

Unmanned Aerial Vehicles in Disaster Rescue: A Systematic Review and Integrated Framework of Functions, Technologies, Institutions, and Trends

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ABSTRACT

Global extreme climate disasters are occurring with increasing frequency. In China, about 100 million people are affected by natural disasters every year, and the direct economic losses exceed 34.54 billion yuan every year. The traditional ground response has some problems, such as slow response, inability to enter complex terrain, high risk of injury and death, and inability to use communication after disaster, which does not meet the needs of modern accurate emergency response. Unmanned aerial vehicles (UAVs) take advantage of its mobility and ubiquity, in all stages of rescue, including disaster investigation, air communication, material handling, asking for help and post-disaster assessment. In this study, English and Chinese literatures from 2015 to 2025 were selected from the databases of Web of Science, Scopus, PubMed and CNKI according to the systematic review guide of PRISMA 2020. Combined with the comparative case analysis of typical disaster in China (Jishishan earthquake, Zhuozhou flood) and abroad (Nepal earthquake, California wildfires), we construct a four dimensional integrated analytical framework encompassing Functions, Technologies, Institutions, and Trends. The results show that UAV has established five closed-loop rescue function systems: reconnaissance and monitoring, communication support, material transportation, search and rescue and post-disaster evaluation. However, if it is to be used on a large scale, it is limited by three technical bottlenecks (cruising range/payload, environmental adaptation and cluster deployment) and four shortcomings of institution (airspace approval procedures, industry standards, cooperation between provincial offices and data privacy). The global emergency response UAV market is growing at a compound rate of 16.6% per year. Artificial intelligence, the reform of low-level economy and the modernization of emergency response system will profoundly change the way of low-level assistance development. The framework will correct the fragmentation of existing research and provide theoretical basis and practical path for embedded policy formulation, instrument R&D and field standard rescue work.

Keywords: Unmanned Aerial Vehicle (Uav); Disaster Relief; Low-Altitude Rescue; Emergency Management; Systematic Review; Four-Dimensional Integrated Framework

1. INTRODUCTION

1.1 Research Background

Due to global warming, earthquakes, floods, typhoons, landslides and other complex disasters are increasing. Roads are broken, base stations are shut down, and a series of secondary disasters are making rescue efforts more difficult ^[1]. According to the statistics of the Ministry of Emergency Management, about 100 million people are affected by disasters in China every year, and the direct economic loss exceeds 345.4 billion yuan. During major disasters, the problem of rescue often arises: “the terrain does not fit, the information is interrupted, the road of supplies does not pass.” There are four major drawbacks to the old-fashioned way of rescuing people and machines that are used on the ground. The first is that it takes longer to collect or clean up broken things, which leads to shorter “golden rescue times.” The second is that there are places where ground teams cannot get in, such as islands isolated by floods or the ruins after earthquakes. The third is that secondary disasters, such as aftershocks and flash floods, are in danger of causing injury to the rescue team. Fourth, the overall information on the disaster lags, and there is no data that can be used immediately when commanding. New low-altitude rescue methods are urgently needed to compensate for the existing systems. At the scene of Qingshan earthquake and Zhuozhou flood in 2023, we found that UAV has changed from an auxiliary tool to an important tool for disaster relief. In Jishishan, within 2 hours after the earthquake, UAV made a map of the whole area and set up an air base station. In Zhuozhou, UAV has been working for 72 hours, dropping materials and using infrared rays to find people,

helping people in isolated places. Through the county-level emergency test, it was found that the delivery of emergency medical supplies by UAV was 7.98 minutes ahead of schedule on average, and timely delivery of AED could greatly improve the survival rate of patients with cardiac arrest, and low-altitude flight had obvious rescue effect [2].

1.2 Research Significance

Theoretical Value

UAV emergency response is an interdisciplinary field spanning aviation, communications, artificial intelligence and public management. Most of the research to date has focused on individual algorithms or single disaster scenarios, and there has been insufficient framework to unite multiple perspectives. In this paper, we will create an integrated framework consisting of four dimensions connecting functions, technology, institutions, and industry trends, and advance the integration of many disciplines. Furthermore, the introduction of the PRISMA systematic review methodology in the area of low-altitude emergency response and standardization of literature search and coding procedures will increase the rigor and reproducibility of research in this area [3].

