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Research on Air-Ground Collaborative Autonomous Reconnaissance and Emergency Delivery System

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Abstract

Aiming at the practical problems of limited operation capability of single unmanned equipment in modern battlefield logistics support and disaster emergency rescue scenarios, this paper designs an air-ground collaborative autonomous reconnaissance and emergency delivery system based on the ROS operating system, with quadrotor UAVs and ground intelligent unmanned vehicles as carriers. Relying on core technologies including binocular vision navigation, image recognition, LAN two-way communication, visual servoing and PID closed-loop control, the system constructs an integrated operation mode of "air global reconnaissance and positioning – ground autonomous navigation and delivery". Experiments show that the system can be adapted to tasks such as frontline battlefield supply, field emergency rescue, and material transportation in complex urban scenarios, providing a feasible practical scheme and technical reference for the construction of an intelligent unmanned logistics support system.

KEYWORDS

Air-Ground Collaboration; Unmanned System; Autonomous Reconnaissance; Emergency Delivery; ROS; Visual Recognition; PID Control

1 | INTRODUCTION

With the vigorous development of the low-altitude economy and the continuous iteration of unmanned intelligent equipment technology, unmanned equipment has been widely used in military logistics, emergency disaster relief, field exploration and many other fields, becoming an important part of the intelligent operation system [1]. The modern information battlefield is characterized by decentralized combat units, complex battlefield environments and timely emergency support. Small frontline combat units and remote disaster-stricken areas often face problems such as blocked supply routes, high difficulty in manual arrival, and high risks of personnel operations. The traditional manual transportation and single unmanned equipment operation modes can no longer meet the needs of efficient emergency support [2].

From the perspective of existing application status, UAVs have the advantages of flexible maneuverability, broad high-altitude vision and global rapid reconnaissance, and can quickly complete large-scale regional inspection and target search. However,

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limited by airframe structure and load, their material carrying capacity is seriously insufficient, and they can only complete the transportation of light and small items, failing to meet the demand for large-batch emergency material delivery. Ground unmanned vehicles have strong bearing capacity and excellent obstacle surmounting performance, which are suitable for long-distance material transportation and fixed-point operations. Nevertheless, affected by terrain occlusion and limited vision, their autonomous reconnaissance and search capabilities are weak. They are extremely easy to lose their paths and cannot accurately lock operation targets in complex environments such as ruins, mountain forests and urban alleys, with obvious application bottlenecks [3, 4, 5].

At the same time, when carrying out emergency material delivery operations at unknown hidden points, there are widespread pain points such as large target positioning deviation, lagging collaborative linkage of air-ground equipment, and insufficient terminal delivery accuracy, which greatly reduce the efficiency and safety of emergency support operations [6]. Against this background, integrating the air reconnaissance advantages of UAVs and the ground carrying advantages of unmanned vehicles to build a collaborative operation system of heterogeneous air-ground unmanned platforms, opening up the whole-process autonomous link of reconnaissance, decision-making, navigation and delivery, and realizing complementary advantages and capabilities have become an important research direction to solve the problem of emergency support in complex scenarios. This paper focuses on the overall design, key technology research and development and practical application of the air-ground collaborative autonomous reconnaissance and emergency delivery system, improves the system operation logic and control strategy, and promotes the practical application of unmanned collaboration technology.



FIGURE 1 Background.

2 | OVERALL SYSTEM DESIGN

2.1 | System Working Principle

The core working principle of this system is complementary advantages of air and ground and hierarchical collaborative operation, with the core logic of “air perception and guidance, ground execution and landing”. The system is divided into two levels: air reconnaissance layer and ground execution layer. As a global perception terminal, the air quadrotor UAV completes environmental detection, target recognition and 3D coordinate calculation relying on the binocular vision system, and grasps the

topography and landform of the operation area and target point information in real time. As a material carrying and execution terminal, the ground intelligent unmanned vehicle completes path planning and obstacle avoidance relying on lidar environmental mapping and autonomous navigation algorithm, receives target coordinates and operation instructions issued by the UAV, and completes the grasping, transfer and accurate delivery of emergency materials.

