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Original Paper

Research on Unmanned Delivery Issues and Optimization in the Context of Low-altitude Economy

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Abstract

Since the 21st century, with the continuous advancement of intelligent technology and the rapid development of aviation technology, the low-altitude economy has gradually attracted global attention and importance, becoming a new growth point for high-quality economic development in various countries. As a new economic form with an activity range of below 1,000 meters, the unmanned delivery system, with its unique advantages of breaking through ground traffic restrictions and improving logistics efficiency, has become one of the most commercially promising application scenarios in the low-altitude economy. The unmanned delivery system is reconfiguring the traditional logistics and delivery system. Technological iterations and policy breakthroughs are driving the unmanned delivery system into a period of rapid development. The integrated application of 5G networks, artificial intelligence, and high-precision navigation has significantly enhanced the autonomous decision-making capabilities of unmanned systems. However, it is worth noting that the current unmanned delivery still faces technical bottlenecks such as short battery life and poor adaptability to adverse weather, as well as systemic challenges like incomplete airspace management rules and high operating costs, which restrict the industry from expanding on a larger scale.

Keywords

Low-altitude economy, Unmanned delivery, Optimization strategy

1. Introduction

In recent years, the low-altitude economy, as an emerging economic form, has developed rapidly. Its core lies in utilizing low-altitude airspace resources to carry out various economic activities. Against this backdrop, unmanned delivery, as an important application scenario of the low-altitude economy, is experiencing unprecedented development opportunities. Unmanned aerial vehicle (UAV) through intelligent and automated logistics solutions, effectively address the pain point of the "last mile" in traditional delivery, demonstrating unique advantages in medical emergency, mountainous area transportation, and urban express delivery.

Currently, unmanned delivery has entered the stage of large-scale application. In the field of UAV delivery, many domestic and foreign enterprises have achieved commercial operation. Amazon Prime Air has completed hundreds of thousands of test flights in the United States, and JD Logistics has built the world's first intelligent UAV delivery network in China, covering remote mountainous areas and offshore islands. However, the development of unmanned delivery still faces multiple challenges. Technically, the insufficient energy density of existing lithium batteries leads to a general flight duration of less than one hour for UAVs, the reliability of autonomous driving systems in rainy and snowy weather is insufficient, and the dynamic obstacle avoidance capability in complex urban environments needs to be improved. In terms of safety, the long certification cycle and inconsistent standards for airworthiness restrict the speed of product launch, and the low-altitude traffic management system has not yet formed a unified standard. Measures to prevent theft and damage during transportation need to be improved. In terms of cost, high-performance sensors and computing units increase equipment costs, and professional operation and maintenance teams and insurance fees keep operating costs high. All these factors restrict the large-scale popularization of unmanned delivery.

2. The Concept

2.1 The low-altitude Economy

Low-altitude (below 1 km of the horizontal line) economy refers to the economic activities related to the civil aviation flight industry that take place within the non-high-altitude airspace, mainly including flying cars, model aircraft, unmanned aircraft, hot air balloons, as well as the application of related industries, and the hardware setup providing basic aviation services for these industries, such as the training industry for helicopter pilots. China has successively promulgated relevant policies and legal documents to vigorously support the vitality of the low-altitude economy and expand GDP growth points by increasing the scope of opening up to low-altitude airspace (Sun, 2024). In 2017, the National Development and Reform Commission issued the "Development Plan for General Aviation in the '13th Five-Year Plan'" and the "Implementation Opinions on Building General Aviation Industry Comprehensive Demonstration Zones". In 2021, the "Outline for the National Comprehensive Transportation Network Planning" pointed out that "it should strengthen cross-industry cooperation in transportation with modern agriculture, production manufacturing, commerce and finance, develop transportation platform economy, hub economy, channel economy, and low-altitude economy".