Practical Value

Using 58 unique case sets of domestic UAV rescue activities owned by China Fire and Rescue Academy, this study summarizes the standard workflow, and provides step-by - step practical suggestions for emergency management departments, R & D enterprises, and front-line rescue teams: Provide empirical evidence for airspace reform and industry standard creation; We will provide guidance on key technologies such as time of flight, cluster collaboration, and intelligent recognition; and provide work guides that can be emulated by local fire departments and private rescue organizations to increase the efficiency of disaster response by everyone [4].

1.3 Research Questions and Paper Structure

In previous studies, more attention was paid to technology, while the system was neglected. In addition, the research is meticulous, and the relationship between function, technology, policy and industrial trends is not clear. There are three central research questions in this paper. First, what is the overall rescue function module of UAV and its actual effect. Second, the mechanism that can restrict technology and system, and what is the relationship between them? The third is how to establish a unified framework to make the low-altitude rescue system generally better.

This paper has six chapters. In Introduction, Literature Review, Research Framework and Methods, Analytical Discussion, Conclusion and Prospects and References.

2. LITERATURE REVIEW

2.1 International Research Trajectory and Industrial Landscape

The emergency research of UAV involves five fields: aviation, communications, AI and emergency management. From 2015 to 2025, research went through three stages: basic hardware and flight control review in 2015-2018, effect investigation in various dangerous situations in 2019-2022, and cluster testing after 2023 [5].

There are great differences in regional research: North America (FEMA) attaches importance to sending large-scale UAV cluster [6]; Europe is committed to cross-border airspace coordination and air self-help organization network; Moreover, China, Japan and South Korea focus on the use of earthquakes and floods at the ground level. According to Industry data, the global emergency UAV market is expected to be US\$470.5 million in 2024 and US\$1.607 billion in 2032, with an annual growth rate of 16.6%. The country's low-altitude policy continues to show the benefits of growth, with North America accounting for 38.6%, Europe accounting for 26.4% and Asia Pacific accounting for 22.8% [7].

2.2 Evolution of Research on Rescue Functions

Previous research only did mapping after disaster [8]. After that, two kinds of division methods appeared. One is divided according to the emergency stage of "prevention, readiness and recovery", and the other is divided into five modules (reconnaissance, communication, transportation, search and rescue and evaluation) according to the machine function. In the database of 58 disaster cases in China, the difficulties of their respective functions have been written down. But up to now, paper has not well analyzed the situation that these five functions run together, nor has it produced a system that can help in the whole cycle [4][9].

2.3 Technological Research: Status and Gaps

Technological literature has the highest proportion, and its main directions are lightweight endurance, path planning, infrared recognition and multi UAV coordination. The improved A and multi-object optimization calibration show very good navigation accuracy in simulation^[10]. The technologies of aviation metabolism base station and spectrum scheduling have gradually matured. Cluster scheduling using graph neural network can achieve more than 85% simulation efficiency^[11].

There are still great challenges. Most algorithm are confirmed to be not feasible in simulation, and they are not tried under the conditions of strong wind or electromagnetic interference in real world, so there is a big gap between simulation and practice. In addition, most researches optimize various technologies separately, and do not sum up the constraints of endurance, recognition and coordination as a whole solution^[12].

2.4 Institutional Research Gaps

Compared with many researches on technology, there are few researches on airspace, standards and data security. The existing research only points out on the surface that it is difficult to license airspace, equipment is inappropriate, cross-regional cooperation is difficult, and privacy will be leaked. They have not deeply analyzed the formation mechanisms of institutional constraints, nor explored the bidirectional interaction between technology and policy, nor proposed adaptive solutions in the context of low-altitude economic reform. Institutions represent the largest research gap in this field^{[13][14]}.