The system abandons the independent operation mode of single equipment, builds a stable data interaction link through wireless LAN, realizes two-way communication of status information, target coordinates and operation instructions between UAV and unmanned vehicle, breaks the barrier of independent operation of equipment, and constructs a complete closed loop of reconnaissance and recognition, coordinate transmission, autonomous navigation and accurate delivery. It completes the whole-process autonomous emergency support tasks without manual remote control or with less manual intervention.

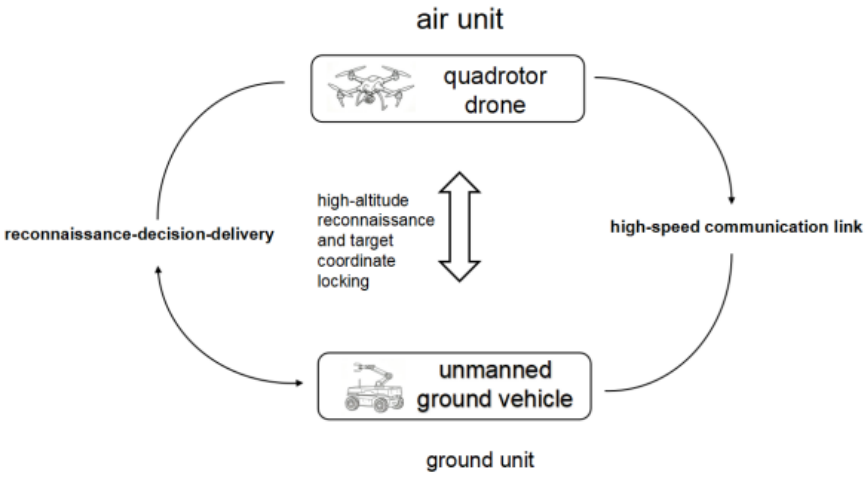


FIGURE 2 Hardware composition of the air-ground cooperative system.

2.2 | Overall System Architecture

The system adopts a hierarchical modular architecture design as a whole, which is divided into two major parts: hardware architecture and software architecture. All equipment is uniformly equipped with Ubuntu 20.04 system and ROS Noetic Robot Operating System to achieve high adaptation of software and hardware.

The hardware is divided into air UAV unit and ground unmanned vehicle unit. The UAV is equipped with Raspberry Pi 4B airborne computer, binocular vision navigation module, flight control unit and wireless communication module, responsible for regional cruise, image collection, target recognition and data transmission. The ground unmanned vehicle integrates main control unit, lidar obstacle avoidance module, multi-degree-of-freedom manipulator, material carrying platform, driving chassis and visual collection module, with functions of autonomous walking, material grasping, accurate delivery and real-time environmental perception. Supporting portable routing equipment builds a local area communication network to ensure stable data transmission of air-ground equipment.

The software architecture is modularly split based on the ROS system, divided into five core modules: visual perception module, autonomous navigation module, collaborative communication module, motion control module and task decision-making module. The visual perception module completes image collection, target recognition and pose calculation; the autonomous navigation module realizes UAV route planning, global path planning and local real-time obstacle avoidance of unmanned vehicles; the collaborative communication module completes air-ground data interaction and instruction transmission based on TCP/IP protocol; the motion control module realizes flight attitude control, chassis walking control and manipulator action control relying on PID algorithm; the task decision-making module coordinates the whole-process operation logic and automatically switches operation modes according to task progress.

