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Application Bottlenecks and Optimization Strategies for Urban Last-Mile Delivery by Unmanned Aerial Vehicles in the Context of the Low-Altitude Economy

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Abstract: Driven by the rapid growth of e-commerce, instant retail, food delivery, and intra-city services, urban last-mile logistics is increasingly characterized by dispersed orders, stricter time-sensitivity requirements, shorter delivery distances, and mounting pressure on ground transportation. Low-altitude unmanned aerial vehicles, or UAVs, can travel along air routes and carry goods over short distances; they work well in fixed places such as industrial parks, school campuses, hospitals, scenic spots and residential communities. This paper collects related literature and sorts out relevant policies, and it discusses the features, current application status and practical troubles of low-altitude logistics UAVs when they deliver goods for the last mile in cities. The discussion mainly covers airspace control, operation safety, running cost, limited flight time and privacy worries from the public. Based on these discussions, this paper puts forward several improving measures; managers should control low-altitude flight zones better, build complete operation rules and related systems, match suitable scenes with supporting facilities, connect airspace management and ground delivery work closely, and strengthen privacy protection work. The study finds that UAVs cannot take the place of couriers and ground delivery services completely right now; they serve as an extra part of the urban last-mile logistics system. If UAVs work together with dispatch stations, ground delivery cars, smart parcel lockers and couriers, they can raise delivery efficiency in some situations.

1. Introduction

Online shopping, instant retail and same-city delivery businesses have grown fast in recent years, and consumers set higher requirements for logistics services. Delivery speed changes from three-day delivery and next-day delivery to same-day delivery and even one-hour delivery [1]; last-mile delivery teams face heavier pressure to finish orders within shorter time limits. Urban last-mile delivery usually has scattered orders, small and light parcels and strict speed requirements.

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Traffic jams, insufficient parking spaces and rising labor costs make these troubles harder to solve. Traditional delivery methods can hardly keep fast speed and stable service at the same time for time-sensitive goods like medicine, fresh food and emergency supplies.

Low-altitude UAVs follow planned routes and send goods to fixed stations or pickup points, so they can avoid some limits from ground traffic; drone delivery has become an important developing direction for the low-altitude economy and smart logistics. Foreign researchers have studied many topics including delivery modes with trucks and UAVs, route arrangement and delivery cost [2-5]. More domestic researchers and practitioners start to pay attention to UAV uses in ordinary express service, medical logistics, emergency distribution and delivery inside closed parks.

Even so, urban low-altitude logistics is still under pilot tests, and businesses can only expand slowly step by step.Its development involves not only aircraft performance but also airspace approval, operational safety, infrastructure, order organization, customer handover, and privacy protection. Therefore, this study uses literature review and policy analysis to examine the application conditions and practical challenges of UAVs in urban last-mile logistics and to propose relevant optimization strategies.

2. Analysis of the Concept, Delivery Models, and Logistics Characteristics of Low-Altitude UAVs

Low-altitude logistics UAVs are unmanned aircraft that operate in low-altitude airspace and are primarily used for cargo transportation and delivery. Their basic systems include the aircraft platform, power system, navigation and positioning system, communication system, cargo-loading device, and ground-control platform. Compared with consumer-grade UAVs, logistics UAVs place greater emphasis on payload capacity, flight endurance, operational stability, obstacle avoidance, and continuous operating capability. As an operational component of the logistics network, a UAV must be integrated with warehousing and sorting, order management, delivery stations, ground vehicles, smart parcel lockers, and customer handover systems in order to provide effective logistics capacity.

Several delivery models have emerged in urban last-mile logistics. The first is the distribution-center-to-terminal-station model, in which UAVs transport goods from regional distribution centers or front warehouses to fixed stations in communities, campuses, industrial parks, or hospitals. The final handover is then completed through customer collection or courier delivery. The second is the station-to-fixed-collection-point model, under which UAVs deliver parcels from lThe third is the transportation mode where ground transportation and UAV transportation cooperate with each other. Ground vehicles are responsible for regional transportation work, and UAVs deliver goods to customers in the surrounding area. In the study by Murray and Chu, it is found that under appropriate conditions, the combination of vehicle transportation and UAV transportation can improve distribution efficiency [2]; however, this mode requires the overall management of ground vehicles, the transportation and recovery of UAVs, the overall arrangement of tasks, and work carried out under safety supervision. This paper believes that hospitals, scenic areas available for flight, schools and industrial parks are suitable as pilot areas, because the management boundaries of these places are relatively clear, and the flight routes are relatively easy to determine.