2.5 Deficiencies in Current Research and Contributions of This Paper

Three major deficiencies exist in current research: unbalanced dimensional focus—overweight on technology and underweight on institutions; fragmented perspectives lacking a holistic integration framework; and insufficient locally adapted research that does not account for China’s specific airspace regulations and disaster characteristics. This paper innovatively constructs a four-dimensional integrated framework (Functions—Technologies—Institutions—Trends) and combines PRISMA systematic review with multi-case comparative analysis to remedy the fragmentation.

3. RESEARCH FRAMEWORK AND METHODS

3.1 Logic of the Four-Dimensional Integrated Framework

The framework takes UAV rescue functions as the core hub, with technologies and institutions as internal and external constraints, and long-term industrial trends as the developmental orientation, forming a closed-loop logic: disaster response needs drive the emergence of diverse operational functions; functional capabilities are constrained by technological limits such as endurance and recognition; airspace regulations and industry standards determine whether equipment can be rapidly deployed; and low-altitude economy, AI, and emergency reforms, in turn, drive technological iteration and institutional optimization. The four dimensions mutually constrain and synergistically enable each other.

3.2 PRISMA Systematic Literature Review

The full literature processing strictly follows the PRISMA 2020 guidelines^[3]:

1. **Databases and time frame:** Web of Science, Scopus, PubMed, CNKI; from January 1, 2015 to December 31, 2025.
2. **Search strings:** English: (UAV OR drone) AND disaster AND rescue; Chinese search terms: UAV, disaster rescue, low-altitude rescue.
3. **Selection criteria:** Included peer-reviewed literature with empirical disaster data; excluded commercial promotion, purely military applications, and duplicate submissions.
4. **Screening results:** Initial retrieval yielded 1,126 records; after removing 879, 247 articles were finally included (168 English, 79 Chinese). Structured coding was applied to scenarios, technologies, and policy viewpoints.

3.3 Multi-Case Comparative Analysis

We chose Jishishan earthquake (6.2) in China, the flood in Zhuozhou, Nepal earthquake and California wildfires in the world for investigation. Using the same analysis method of “disaster background--UAV configuration-operation effect-technical system topic”, we compared the Chinese and foreign airspace permission and cluster dispatch modes, and summed up the development path that conforms to China’s low-altitude rescue system^[15].

4. ANALYTICAL DISCUSSION

4.1 Five Fully Coordinated Full-Chain Rescue Functions

4.1.1 Reconnaissance and Monitoring (Prerequisite foundation)

Uavs using “multi spectral sensors” and “synthetic aperture radar” can quickly create 3D terrain models. In Jishishan, a map of the whole area was made within 2 hours after the earthquake. In rainy and flood seasons, regular inspection of dams can quickly find the danger of landslides and piping, and can transmit accurate location data to the commander’s decision. High-resolution optical cameras can shoot the whole central position within a few minutes after the disaster, and can take fine photos in centimeters, which is very useful for the initial investigation of the size of the disaster.

4.1.2 Communication Support (Lifeline backup)

Fixed-wing UAV uses aviation mobile base stations, each of which can cover more than 100 square kilometers. When Zhuozhou was flooded, they stuck to the communication in remote areas for more than 72 hours, which solved the big problem of the interruption of emergency calls and material coordination information ^[16]. UAV for relay can move at an altitude of 5,000m for more than 8 hours, supporting the relay of 4G/5G signals, successfully overcoming the “information island” formed by the damage of ground base stations, and providing uninterrupted communication connection for rescue command.

4.1.3 Material Delivery (Life-sustaining support)

Use accurate airdrop to deliver AED, drugs and life-saving tools, and connect the “last mile” when the road is cut off. Large things will get rid of tent and portable generators to meet the basic needs of survival. Multi rotor UAV can be accurate to centimeters in hover mode, and the goods transported at a time are 5 kg to 50kg, which has well solved the problem of emergency materials in places isolated by floods and earthquakes.

4.1.4 Search and Rescue (Core function)

Infrared thermal imaging will go through smoke and shallow water to find trapped people. At night, searchlights and loudspeakers can also be used together, so the number of people looking for them on the ground will be reduced all the time. Very accurate infrared sensors can also find a small temperature thermal signal of 0.1°C, and accurately tell the location of people trapped in rubble and dense forests. The search efficiency is more than three times better than the previous manual search method, which can effectively shorten the prime time when help is very important.