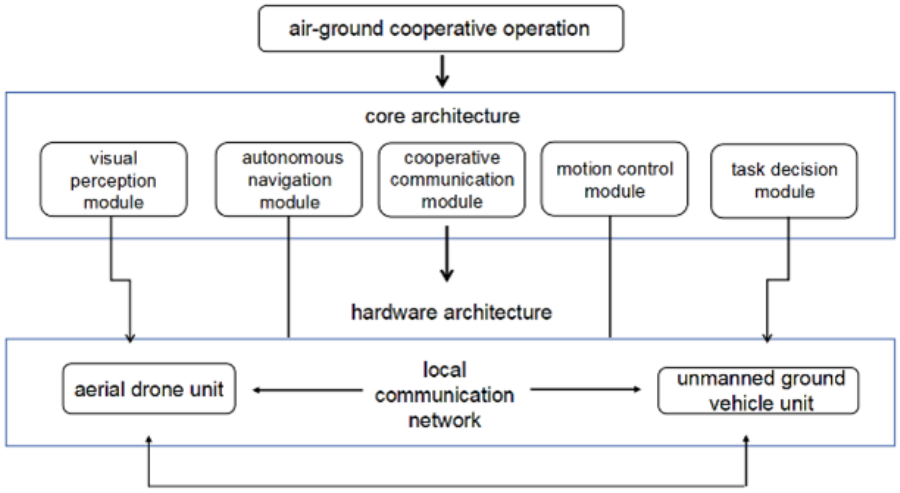


FIGURE 3 Software composition of the air-ground cooperative system.

2.3 | Workflow

1. System power-on initialization. Start the hardware equipment of UAV and unmanned vehicle in sequence, complete sensor self-inspection, driver program loading and ROS master node startup, automatically access to the unified wireless LAN, complete communication IP configuration, establish communication connection between air-ground equipment, and enter the standby monitoring state.
2. UAV autonomous cruise reconnaissance. The operator delineates the scope of the operation area, and the UAV takes off and cruises autonomously according to the preset plow-type route, scanning the global environment in real time with binocular vision to complete full-coverage search of the area.
3. Target recognition and coordinate calculation. The UAV vision module collects on-site images, identifies emergency delivery targets through optimized image algorithms, and accurately calculates the 2D plane coordinates and spatial position information of the target relative to the global coordinate system.
4. Air-ground instruction collaborative transmission. The UAV encapsulates the identified target coordinates and operation task instructions into a standardized data format and sends them to the ground unmanned vehicle in real time through the LAN.
5. Unmanned vehicle wake-up and preliminary preparation. The unmanned vehicle in low-power monitoring state receives task data, automatically parses and stores target point information, and drives the on-board manipulator to complete autonomous grasping of emergency materials to confirm stable material grasping.
6. Autonomous navigation and travel of unmanned vehicle. The unmanned vehicle constructs an on-site environment map combined with lidar, fuses the received target coordinates to plan the optimal travel path, identifies obstacles in real time during travel, autonomously adjusts the travel route to avoid obstacles, and travels smoothly to the target point.
7. Terminal visual precise alignment. After the unmanned vehicle arrives at the target area, it starts the on-board vision module, corrects its own position in real time through visual servo algorithm, eliminates position deviation, and completes precise alignment of the delivery point.
8. Material delivery and task closing. After alignment, the manipulator automatically completes material release and placement, and the emergency delivery task is completed. After the task, the UAV returns and lands, the unmanned vehicle returns to the standby point, and the system automatically sleeps and waits for the next task instruction.

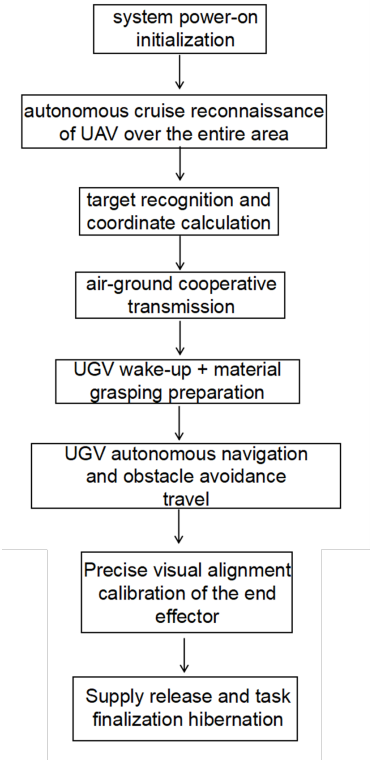


FIGURE 4 Workflow of the air-ground cooperative emergency delivery system.