From the perspective of logistics, compared with ground delivery, the delivery routes of UAVs are relatively more flexible, and the delivery efficiency is also higher, especially when the flight routes are relatively fixed, and the dependence on labor is low. Especially when roads are congested, or in scenarios where ground routes need to take a long detour, UAVs can significantly shorten delivery time. They are especially suitable for transporting goods that are light in weight,

small in size, high in value and have strict time requirements. However, when low-altitude UAVs operate, their endurance and load capacity are limited by battery conditions; in addition, bad weather, signal interference and densely built environments will bring considerable risks to flight safety. UAV delivery also requires special take-off and landing sites, supporting charging facilities and on-duty monitoring personnel. Therefore, low-altitude UAV logistics cannot replace the entire logistics network at this stage. We cannot judge its value only by flight speed, but make comprehensive considerations combined with specific delivery scenarios.

Analysis of the Development Environment and Scenario Selection of Low-Altitude Logistics UAVs

At the policy level, China has been promoting the digital and intelligent upgrading of modern logistics. The 14th Five-Year Plan for Modern Logistics Development proposes to accelerate the digital transformation of logistics infrastructure and improve organizational operation efficiency [6]; the Interim Regulations on the Flight Management of Unmanned Aircraft clarifies the basic requirements for the production, registration, operation and flight activities of UAVs, laying an institutional foundation for the application of logistics UAVs [7]; the 2024 Implementation Plan for Innovation and Application of General Aviation Equipment (2024–2030) further lists logistics transportation, emergency rescue and urban services as key application directions [8]. A series of policies show that low-altitude logistics is gradually moving from the technical test stage to large-scale industrial implementation.

However, policy support does not mean that urban airspace can be opened without restrictions; regions differ greatly in airspace openness, flight approval procedures, communication supporting facilities and infrastructure. Enterprises must complete route planning and operation filing in accordance with local regulations.ocal stations to smart parcel lockers, unmanned service stations, or designated building platforms.

In terms of practical implementation, UAV delivery demonstrates clear scenario selectivity. Industrial parks and large business parks can use UAVs to reduce the travel time between factories and warehouses and avoid repeated ground transport. Campuses and hospitals, owing to their enclosed management and clear operational authority, can support the rapid transportation of pharmaceuticals, laboratory samples, and other medical materials. Scenic areas and geographically complex locations can use direct aerial routes to deliver catering supplies and emergency materials where road access is constrained. Community delivery is generally organized through fixed collection stations, smart parcel lockers, or service points to distribute groceries and daily necessities while reducing safety risks. Emergency logistics can also benefit from UAVs during flooding, traffic disruption, or other incidents, although demand in such cases is usually unstable.

Supporting facilities and operational systems remain underdeveloped. UAV logistics requires landing sites, charging or battery-swapping facilities, cargo storage areas, remote monitoring systems, and customer handover equipment. Although some enterprises and parks have begun developing these facilities, most projects remain at the pilot stage, and the standardization and network coverage of infrastructure are still insufficient. In addition, procurement, maintenance, training, platform operation, insurance, and station construction all increase operating costs.

When the number of orders is small, it is difficult to support the operating cost due to the lack of orders, so the average transportation cost for a single delivery will be higher than that of the traditional delivery mode. Because UAV delivery, like logistics transportation, needs a certain number of orders to average the transportation cost. Or choose goods with high unit transportation price and increase the added value of goods to meet the high transportation cost. So UAVs should be given priority to tasks with high time requirements, fixed routes and high ground delivery costs. Therefore, at present, UAV transportation is still difficult to fully replace the existing transportation network.

3. Problems Existing in the Application of Low-Altitude Logistics UAVs

3.1 Constraints of Airspace Coordination and Operation Safety

UAV flight is subject to many restrictions, because urban airspace is generally divided according to airports, railways, communication facilities, high-rise buildings, schools, hospitals and other densely populated or highly sensitive areas. When the operators of low-altitude logistics UAVs set the flight altitude and routes, they need to obtain the temporary flight permission from the government, meteorological information and dynamic information of surrounding air traffic. However, the management platforms and approval procedures in different regions are not connected with each other, the relevant procedures are inconsistent, and the required materials and approval time are also different. If the information of no-fly zones, restricted zones or temporary airspace control cannot be obtained in time, it will directly disrupt the delivery plan. Secondly, carrying out cross-regional operations also needs to complete route filing, information exchange and clarify the jurisdiction responsibilities of all parties, so that the rights and responsibilities can be quickly divided in case of accidents.

In addition, there are very few safe landing sites available in cities. Even if there are no obstacles on the air route, the landing point may be blocked by high-rise buildings, power lines, trees or crowds. Therefore, airspace management needs to cooperate with urban planning, logistics infrastructure construction and public safety governance. Existing studies show that the flight approval procedures and operation restrictions in densely populated areas will significantly affect the operation efficiency of UAV logistics [9].