2.2 The Drone Delivery

2.2.1 The Drones Delivery Network

The unmanned aerial vehicle (UAV) delivery network refers to the transportation and distribution of goods using UAVs, forming an aerial logistics network covering a certain area. The core of the UAV delivery network lies in replacing traditional ground transportation tools with UAVs to achieve point-to-point rapid cargo delivery. Currently, the composition of the UAV delivery network mainly includes the following types:

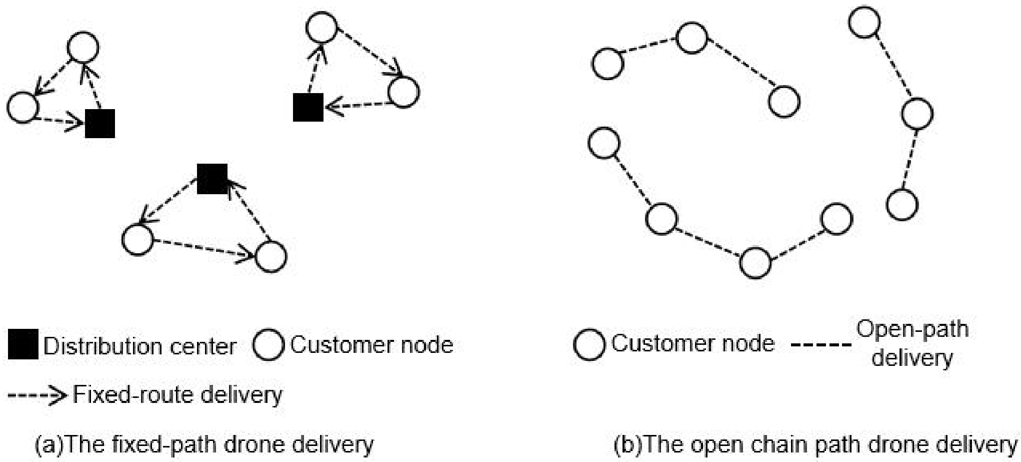

Figure 2.1 Drone Delivery Network Model

As can be seen from Figure 2.1, fixed-path unmanned aircraft delivery is when the known package information is provided, and the unmanned aircraft loads the goods at the distribution center and delivers to the designated customer point, with lower flexibility. Open-loop path unmanned aircraft delivery is when each unmanned aircraft departs from its current position, visits some nodes in sequence, and finally stops at the last visited node to wait, ensuring that all nodes are visited once.

2.2.2 The Analysis of Mode Characteristics

Using drones as the main mode of transportation is different from other transportation methods (such as truck transportation, public transportation, etc.). It has the following characteristics:

(1) Convenient and efficient: Drones are not affected by ground traffic conditions and can quickly traverse congested urban streets or remote mountainous areas, directly delivering goods to the destination. In addition, the flight speed of drones can be adjusted according to needs, thereby shortening the delivery time.

(2) Resource conservation: Drones do not consume fuel and only use electricity for propulsion, so they have significant advantages in terms of environmental protection. At the same time, the operation and maintenance costs of drones are relatively low, which can effectively reduce logistics costs.

(3) Flexible scheduling: Drone delivery is not restricted by fixed routes and can adjust flight routes and delivery tasks according to actual needs, with high flexibility. This helps to deal with emergencies and meet special transportation needs.

(4) Real-time monitoring: Drone delivery can be monitored and tracked in real time, making it easy to fully control and manage the delivery process. In addition, drones can be equipped with high-definition cameras and sensors for tasks such as goods inspection and quality assurance.

(5) High safety: Drone delivery can reduce the involvement of human intervention and lower the risk of human safety. At the same time, drones can perform precise positioning and intelligent control, improving the safety and accuracy of delivery.

(6) Extensive: The continuous advancement of technology and changes in market demand have led to the significant expansion potential of drone delivery. For example, drones can carry more goods and fly over longer distances.