4.1.5 Post-Disaster Assessment (Reconstruction support)

With lots of aerial surveys at a time, it automatically counts destroyed buildings and farmland to create a standard damage report in no time. It also shortened the time required to plan for reconstruction, replacing the method of people going to the site and investigating ^[17]. UAV based 3D reconstruction can create a complete digital twin of an affected area within 24 hours. This gives us a scientific, numerically based basis for accurate damage calculations and for the allocation of resources for reconstruction.

These five functions form a closed loop chain of “reconnaissance → communications → delivery → search and rescue → evaluation,” covering the entire period of an emergency.

4.2 Three Core Technological Bottlenecks

First of all, the limit of flight time and transportable weight. The flight time of mainstream multi rotor UAV is only 30~60 minutes, and the small body can only carry less than 10kg. This is not enough for a large-scale and long-term search, and it is not enough to transport heavy objects. The method of using hydrogen energy and solar is unreliable because it costs a lot of money, so it cannot be widely used. Because battery’s energy density can only be improved by less than 5% a year, there is a big gap between it and the demand of emergency sites that want to fly for a long time. This is the biggest reason why low-altitude rescue is difficult to play a role.

Secondly, the ability to cope with various environments and the ability to distinguish things are not enough. If there is wind or rain or electromagnetic interference, the flight will become unstable or the signal will be interrupted. The recognition function of AI often mistakes people for animals where rubble and grass are mixed. In addition, because the function of avoiding obstacles is not easy to fail, the search work relies heavily on manual confirmation on the back ^[12]. In the actual disaster scene, due to the influence of smoke, dust, rain and snow, the infrared imaging will be weakened by

30%~50%, and the distance and accuracy of finding the target will be very low. The current sensing algorithm is far from the intensity required by the actual field.

Third, the gap between algorithmic simulation and practical deployment. Path planning and cluster scheduling algorithms show excellent simulation results, but real rescue operations involve communication delays, individual UAV failures, and airspace conflicts; current fault-tolerance mechanisms are poorly adapted. There is no uniform standard for air ground coordination, and human machine synergy is not fully utilized ^[11]. Simulation environment usually assumes ideal communication and stable wind conditions, but in real disaster sites, the wind speed may exceed 15 m/s and the packet loss rate may reach more than 20%. Therefore, most algorithm actually become less good, and this gap is difficult to make up.

4.3 Four Persistent Institutional Constraints

First, airspace has a tight schedule. Usually, the licensing procedures are very long, and the authority to temporarily open airspace in the event of a disaster is not enough. The role of what to do among civil aviation, emergency management and public security is not clear. In Zhuozhou, there are many teams working in the same area, but there is a danger of conflict because there is no instruction, or the same work is repeated ^[16]. At present, the General Aviation Flight Control Regulations, the exception in an emergency is only the principle, and there is no mechanism for issuing permits immediately in the local area.

Second, there is no industry standard. Each manufacturer's equipment protocol and data format are different. Because there is no uniform standard for pilot training and emergency actions, different teams can do different things. At present, there is no UAV professional technical calibration system for emergency rescue in China. Due to the different interfaces of equipment, communication frequency bands and data formats, various UAVs can't cooperate well when working together, and it is difficult for many UAVs to run together.

Third, cross-regional cooperation is weak. Rescue forces are divided into fire departments, emergency management agencies and civil organizations. Because there is no dispatch of UAV cluster in emergency plans, the cost of cooperation across disaster areas is very high. Because there is no mechanism to move equipment immediately across provinces and cities, it is easy to be in a passive state when disasters spread, like "the water in the distance can't put out the fire". Fourth, the limitation loopholes of data privacy. Take sensitive photos of residential areas through aerial surveys. The lines of collection, preservation and sharing are not clearly defined in the current rules, so it is difficult to give consideration to the needs of disaster relief and the privacy of citizens ^[14]. The aerial photography data in the disaster area contains a lot of information and property details that individuals can determine. Because the Personal Information Protection Law has no specific operating guidelines for exceptions in emergencies, people on the spot will be troubled by legal rules when collecting data.