3 | KEY TECHNOLOGIES AND IMPLEMENTATION

In the actual operation process, the air-ground collaborative system developed in this paper faces three core problems: interference in target recognition in complex environments, poor collaborative linkage of air-ground equipment, and insufficient accuracy of terminal material delivery. This paper clarifies the applied technologies, sorts out existing challenges, and formulates targeted solutions for each problem.

3.1 | Precise Target Recognition Technology in Complex Environments

3.1.1 | Image Recognition Technology

The image recognition technology based on color purity threshold binarization is adopted, combined with the OpenCV visual processing library to complete image preprocessing, pixel feature extraction and target feature matching, and target spatial coordinate calculation is completed relying on binocular vision.

3.1.2 | Challenges

In actual operation scenarios such as strong field light irradiation, rainy and foggy occlusion, and complex background mixing, traditional RGB and HSV basic color recognition algorithms are extremely vulnerable to illumination changes and background debris interference, resulting in missed detection, false detection and recognition offset of target recognition. At the same time, blurred long-distance image collection further reduces target recognition accuracy, which cannot meet the recognition needs of complex battlefields and disaster relief sites.

3.1.3 | Solutions

A color purity judgment index is innovatively defined:

$$C = \frac{R^2}{G \cdot B} \tag{1}$$

A color purity calculation formula is set to quantify the target color purity based on the red, green and blue channel values of pixel points, screen high-purity target pixel areas, and eliminate invalid interference pixels formed by shadows and strong light. In this context, R represents the red weight, while G and B represent the green and blue components respectively. The collected images are denoised by binarization with a fixed purity threshold to filter visual noise caused by complex backgrounds and variable illumination, and retain effective target feature areas. At the same time, combined with the binocular vision depth ranging algorithm, on the basis of accurate target recognition, the actual spatial distance of the target is synchronously measured, and the global coordinates are accurately calculated, which greatly improves the stability and accuracy of target recognition in complex environments.

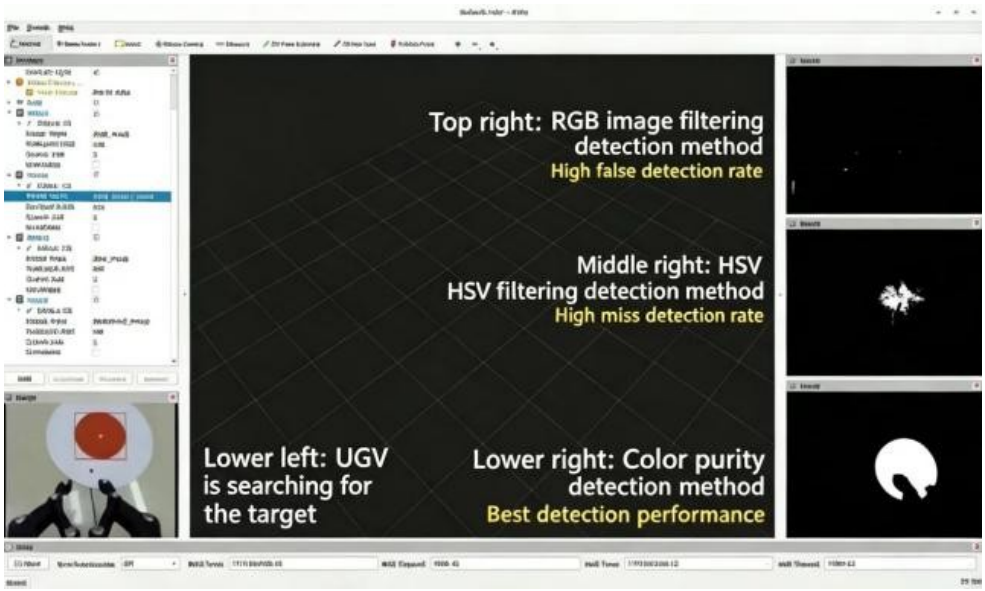


FIGURE 5 Comparison chart of different color algorithms.