3. The Analysis of Drones' Delivery Issues in Low-altitude Economic Distribution

3.1 The Network Issues

With the acceleration of urbanization, the service radius of cities continues to expand, and the logistics distribution network also extends to a wider area. This expansion brings convenience to residents while also placing higher demands on the logistics distribution system. Among them, the unmanned aerial vehicle (UAV) delivery technology faces two core challenges: the balance between endurance and payload capacity, and the stable and reliable communication network guarantee.

From a technical perspective, the traditional radio remote control method is no longer able to meet the operational needs of modern urban logistics UAVs. On one hand, the transmission quality of wireless signals in the complex urban environment is easily affected by factors such as high-rise buildings and electromagnetic interference; on the other hand, as the delivery distance increases, the delay and stability of the remote control signal become increasingly prominent. These problems not only affect the delivery efficiency but also may pose a threat to flight safety (Zhou et al., 2021).

Communication network quality, as the key support of the UAV logistics system, whose stability directly determines the reliability of the delivery service and the user experience. Currently, it is urgently necessary to build a comprehensive, rapid response, and highly resistant to interference dedicated communication network to ensure the precise navigation and real-time control of UAVs in complex urban environments. This requires integrating advanced technologies such as 5G communication and edge computing to establish a multi-level network guarantee system.

3.2 The Diverse Customer Demands Increase the Difficulty of Delivery

The urban logistics distribution sector is currently undergoing unprecedented changes and challenges. With the vigorous development of e-commerce, the unmanned aerial vehicle (UAV) delivery system has become an important component of the modern logistics system. The current market presents three notable characteristics: Firstly, the service targets cover the entire spectrum of demands from enterprise-level customers to individual consumers; Secondly, due to the periodic bursts of e-commerce promotional activities and the continuous growth of consumers' personalized demands, the delivery demands exhibit a distinct fluctuating feature; Finally, the delivery scope is extending from the core urban areas to the broader surrounding areas of the city.

This structural change in the demand side poses higher requirements for the UAV delivery system. On one hand, a highly flexible intelligent scheduling system needs to be constructed to cope with the drastic fluctuations in order quantities; on the other hand, standardized service processes must be established to ensure that customers of different scales and regions can all receive consistent high-quality service experiences. It is particularly noteworthy that the surge in personalized delivery demands has made the traditional batch delivery model unable to meet market demands, which requires logistics enterprises to invest more in UAV resources and optimize the distribution network layout.

From the perspective of operational efficiency, this one-to-one precise delivery mode not only improves service quality but also brings significant pressure on resource investment. How to balance service quality and operational costs has become a key issue that drone logistics enterprises urgently need to solve. This requires systematic innovation from multiple dimensions such as technological upgrading, process optimization, and resource allocation.

3.3 The Range Issue

The single flight range of a drone refers to the maximum distance it can travel when fully charged. As an important component of the modern air logistics system, the power performance of drones directly determines their operational radius and transportation efficiency. Currently, the mainstream commercial drones generally use lithium polymer batteries as their energy source. Although this high energy density power source has the advantage of lightweight, its inherent energy storage limit is always a key factor restricting flight performance.

When carrying out cargo delivery tasks, the actual flight range of the drone is affected by multiple variables: including but not limited to battery degradation, environmental temperature fluctuations, load changes, and flight route planning. Especially when performing high-frequency tasks such as urban end-point deliveries, the issue of energy management becomes particularly prominent. Engineering practice has shown that there is a clear positive correlation between battery capacity and flight range, but this relationship is often constrained by the non-linear discharge efficiency curve.

3.4 The Charging Problems

In the context of the rapid development of drone delivery technology, the charging issue has become a key bottleneck restricting the industry's growth. The reliability of charging facilities and the rationality of charging strategies directly determine the operational efficiency and service quality of the drone delivery system. Currently, the planning and construction of drone charging infrastructure worldwide are still in the exploratory stage and have not yet formed mature solutions.

From a technical perspective, the drone charging system needs to address three core issues: the network layout of charging stations, the intelligent scheduling of charging times, and the standardized construction of charging equipment. If these problems cannot be effectively resolved, it will significantly reduce the reliability and economy of the drone delivery system, especially in small and medium-sized cities with relatively weak infrastructure, where this impact is more prominent.

