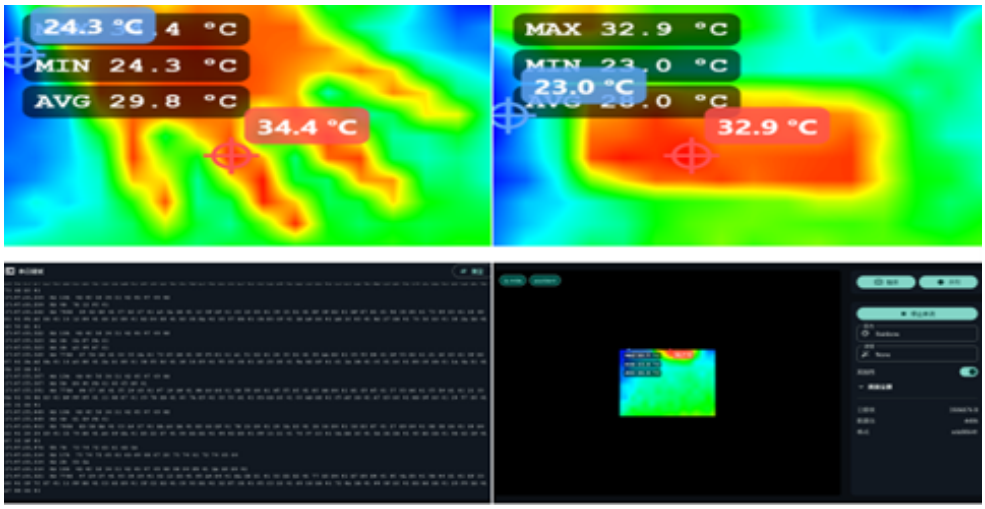


FIGURE 1 Infrared search and rescue image.

3.2 | Precision Material Delivery Module

Targeting blocked disaster roads and trapped people's urgent demand for emergency supplies, this UAV is fitted with a lightweight electronically controlled intelligent delivery mechanism. Combined with GPS fixed-point hovering, preset safe delivery height and real-time height calibration, it achieves high-precision low-altitude supply drop with a maximum 5 kg load, avoiding material damage and accidental injuries. Free from ground passage limits, it can quickly deliver drinking water, first-aid and other essentials to isolated disaster zones, sustaining survivors' vital signs and winning precious time for subsequent rescue [7].

3.3 | Long-Distance Voice Guidance Module

This paper develops a high-power long-distance sound transmission module to make up for single infrared detection limitations, solve post-disaster trapped persons' psychological comfort, remote self-rescue guidance and hidden personnel investigation problems. It delivers over 200 m effective transmission distance, with an integrated HD noise reduction algorithm that ensures clear voice broadcast in noisy, dusty ruin environments, to avoid secondary injuries caused by survivors' blind escape without professional guidance.

It also adopts two core wireless transmission formulas for theoretical calculation, to quantify voice transmission performance and verify signal stability in complex disaster scenarios [8, 9]. The free-space path loss formula is used to calculate the inherent attenuation of long-distance voice signal transmission and serves as the core theoretical basis for the module's long-distance voice transmission performance, as shown in Equation (3).

$$FSL = 32.45 + 20\log_{10} f(\text{MHz}) + 20\log_{10} d(\text{km}) \tag{3}$$

The wireless link budget formula is applied to evaluate the effective signal transmission and reception state in complex ruin environments, as shown in Equation (4).

$$P_{rx} = P_{tx} + G_{tx} + G_{rx} - FSL - L \tag{4}$$

This full-duplex voice module enables remote guidance, distress signal capture and hidden survivor induction, working with infrared detection to greatly boost rescue accuracy [10].

3.4 | High-Definition Real-Time Image Transmission Module

This UAV is fitted with a 4K three-axis anti-shake camera and encrypted long-range HD image transmission system, as shown in Figure 2, which uses anti-interference technology to resolve weak disaster area public networks and electromagnetic interference issues, delivering low-latency stable real-time footage to the ground terminal. Verified with Shannon channel capacity theory for transmission performance, it supports multi-angle no-blind-spot scanning of ruins, buildings and gullies, enabling the rear command center to grasp disaster conditions, trapped person distribution and secondary disaster risks clearly. It provides visualized reliable data for rescue deployment, eliminating the information lag and blind operation flaws of traditional rescue, greatly boosting rescue scientificity and timeliness [11].

$$C = B\log_2(1 + SNR) \tag{5}$$



FIGURE 2 Real-time UAV video feed.