Flight safety during UAV flight and whether the goods can be kept intact in transportation are still difficult problems. Power system failures, battery abnormalities, positioning deviations, communication interruptions and bad weather are easy to cause safety accidents in densely populated areas. During the whole process of loading, transportation flight and UAV landing, the goods may be damaged, lost, misdelivered or deteriorated due to temperature changes. So when transporting medicines, fresh food and other high-value goods, complete transportation and handover records must be kept. High-frequency operations will accelerate the loss of batteries, propellers and other UAV parts. If operators only pay attention to equipment procurement and flight procedures, and ignore daily maintenance, personnel training and emergency drills, it will be difficult to achieve continuous and safe operation.

3.2 Constraints brought by cost, endurance and public acceptance

Regarding the cost of UAVs, many expenses will be incurred in the process of UAV logistics transportation, including equipment procurement, landing site construction, charging and battery swapping facilities, communication services, scheduling platforms, on-site supervision, equipment maintenance and insurance. Because the current ground transportation has been developed for a long time, there is a more mature distribution system now. Especially for short-distance and low-value orders, the cost of electric vehicles or delivery vehicles is even lower. However, when UAVs are used for transportation, the frequent use of equipment will bring battery aging and wear of related parts that need replacement, which will further increase depreciation costs. In addition, the current UAV models are different, and there are no mass-produced universal parts. The hardware specifications of different UAV models vary greatly. Operators need to store a wide variety of batteries and spare parts, which increases the operating cost of UAVs. Moreover, most UAV deliveries can only send parcels to fixed landing points and cannot be handed directly to recipients; the final delivery link often relies on couriers, which means UAVs only assist manpower instead of replacing manpower, and manpower cooperation is still required. To achieve economic

feasibility, it is necessary to gather enough orders, optimize station locations and improve route scheduling to reduce costs.

Flight duration and load capacity are limited by battery capacity, flight distance, weather and parcel weight. In terms of weight, the heavier the transported goods are, the faster the power consumption is; the longer the flight distance is, the smaller the weight of goods that can be carried because the battery capacity is fixed. In particular, the delivery addresses, weights and time requirements of current urban delivery orders are quite different, so it is difficult to combine orders according to fixed routes. Delivering a single small parcel separately will cause energy waste and low equipment utilization rate; delivering multiple orders together may fail to meet the time commitment. Frequent charging will make UAVs stop working; the battery swapping mode can reduce downtime, but it requires batteries of unified specifications and supporting facilities. Therefore, the shortcoming of endurance is not only a technical problem, but also related to station network layout and order combination strategy.

Public acceptance is another aspect. Because UAV transportation needs to carry cameras and sensors, it may capture information of residential buildings, roads and pedestrians, causing privacy concerns. The noise and visual interference of UAVs will affect residents, students and patients in hospitals. People's worries about mid-air collisions, falling goods and man-made signal interference will also reduce people's trust in the UAV logistics system.

4. Optimization Countermeasures for the Application of Low-Altitude Logistics UAVs

4.1 Strengthen airspace coordination and whole-process safety governance

For low-altitude flights in urban areas, factors to be considered include population density, the height and density of buildings in the area, the distribution of public facilities, and logistics demand. Classification management should be carried out to clearly define areas suitable for UAV flights, no-fly zones and controlled zones. This paper argues that for sites with well-defined management boundaries such as schools, industrial parks and hospitals, regular flight paths can be designated after a thorough safety risk assessment to improve the efficiency of daily transportation.

At the same time, it is necessary to improve the unified low-altitude flight service platform to integrate airspace information, meteorological data, route information, UAV identification and operation status information.

Enterprises could submit flight tasks through a single platform, while regulatory authorities could monitor UAV location and operating conditions in real time. The responsibilities of logistics enterprises, manufacturers, platform operators, and station managers should be clearly defined to ensure prompt identification of responsibility and effective response in the event of communication failures, cargo damage, or flight accidents.

This paper argues that to ensure flight safety during flight, enterprises operating UAVs need to cover all possible risks that may occur during flight as much as possible, including before flight, during flight and after flight. Before the UAV takes off, enterprises should require staff to conduct a comprehensive inspection of the power system, power supply voltage and flight equipment to ensure that the UAV is in good condition before flight for normal flight. During the flight, it is necessary to carry out real-time monitoring of the UAV's position, flight route, battery level and communication status to ensure normal operation during the flight. After the flight, it is required to record the flight duration, cargo handover information and abnormal events during the flight.

During the transportation of goods by UAVs, the transported goods need to be inspected first. First of all, the weight of the goods needs to be pre-estimated. Different UAV models have different load weights and applicable goods. Therefore, before transportation, operating companies need to classify goods according to their weight, volume and product characteristics. For example, DJI

Matrice M350 RTK has a maximum payload of 2.7 kg; DJI Matrice M400 has a maximum payload of 6 kg. These are mainly light industrial inspection UAVs, which are mostly used for daily inspection and maintenance. The DJI T25 agricultural drone has an operating payload of 25 kg, mainly for pesticides and fertilizers, suitable for spraying and sowing on small farmland. The DJI T60 agricultural drone has an operating payload of 50 kg, used for large-field agricultural aerial prevention, supporting both spraying and sowing. These are medium-sized plant protection UAVs. Different types of UAVs are suitable for different cargo weights and transportation scenarios.