3.5 The Cost Issues

Currently, although the application of drone technology in the logistics distribution sector shows the potential to replace human labor, the issue of its overall operational costs urgently needs to be addressed. From an industrial perspective, the cost composition of the drone delivery system is far more complex than it appears.

Firstly, hardware investment is a fundamental expenditure. The procurement cost of high-performance logistics drones remains high, and the cost of their precision components and specialized payload systems far exceeds that of traditional delivery tools. More crucially, such equipment requires the establishment of a professional maintenance system, including regular maintenance, component replacement, and system upgrades. These subsequent expenditures are often underestimated by enterprises.

Secondly, the construction of the talent team forms a continuous expenditure. Even with the adoption of intelligent operating systems, a team with aviation knowledge and proficiency in drone operation technology is still needed. The training and retention costs of such talents are significantly higher than those of ordinary logistics personnel, especially in the context of increasingly strict safety supervision, where the salary levels of professional qualification personnel continue to rise.

Intelligent transformation is also a double-edged sword. Although automated systems can reduce reliance on human resources, the initial research and development investment is huge. Logistics enterprises need to bear high costs such as algorithm development, system integration, and scenario testing. The investment during the technology accumulation period may lead to an increase in short-term costs instead of a decrease.

4. The Optimization Strategies for Unmanned Delivery in the Low-flying Economy

Under the wave of digital transformation, intelligent security systems and automated logistics equipment have gradually achieved industrialized applications. However, most products on the market still have significant drawbacks such as single functionality and insufficient scene adaptability. According to the research data of Lu Ning et al. (2021), the independent operation mode of traditional intelligent access control and unmanned stations not only leads to low system resource utilization but also causes an additional 15%-20% operating cost. The study adopts a systematic design, with the unmanned aerial vehicle mobile platform as the core of the design, and through the delivery module, to address different scenarios to achieve different functions and improve the environmental adaptability of the equipment.

This paper addresses the above issues and proposes a solution for the unmanned aerial vehicle mobile platform. Based on the powerful power system and attitude control system of the unmanned aerial vehicle, the unmanned aerial vehicle can operate without the limitations of climate and roads, greatly reducing the transportation time and thus improving work efficiency. The unmanned aerial vehicle mobile platform has high flexibility, so the application of unmanned aerial vehicles has broad market prospects.

4.1 The Further Optimize the Design of the Unmanned Aircraft

During the design process, the equipment adopts a quad-rotor design, which gives the equipment a powerful power system, an advanced attitude adjustment system, no road traffic restrictions, the ability to quickly reach the destination, high flexibility, and stable operation in complex environments. By carrying high-precision map data and GPS, Beidou and other satellite positioning systems, the unmanned aerial vehicle mobile platform can accurately perform path planning, and use the RTK module to correct the user's measurement data to improve GPS positioning accuracy. Through precise modeling, estimation and elimination of various error values of the observed values, it can ultimately achieve real-time centimeter-level positioning accuracy. The unmanned aerial vehicle mobile platform also has CMOS image sensors, DSP digital processing chips, and RTK modules. It uses data collection from the surrounding environment to communicate with the external environment, and then processes the collected information to identify road conditions and obstacles (Han et al., 2021), thereby achieving precise path planning for the unmanned aerial vehicle. With the development of 5G, the unmanned aerial vehicle platform has high-definition video transmission functions, enabling ultra-long-distance real-time monitoring, and improving the operational efficiency of the unmanned aerial vehicle mobile platform. The key focus is on the use of 5G technology, effectively solving the communication and network problems of unmanned aerial vehicles, and ensuring that each unmanned aerial vehicle is controllable.The relevant staff can understand the specific situation of each unmanned aerial vehicle, avoiding abnormal situations caused by communication or network issues, and preventing unnecessary losses.