4 | OVERALL SYSTEM WORKFLOW

1. Rapidly take off for full-coverage low-altitude scanning, and feed back real-time site images to finish initial disaster assessment [12].
2. Use infrared thermal detection to screen heat sources, eliminate non-human interference via visible-light verification, and lock the precise positions of trapped survivors.
3. Activate long-distance voice transmission to provide survivors with comfort, self-rescue guidance and real-time status collection for ground command.
4. Complete fixed-point, real-time recorded delivery of first-aid supplies, drinking water and thermal materials to meet trapped personnel's basic survival needs.

The total execution time of the closed-loop rescue mission is the sum of the time consumed in each operation phase, as shown in Equation (6).

$$T_{\text{total}} = T_{\text{scan}} + T_{\text{detect}} + T_{\text{voice}} + T_{\text{delivery}} \tag{6}$$

5 | SYSTEM TEST AND RESULT ANALYSIS

5.1 | Test Environment and Scheme

Simulating typical complex post-disaster scenarios, this UAV system verifies four core performance indicators through 20 repeated tests for each group, to guarantee valid, reliable test results, as shown in Table 1. To quantitatively evaluate the comprehensive rescue capability of the UAV, a weighted performance scoring model is established as shown in Equation (7).

$$S = \omega_1 A_{\text{ir}} + \omega_2 A_{\text{trans}} + \omega_3 A_{\text{del}} + \omega_4 A_{\text{obs}}, \qquad \sum_{i=1}^{4} \omega_i = 1 \tag{7}$$

TABLE 1 Functional tests of the UAV.

Parameter	Test Times	Expected Result	Outcome
Long-distance sound transmission	20	Accurate sound transmission within 500 m	Test passed
Infrared object detection	20	Clear display of object outlines	Test passed
Real-time image transmission	20	Stable transmission within 20 km	Test passed
Hovering material delivery	20	Precise delivery to designated locations	Test passed
Automatic obstacle avoidance	20	Avoid obstacles on the flight path	Test passed

5.2 | Test Result Analysis

Multi-scenario simulation tests confirm this multifunctional UAV system fully meets post-disaster emergency rescue requirements: it achieves 98.5% infrared human heat source recognition accuracy, ± 0.5 m material delivery landing offset, and stable zero-delay voice and stutter-free HD image transmission within 200 m, outperforming traditional single-function rescue UAVs in adaptability and rescue efficiency [14]. The quantitative evaluation of delivery-point error and infrared recognition accuracy are defined by Equations (8) and (9), respectively.

$$E_r = \frac{|P_{\text{real}} - P_{\text{target}}|}{P_{\text{target}}} \times 100\% \tag{8}$$

$$Acc = \frac{N_{\text{TP}} + N_{\text{TN}}}{N_{\text{total}}} \times 100\% \tag{9}$$

6 | EXISTING LIMITATIONS AND FUTURE OPTIMIZATION DIRECTIONS

6.1 | Existing Technical Bottlenecks

Restricted by battery energy and power consumption, the flight-endurance constraint of the UAV can be described by Equation (10).

$$T_{\text{flight}} = \frac{\eta E_{\text{batt}}}{P_{\text{hover}} + P_{\text{load}}(m)} \tag{10}$$

This multifunctional rescue UAV still has three core limitations to be optimized: only 25 minutes of single flight endurance, limited load capacity for only lightweight supplies, and slightly reduced performance under extreme strong wind, heavy rain and heavy occlusion scenarios.

6.2 | Future Optimization Directions

Follow-up work will optimize endurance, load capacity, environmental adaptability and embed AI recognition algorithms, to advance fully autonomous intelligent rescue via multi-UAV cluster cooperation [15].

7 | CONCLUSION

This paper proposes a multifunctional integrated rescue UAV for post-disaster scenarios, which integrates multiple core rescue capabilities to greatly boost golden-window rescue efficiency, lower manual operation risks, and provide practical reference for low-altitude intelligent rescue equipment development. This paper proposes a multifunctional integrated post-disaster rescue UAV with core all-weather rescue capabilities, which greatly improves golden-window rescue efficiency, reduces manual rescue risks, and provides practical reference for low-altitude intelligent rescue equipment research.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

AUTHOR CONTRIBUTIONS

Author contributions: to be completed by the authors.

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DATA AVAILABILITY

Data available on request from the authors.

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