4.4 Three Major Development Trends in Low-Altitude Rescue

1. Various technologies are deeply integrated. High-energy battery, 6G low-delay communication, multimodal AI and edge computing are now used at the same time, which can realize UAV's automatic flight, long-distance collective operation, and a little intelligent judgment system for the sky and the ground ^[18]. Even if communication is interrupted, the automatic judgment system can find the target, plan the road and divide the work by itself, and the accuracy of rescue in harsh environment is greatly improved.
2. Good effects brought by low-altitude economic policies. The reform of airspace classification makes it easy to temporarily permit in an emergency. Through the leasing mechanism named DaaS (Drone as a Service), the cost of purchase and maintenance is reduced. The unified management system of urban air mobility is also being improved ^[19]. By the end of 2025, more than 10 provinces and cities in China have started the experiment of low-altitude airspace management reform, and the temporary flight permission time of emergency UAV has been shortened from 72 hours to less than 2 hours.
3. Professional upgrade of emergency response system. National, regional and state-level UAV rescue teams are being formed; UAV also began to be used for usual training; New scenes such as maritime rescue, urban high-rise accidents and cross-border cooperation are also increasing. The "Fourteen-year Plan" of Ministry of Emergency Management clearly regards cultivating UAV's emergency response capability as an important project. In China, more than 200 professional UAV rescue teams have been set up, equipped with more than 3,000 UAVs of various types.

Technology, airspace reform and emergency modernization help each other, transforming UAV from an auxiliary tool into a central emergency equipment.

5. CONCLUSION AND PROSPECTS

5.1 Core Research Conclusions

Empirical findings: ① UAV has five modules that work together: reconnaissance, communication, material delivery, search and rescue, and evaluation. It has achieved many effects in major disasters, shortened the rescue time and reduced the number of victims. ② The weight that can fly for a long time, the ability to distinguish the surrounding environment and the simulation experiment for practice are three technical difficulties. ③ The use, rules, ways of cooperation and provisions of privacy of empty space, four institutional problems that have always hindered its widespread use, have been considered very little in previous studies. ④ AI, low-altitude economy and emergency modernization can solve these two problems together, and the low-altitude rescue of smart systems must be such a trend.

Theoretical contributions: This paper has formulated a comprehensive framework from four aspects, filling the theoretical gap of systematic research in this field. In addition, PRISMA method is introduced into low-altitude emergency research, and the structure of the interaction between technology and system is clarified with 58 domestic cases.

5.2 Tiered Practical Recommendations

For emergency management authorities:

Transfer the authorization to the municipal emergency management department to simplify the temporary airspace approval for disasters. In addition, between civil aviation and emergency agencies, a platform is always made to share information with the coordination mechanism.

Lead the production of national standards for UAV for emergency rescue. The standards include equipment interface rules, data format conventions, pilot qualification, operation steps in emergency, etc.

The detailed implementation rules for privacy protection of post-disaster sky data are given. Define the data collection boundary in case of emergency, the standard of data can not be determined, and the time limit for deleting data.

Incorporate the dispatch of UAV groups and air and ground cooperation into the standard procedures of emergency plans at all levels. It will also be included in the annual emergency training evaluation system.

For R&D enterprises:

There are three important things to do: solid state batteries with high energy density, airframe which is light and can carry a lot of luggage, and infrared recognition algorithms which can work reliably even in complex places.

According to different disasters such as earthquake, flood and mountain fire, special models and model payments are made.

Create a standardized multi-UAV composite distribution platform so that all types of UAVs can be commanded together.

Carry out large-scale disaster test in real environment, collect field data of wind, electromagnetic interference and obstacles, do a good job in algorithm, and eliminate the gap between simulation and reality.

For frontline rescue teams:

Based on domestic cases such as Jishishan and Zhuozhou, the standard operation manual and emergency flow chart of five functional modules are compiled.

Establish regular pilot training and annual re-certification mechanism, and also conduct professional drill for bad weather and night search activities.