3.2 | Collaborative Communication and Linkage Technology for Heterogeneous Air-Ground Platforms

3.2.1 | Communication Technology

A communication system is built based on wireless LAN, and TCP/IP communication protocol is adopted to construct an event-triggered two-way data interaction mechanism to realize point-to-point real-time communication between UAV and unmanned vehicle.

3.2.2 | Challenges

Traditional wireless communication methods have problems such as high transmission delay, high data packet loss rate and disordered instruction transmission sequence. At the same time, the operation states of air-ground equipment are independent of each other, and the unmanned vehicle cannot autonomously respond to UAV reconnaissance instructions, resulting in lagging equipment wake-up and disjointed task linkage, making it difficult to achieve seamless connection between reconnaissance and

delivery tasks.

3.2.3 | Solutions

A dedicated low-latency wireless local area network is built, fixed static IP addresses are assigned to UAV and unmanned vehicle, and a stable dedicated communication link is established to reduce data transmission delay and packet loss probability. A hierarchical communication logic is set: the UAV, as a communication client, actively initiates data connection, and the unmanned vehicle, as a server, is in the background monitoring state for a long time. Only when valid target coordinates and operation instructions are monitored, the internal task execution program is automatically triggered to complete a series of actions such as coordinate analysis, material grasping and path planning, realizing an autonomous linkage mode of "reconnaissance triggers immediately, instructions execute immediately", and completely solving the problems of lagging collaborative wake-up and poor linkage of air-ground platforms.

3.3 | Visual Servoing and PID Closed-Loop Precise Delivery Control Technology

3.3.1 | Positioning Technology

The eye-in-hand visual servoing positioning technology and PID negative feedback closed-loop control algorithm are integrated to convert image pixel deviation into equipment motion control variables, realizing dynamic fine-tuning and precise alignment of unmanned vehicle position.

3.3.2 | Challenges

The unmanned vehicle is prone to cumulative position error when traveling by global navigation, and cannot complete centimeter-level precise alignment at the terminal only relying on navigation data. The vehicle is prone to problems such as unstable traveling speed, attitude shaking and positioning overshoot during traveling, which directly lead to material delivery offset and failure to complete fixed-point precise delivery operations.

3.3.3 | Solutions

A visual collection device is mounted at the end of the unmanned vehicle manipulator to collect images of the delivery area in real time and calculate the pixel offset error between the target delivery center and the image frame center. A two-dimensional independent PID controller is built to control the lateral and longitudinal traveling attitude and speed of the unmanned vehicle respectively. The position deviation obtained by visual recognition is taken as the input error value of the PID controller, and the motion control variables are output through real-time calculation of proportional, integral and differential parameters to dynamically adjust the traveling speed and direction of the unmanned vehicle chassis, and continuously eliminate position deviation. Relying on the closed-loop negative feedback control mode, the problems of equipment traveling shaking and positioning overshoot are suppressed, taking into account the traveling response speed and terminal positioning accuracy, and realizing accurate material grasping and fixed-point delivery.

4 | EXPERIMENTS AND RESULT ANALYSIS

4.1 | Experimental Setup

To verify the overall operation performance, collaboration efficiency and delivery accuracy of the system, a simulated actual combat experimental scenario was built to complete multiple groups of comparative experimental tests. The experimental equipment selected Owl mini2 quadrotor UAV, manipulator unmanned vehicle, Raspberry Pi 4B airborne control terminal, binocular vision module, lidar, emergency material model and portable wireless router. Three typical complex operation