4.2 The Optimization of the Drone Delivery Module

The unmanned aerial delivery platform represents a significant technological breakthrough in the field of modern logistics transportation. By integrating advanced material delivery modules, this platform enables high-speed aerial transportation of materials, completely breaking through the road limitations faced by traditional ground transportation. This innovative delivery method not only significantly shortens the delivery time but also effectively reduces the risk of interpersonal contact during special periods, providing a strong guarantee for public health safety.

In terms of functional design, this delivery platform demonstrates outstanding adaptability. According to different types of cargo requirements, the platform is equipped with specialized transportation modules: medical supplies transportation module, catering transportation module, and daily necessities transportation module. The platform adopts an innovative layered structure design, with a maximum capacity of accommodating 8 independent materials. Each transportation compartment is equipped with a UV disinfection system, through 254nm wavelength UV irradiation, which can effectively kill 99.9%

of common pathogenic microorganisms, providing comprehensive hygiene protection for the transported items. The intelligent temperature control system can precisely regulate the cabin temperature to meet different requirements from -18℃ freezing to 60℃ insulation.

In terms of user interaction, the platform achieves full-process digital management. By scanning the exclusive QR code on the mobile terminal, users can complete the entire process from ordering to picking up. The system uses blockchain technology to ensure transaction security and updates logistics information in real time, significantly improving delivery efficiency and user experience. According to actual measurement data, this platform can shorten traditional delivery time by 60%-80%, demonstrating significant advantages in emergency material transportation scenarios.

4.3 The Creating of an Exclusive flight Path for Drones

The core of establishing an urban drone logistics delivery system lies in scientifically planning the low-altitude delivery routes. By establishing a specialized drone logistics network, it is possible to achieve a breakthrough in the timeliness of medium and short-distance end-point deliveries, significantly reducing the single transportation duration, and optimizing the overall operational cost structure. This innovative delivery model is particularly suitable for the high-frequency and highly flexible immediate delivery demands in cities, injecting new technological impetus into the modern logistics system.

As an innovative logistics delivery solution, the unmanned aerial vehicle mobile platform equipped with intelligent delivery modules demonstrates significant technical advantages. Compared with the traditional ground transportation mode, this system breaks through geographical space limitations and realizes a three-dimensional transportation network for materials. In terms of transportation efficiency, the drone delivery system, through the planning of straight-line paths in the air, completely avoids constraints such as ground traffic congestion and road regulations. Its advanced hovering positioning technology enables precise aerial material handover without the need for landing to complete the delivery task, which is particularly suitable for the delivery needs of users in high-rise buildings. This vertical delivery capability significantly improves the efficiency of the last mile service.

From the perspective of resource allocation, the drone logistics system has obvious advantages in concentration. On the one hand, this system significantly reduces the reliance on ground transportation infrastructure, saving valuable urban land resources; on the other hand, the intelligent delivery module can be dynamically configured according to the characteristics of the goods, achieving the optimal utilization of transportation resources. This not only solves the problem of low traditional logistics efficiency but also significantly reduces the overall operational costs.

In scenarios with high timeliness requirements such as emergency material transportation and medical emergency response, the drone delivery system demonstrates an irreplaceable value. Its rapid response capability and all-day-round delivery characteristics provide reliable technical support for material security during special periods.

4.4 The Optimization the Battery Life of Unmanned Aircraft

From a technical perspective, the endurance bottleneck faced by the drone logistics sector has achieved a substantial breakthrough. The effective operational radius of the current mainstream commercial drones has been increased to 20 kilometers, and the single-distribution duration is controlled within the range of 20-25 minutes. This performance indicator has fully covered the timeliness requirements for short-distance local delivery within the same city. To expand the application boundaries of urban long-distance delivery scenarios, the industry is currently focusing on advancing three key technological upgrades:

Firstly, in the optimization of the power system, a combination of high-energy-density battery packs and efficient motors, along with an intelligent power consumption management system, can increase the current endurance capacity by 30%-40%. Secondly, in the construction of the safety protection system, by integrating millimeter-wave radars, visual recognition systems, and flight control computers, a triple obstacle avoidance mechanism significantly reduces the flight accident rate to below 0.01%. Finally, in the energy management dimension, the introduction of a dynamic power monitoring algorithm enables the system to automatically trigger a three-level warning when the remaining power drops to a preset threshold (suggested to be set at 35%). This will send a real-time alert to the control center, activate the backup power module, and plan the optimal return route to ensure seamless connection of the delivery task. Some leading enterprises have begun testing the "air charging station" network layout, by deploying wireless charging devices at high points in the city, to achieve power replenishment for drones during their missions. This innovative model has the potential to expand the single-operation radius to over 50 kilometers, providing key technical support for the construction of a 24/7 urban air logistics network.

4.5 The Enhancing of the Safety Delivery Capabilities of Unmanned Aircraft

The issue of the safe operation of unmanned aircraft has always been of the greatest concern. Therefore, it is necessary to fully consider the attributes of each unit involved in the transportation network, and conduct operation scheduling through intelligent algorithms to form the overall architecture of the transportation network. To ensure the safe delivery of unmanned aircraft, it is still necessary to optimize various issues related to unmanned aircraft, such as institutional setup, personnel training, system configuration, emergency operations, simulation training, auxiliary facilities, control links, and safety protection. Safe delivery involves multiple aspects. In the subsequent process of promoting urban logistics unmanned aircraft delivery, it is necessary to actively absorb relevant experience and continuously optimize, especially paying attention to safety issues brought about by weather changes, while striving to improve the quality and efficiency of unmanned aircraft delivery, which helps to ensure the safety of unmanned aircraft and avoid accidental damage to them.

4.6 The Reducing of the Cost of Drone Delivery

The drone delivery cost system is composed of multiple interrelated elements, mainly including equipment purchase costs, energy consumption, maintenance expenses, personnel expenditures, and system operation costs, which are the core components.

Model selection and task matching are the first steps in technical optimization. Choosing the most suitable drone type for different delivery scenarios (urban short-distance, suburban medium-distance, rural long-distance) can significantly improve efficiency and reduce costs. For example, urban "last mile" delivery is suitable for using small multi-rotor drones, while cross-regional transportation may require fixed-wing models. The advancement of battery technology brings new opportunities for cost reduction, as using high-energy-density batteries can extend the flight distance per charge and reduce the number of charging station constructions.

The introduction of intelligent scheduling systems can maximize the utilization of drone resources. Through algorithm optimization of delivery routes, considering factors such as weather, airspace restrictions, and delivery priorities, multi-robot collaborative operations can be achieved, avoiding empty return flights. The application of predictive maintenance technology can detect potential equipment problems in advance, avoiding high repair costs and delivery delays caused by sudden failures. In addition, the integration of computer vision and AI technologies can enhance autonomous flight capabilities, reduce reliance on human-machine interaction, and thereby lower labor costs.

5. Suggestions for Optimizing Cost Management

With the vigorous development of the low-altitude economy, unmanned delivery, as its core application scenario, has demonstrated great potential. This study systematically analyzed the existing problems of unmanned delivery and proposed targeted optimization strategies, and reached the following conclusions: At the technical level, key breakthroughs are needed to address the bottlenecks of battery endurance and autonomous driving algorithms; at the safety level, a standardized airworthiness certification system needs to be established urgently; and at the cost control level, the marginal benefits brought by large-scale application are relied upon. Future research should focus on the coordinated development of three aspects: Firstly, it should promote the cooperation among industry, academia, and research in high-energy-density batteries and fast-charging technologies; secondly, it should build a simulation testing platform based on digital twins to accelerate algorithm iterations; finally, it is suggested that the government lead in formulating classified airworthiness standards, and at the same time, explore the feasibility of business models through the construction of demonstration parks. Only when the technical breakthroughs, safety guarantees, and cost optimization form a closed loop can the market value of unmanned delivery be truly unleashed.

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