Formulate cross-team equipment sharing and personnel dispatching rules, so that regional rescue forces can immediately gather together to command.

5.3 Research Limitations and Future Directions

Limitation: only the literature of Chinese and English is investigated, excluding the research of other languages. Organizational analysis uses the document that everyone can see, and there is no operational data in the organization.

Trend prediction is based on current policy and technology. If disruptive innovation comes, the development path may change.

Future research directions:

Formulate an index mechanism that can be expressed by numbers to measure the importance of institutional constraints on the efficiency of rescue.

Establish a model to evaluate whether the three levels of function, technology and system are consistent.

We have been pursuing the results of experimental measures for airspace reform and extracting other experiences that can be emulated.

This paper makes an in-depth study on the legal responsibility division method and ethical management mechanism of collective rescue system using AI.

Promote the research and training program of University of Technology, and make China's intelligent and systematic disaster emergency response capability reach a higher level.

REFERENCES

- [1] IPCC. Climate Change 2022: Impacts, Adaptation and Vulnerability: Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change[R]. Cambridge: Cambridge University Press, 2022. DOI: 10.1017/9781009325844.
- [2] Ministry of Emergency Management of the People's Republic of China. Statistical Bulletin on Basic National Natural Disaster Situations [R]. Beijing, 2024.
- [3] Page MJ, McKenzie JE, Bossuyt PM, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ. 2021;372: n71. doi:10.1136/bmj.n71.
- [4] China Fire and Rescue Academy. Report on the Construction of a Typical Case Database for UAV Emergency Rescue [R]. Beijing, 2024.
- [5] Liu J, Wang Y X, Gong Q. A review of UAV applications in natural disaster emergency rescue[J]. Acta Aeronautica et Astronautica Sinica, 2023, 44(12): 627 645.
- [6] FEMA. Unmanned aircraft systems in emergency response: Operational guidance [R]. Washington D.C., 2023.
- [7] Credence Research. Emergency response drone market size, share & trends analysis report [R]. 2024.
- [8] Zhao Y, Li D R. Application of remote sensing UAVs in rapid earthquake damage assessment[J]. Geomatics and Information Science of Wuhan University, 2022, 47(5): 675 683.
- [9] Restas A. Drone applications for supporting disaster management[J]. World Journal of Engineering and Technology, 2015, 3(3): 316 321.
- [10] Saha S, Rakshit A, Sarkar A. A review on path planning algorithms for UAVs in disaster management[J]. Archives of Computational Methods in Engineering, 2024, 31(1): 323 349.
- [11] Huang C, Zhang J, Liu Z, et al. Multi UAV cooperative task allocation in dynamic scenarios using deep graph neural networks[J]. IEEE Transactions on Intelligent Transportation Systems, 2024, 25(3): 2456 2469.
- [12] Shakhathreh H, Sawalmeh A H, Al Fuqaha A, et al. Unmanned aerial vehicles (UAVs): A survey on civil applications and key research challenges[J]. IEEE Access, 2019, 7: 48572 48634.
- [13] Shan C C, Xue L. Modernization of emergency management systems: Challenges and pathways[J]. Management World, 2023, 39(6): 1 12.
- [14] Chen Z J, Tang J H. Low altitude economy development and airspace management reform[J]. Strategic Study of CAE, 2024, 26(2): 89 98.
- [15] Erdelj M, Natalizio E, Chowdhury K R, et al. Help from the sky: Leveraging UAVs for disaster management[J]. IEEE Pervasive Computing, 2017, 16(1): 24 32.
- [16] Zhang H, Liu Y. UAV emergency response in urban flood disasters: A case study of Zhuozhou[J]. China Emergency Management, 2024(2): 34 42.
- [17] Wang F Y. Parallel intelligence and emergency management: Prospects of intelligent technology in disaster response[J]. Acta Automatica Sinica, 2023, 49(8): 1572 1585.
- [18] General Office of the State Council. Several opinions on promoting the development of the low altitude economy [Z]. Document No. 12 [2024] of the State Council, 2024.
- [19] China Academy of Information and Communications Technology. Low altitude economy white paper (2025) [R]. Beijing, 2025.