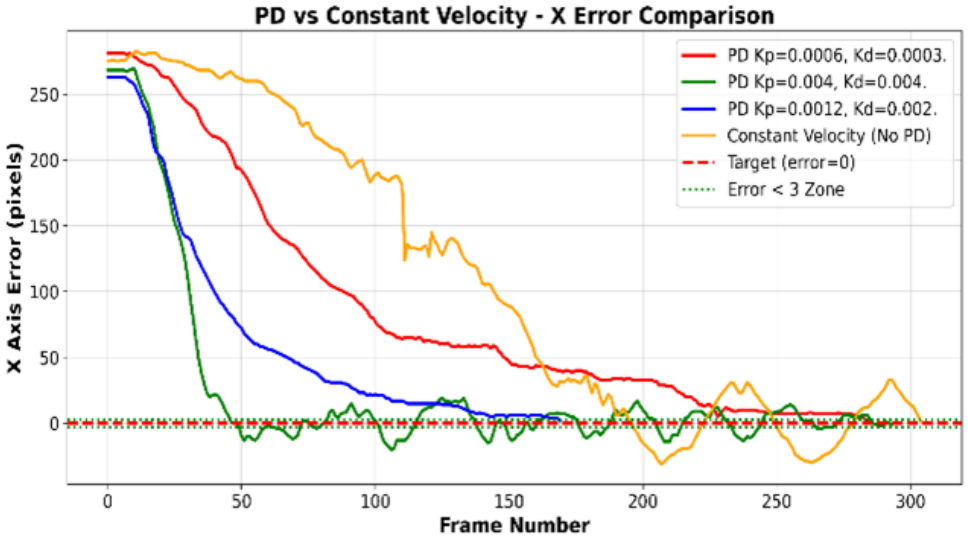


FIGURE 6 PD vs constant velocity – X error comparison.

environments were set up in this experiment: simulated mountain obstacle scenario, urban ruin obstacle scenario and strong light field natural scenario. The main test items included global regional reconnaissance coverage rate, target recognition accuracy in complex environments, air-ground instruction transmission delay, autonomous obstacle avoidance success rate of unmanned vehicles, and terminal material delivery positioning error. The traditional single UAV reconnaissance and single unmanned vehicle transportation modes were selected as the control group to compare the operation efficiency and effect.

4.2 | Experimental Results

After multiple rounds of repeated simulation experiments, the core data of each experiment were statistically sorted out, and the experimental results are as follows: after optimizing the color purity recognition algorithm, the target recognition accuracy in complex illumination and complex background environments is increased to 90.95%, which is 24.62% higher than that of traditional color recognition algorithms, and the problems of missed detection and false detection are basically solved; the average transmission delay of air-ground equipment LAN instructions is controlled within 0.196 s, data transmission is stable without packet loss, and the collaborative response speed meets the needs of emergency operations; the autonomous navigation and obstacle avoidance success rate of unmanned vehicles reaches 97.44%, which can smoothly pass through complex terrains such as low obstacles, gullies and gravel roads; the average positioning error of the system terminal emergency material delivery is less than 2.59 cm, realizing high-precision fixed-point delivery.

4.3 | Result Analysis

Compared with the single unmanned equipment operation mode, the overall emergency material delivery operation efficiency of this air-ground collaborative system is improved by more than 45.62%, and the manual participation rate in high-risk scenarios is minimized.

It can be seen from the overall experimental data that all performance indicators of the air-ground collaborative autonomous reconnaissance and emergency delivery system designed in this paper meet the expected design standards. At the environmental perception level, the optimized visual recognition algorithm effectively adapts to various types of complex operation scenarios, the anti-environmental interference ability is greatly enhanced, and target search and positioning can be stably completed; at the collaborative linkage level, the LAN two-way communication architecture has low delay and strong stability, realizing the seamless connection of air reconnaissance and ground delivery tasks, and completely solving the problem of platform linkage lag; at the terminal execution level, the visual servoing combined with PID closed-loop control strategy effectively corrects the

navigation cumulative error, and the precise delivery effect is excellent.

At the same time, comparative experiments confirm that the air-ground collaborative operation mode gives full play to the core advantages of the two types of unmanned equipment, avoids the shortcomings of single equipment operation, not only greatly improves the overall efficiency of emergency material delivery, but also minimizes the safety risks caused by manual in-depth high-risk operation areas. It has strong practicability and landing feasibility whether it is frontline battlefield supply or emergency material transportation at natural disaster sites. However, it is also found in the experimental process that the visual recognition effect and communication stability of the system will decrease slightly in extreme smoke occlusion and strong electromagnetic interference scenarios, and there is still room for optimization and improvement.