Therefore, before cargo transportation, goods should be divided by their states into solid goods, liquids and bulk goods, and divided by product attributes into fragile goods and hazardous materials. From the above cases of DJI models, it can be seen that goods of different attributes or different UAV operation tasks need to follow different operating procedures to realize risk control during transportation.

Meanwhile, during UAV flights, case analysis should be carried out for abnormal situations such as communication loss, low battery voltage and sudden abnormal weather. Corresponding emergency drills and cross-departmental training also need to be conducted to ensure that relevant personnel can operate relevant equipment quickly and correctly in emergency situations, so as to reduce corresponding losses and personal injuries as much as possible.

4.2 Coordinated Optimization of Cost Control, Energy Replenishment, and Public Communication

UAV logistics should follow a scenario-based development approach. Priority should be given to industrial parks, campuses, hospitals, and scenic areas where orders are stable, routes are fixed, and ground-delivery efficiency is relatively low. The “UAV-to-station, customer self-collection” model can reduce the risks associated with direct landing in densely populated areas. Heavy, bulky, and address-complex orders should remain the responsibility of ground vehicles or couriers.

At present, operating UAV enterprises should accelerate the promotion of shared UAV takeoff and landing platforms, charging facilities and UAV after-sales maintenance service platforms as much as possible. When each UAV enterprise carries out route planning, there will be more or less common takeoff and landing points. If each enterprise builds its own platforms, it will increase transportation costs and expand the operating area. Enterprises should reduce the initial operating costs as much as possible to ensure the stable operation of business. At the same time, unified planning should be carried out for smart parcel lockers and delivery routes connected with UAVs to assist UAV transportation, maximize logistics efficiency and improve delivery timeliness.

With regard to charging and scheduling, UAV models should be selected according to delivery distance, cargo weight, and order volume to avoid mismatches between equipment capability and operational tasks. Standardized charging and battery-swapping facilities should be deployed at fixed landing sites, together with systems for battery inspection, circulation, and retirement. Scheduling systems should consider weather conditions, battery levels, cargo weight, and delivery-time requirements when consolidating orders in similar directions and reducing empty flights. For longer-distance tasks, ground vehicles can undertake the main transport stage while UAVs perform local feeder delivery, thereby improving energy efficiency.

In terms of privacy and public communication, enterprises should apply the principles of necessity and data minimization. The scope of image and data collection should be limited, retention periods should be shortened, and collected data should be encrypted, desensitized, and access-controlled. Before operating in residential areas, schools, or hospitals, enterprises should disclose flight routes, operating times, equipment functions, and complaint channels. Image blurring or area-masking technologies should be applied where residences and individuals may be recorded.

Flight schedules should also be arranged to reduce noise disturbance, and routes should be adjusted or converted to fixed-station delivery when persistent complaints arise. The sustainable development of low-altitude logistics depends on coordinated progress in regulation, safety, cost control, energy replenishment, and public communication.

5. Conclusion

This paper holds that with the rapid development of UAVs, low-altitude logistics UAV delivery provides a new solution in enterprises' last-mile delivery. Because UAVs fly faster and more conveniently and are not affected by current traffic, they can transport goods quickly. This transportation mode has high utilization value in scenarios with fixed transportation routes such as industrial parks, campuses and scenic spots.

Nevertheless, the development of UAVs is still restricted by many factors. The low-altitude flight management system for UAVs is imperfect, and approval procedures vary from region to region. Safety standards need to be formulated according to different cargo characteristics. Besides, equipment management and operation costs during flight are high, while flight endurance and payload capacity are limited. Moreover, cameras equipped on UAVs may invade public privacy, resulting in inadequate privacy protection for the public.These constraints demonstrate that the maturity of low-altitude logistics depends not only on aircraft performance but also on the coordination of logistics networks, infrastructure, governance mechanisms, and public acceptance. UAVs should not be viewed as a complete substitute for conventional delivery. Instead, they should function as a complementary tool within the last-mile logistics system. Enterprises should adopt a demand-oriented and scenario-based approach, prioritizing areas with clear management boundaries, high order density, and strong time-sensitivity requirements. Government authorities should improve low-altitude flight service platforms and operational rules, while enterprises should establish whole-process safety and privacy-protection mechanisms and strengthen coordination among UAVs, ground vehicles, smart parcel lockers, and couriers. Through gradual pilot implementation and continuous optimization, UAVs can develop into a stable, regulated, and sustainable component of urban last-mile logistics.

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