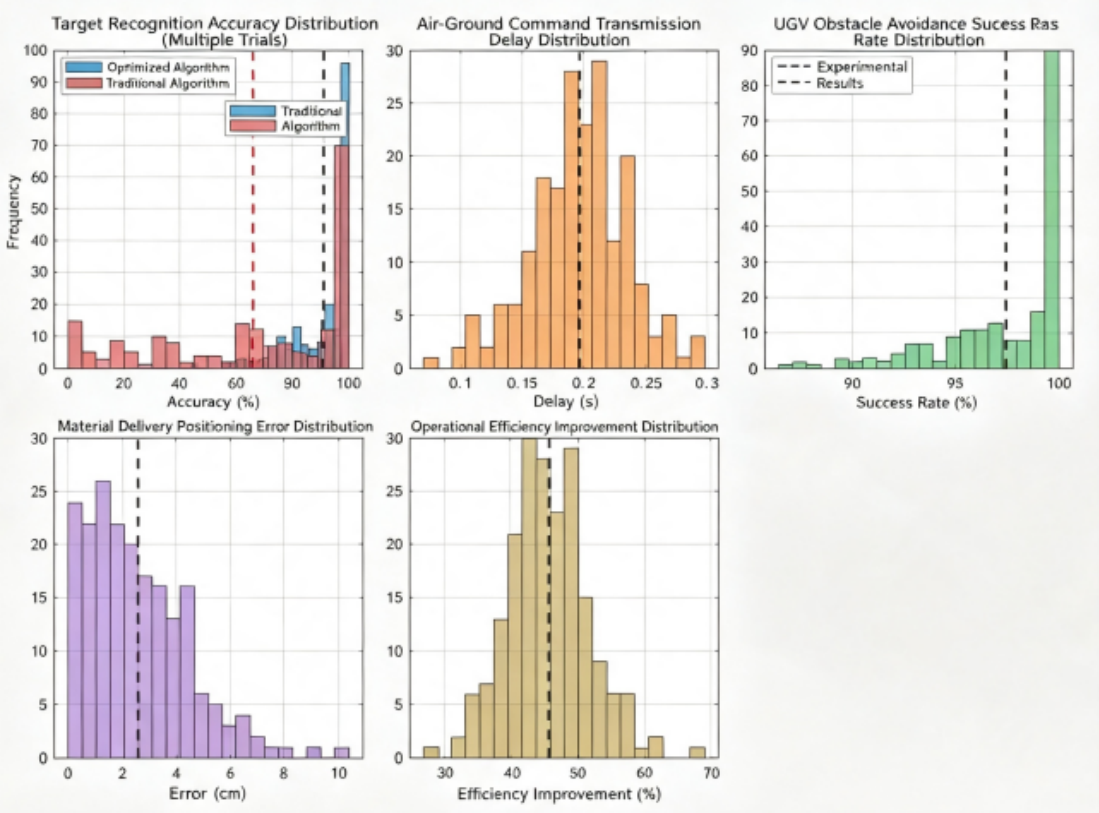


FIGURE 7 Simulation experiment results.

5 | CONCLUSION AND PROSPECT

5.1 | Research Conclusion

Based on the actual needs of emergency support in complex scenarios, this paper completes the overall design, hardware construction, software program development and core technology optimization of the air-ground collaborative autonomous reconnaissance and emergency delivery system, and mainly draws the following research conclusions:

The air-ground collaborative architecture design of UAV and unmanned vehicle built based on ROS operating system is reasonable, the hierarchical modular design idea is clear, the software and hardware compatibility is strong, and it can stably realize the whole-process autonomous operation of autonomous cruise, target recognition, data transmission, autonomous navigation and material delivery, with good overall system operation stability.

The image binarization recognition algorithm based on color purity can effectively solve the industry pain point of low target recognition accuracy under complex illumination and cluttered backgrounds, and significantly improve the field environmental perception ability of unmanned equipment; the two-way event-triggered communication mechanism built relying on LAN realizes

efficient collaborative wake-up and instruction intercommunication of air-ground platforms, and the collaborative operation logic is scientific and feasible.

The visual servoing combined with PID closed-loop control strategy can effectively correct the traveling positioning error of unmanned vehicles, realize high-precision terminal material delivery, and meet the core use demand of precise delivery in emergency support scenarios.

The actual measurement proves that the air-ground collaborative system has strong environmental adaptability, high operation efficiency and high safety factor, and can be widely used in scenarios such as emergency supply for battlefield individual soldiers, earthquake and flood disaster rescue, and material transportation in remote field areas, with high practical value and popularization and application value.

5.2 | Future Prospect

This research has completed the research and development and testing of the basic air-ground collaborative reconnaissance and delivery system, and the overall functions of the system tend to be perfect. The follow-up can be further optimized and upgraded from four dimensions: perception ability, communication system, control strategy and operation mode.

1. Optimize the environmental perception algorithm. On the basis of the existing color purity recognition algorithm, introduce deep learning semantic segmentation algorithm, integrate target shape, texture and multi-spectral features for comprehensive recognition, further improve the target recognition ability in harsh extreme environments such as heavy smoke, rain and snow, and extreme dust, and broaden the applicable scenarios of the system.
2. Upgrade the air-ground communication system. Abandon the single LAN communication mode, build an ad hoc network relay communication system, and improve the anti-interference and anti-damage ability of the communication link; at the same time, upgrade the data interaction content, upgrade from single coordinate instruction transmission to real-time sharing of 3D global situation map, and strengthen the autonomous global decision-making ability of unmanned vehicles.
3. Optimize the motion control strategy. On the basis of traditional PID control, introduce adaptive control and model predictive control algorithms, optimize the traveling and manipulator action control logic of unmanned vehicles, improve the motion flexibility and action smoothness of equipment, add the manipulator compliance control function, and improve the safety of material grasping and delivery.
4. Expand the cluster collaborative operation mode. On the basis of the existing single UAV with single unmanned vehicle, develop a multi-UAV and multi-vehicle formation collaborative control system to realize synchronous reconnaissance in multiple areas and distributed delivery of large quantities of materials, complete advanced functions such as automatic task allocation and formation collaborative obstacle avoidance, and upgrade the system from single-machine collaboration to a cluster intelligent operation platform, further exploring the application potential of the unmanned air-ground collaborative system.

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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.

REFERENCES

[1] Liu Feng, Lv Qiang, Guo Feng, et al. Research on autonomous UAV VSLAM based on ROS. *Modern Defense Technology*. 2016;44(6):61–66. (in Chinese)
[2] Liu Wei. Development status of drones in China and their application in logistics support. *Wireless Internet Technology*. 2020;17(3):5–6. (in Chinese)
[3] Zhai Zheng, He Ming, Zhu Zihan, et al. Path planning method for air-ground cooperative unmanned system reconnaissance. *Journal of Computer Applications and Software*. 2026;43(4):296–302. (in Chinese)
[4] Liang Ying, Zhou Ling, Cao Chongchong, et al. Design and implementation of air-ground cooperative intelligent firefighting system. *Development & Innovation of Machinery & Electrical Products*. 2026;39(1):23–26. (in Chinese)
[5] Zhang Xiaolei, Liu Xiangquan, Chen Zhaopeng, et al. Research on robot visual servo control algorithm based on fuzzy adaptive PID. *Manufacturing Automation*. 2024;46(6):146–151. (in Chinese)
[6] Wang Haoyu. Research on autonomous navigation and obstacle avoidance technology for ground unmanned vehicles. *Machinery Design & Manufacture*. 2023;(8):189–192. (in Chinese)
[7] Chen Yuxuan. Research on application of binocular vision target positioning technology in UAVs. *Electronic Measurement Technology*. 2025;48(2):78–83. (in Chinese)



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