Urban Logistics UAV System Planning, Operation and Comprehensive Governance: A Review and Prospects

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Abstract. Aiming at the problems of low efficiency, high cost and insufficient emergency resilience of traditional urban ground logistics distribution, as well as airspace governance, system planning, collaborative operation and safety control in the large-scale application of unmanned aerial vehicles (UAVs), this paper systematically reviews the research progress of urban logistics UAVs from six dimensions against the background of low-altitude economy. The results show that a complete academic system has been formed in this field, with breakthroughs in site selection, path planning, control and collaboration. However, there are limitations such as weak dynamic adaptability, insufficient constraint integration, shallow collaboration, difficult engineering implementation and fragmented governance. In the future, an integrated comprehensive governance framework centered on artificial intelligence and digital twin should be constructed to provide theoretical guidance for the safe, efficient and sustainable development of urban logistics UAVs.

Keywords: Urban logistics UAV; Low-altitude economy; UTM system; Truck-UAV collaborative delivery; Comprehensive airspace governance

1 Introduction

Driven by accelerated urbanization and the surging demand for e-commerce and instant retail, traditional ground logistics networks are facing severe challenges in efficiency, cost and resilience [1]. Meanwhile, the continuous maturity of UAV, electric vertical takeoff and landing aircraft (eVTOL) and other technologies, together with the advancement of global low-altitude airspace management reform, have given birth to a new "low-altitude economy" paradigm centered on urban aerial logistics [2,3]. By constructing a three-level three-dimensional distribution network of "trunk-line-branch-end", UAV logistics is regarded as a revolutionary direction to promote the intelligent upgrading of urban logistics system and foster new quality productive forces [4].

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However, the large-scale, routine, safe, and orderly integration of UAVs into complex and dynamic urban environments is far more than a simple technical application. This indicates a profound transformation in the research paradigm of this field: from the early "technical single" research focusing on the performance of a single aircraft platform, to treating UAVs as a schedulable, collaborative and manageable intelligent mobile node in the complex system engineering of smart cities [5]. This systematic engineering spans multiple highly interdisciplinary fields such as macro policy governance, meso network planning, micro flight control, cross-level business models and social acceptance. This paper systematically sorts out domestic and foreign research results of urban logistics UAVs, reviews the progress, deficiencies from six dimensions of policy, planning, technology, collaboration, safety and emergency, and puts forward the future research direction of integrated comprehensive governance..

2 Evolution of Low-Altitude Economy Policy and Airspace Governance Framework

Low-altitude airspace is the basic resource for UAV operation, and the orientation and sophistication of its management policies directly determine the boundary and pace of commercial application.

2.1 Evolution and Implementation Mechanism of Domestic Policies

China's low-altitude airspace management reform follows a prudent and gradual path. Policy discourse has evolved from "absolute safety dominance" to "dynamic balance between safety and development", with national top-level design as the core driving force [6]. The sustainability of policies depends on refined institutional design and efficient cross-departmental collaboration [7]. In key fields such as emergency logistics, it is necessary to build an emergency logistics system integrating new aviation equipment and supporting mechanisms [8].

2.2 International Experience and Forward-looking Concepts

International experience provides important references for China. The experience of the United States shows the importance of improving the legal system and market ecology [9], and the EU system provides a reference for refined management and control [2]. Forward-looking directions include personal air transport systems [10], magnetic levitation assisted take-off and landing technology [11], and IEEE standards provide standardized templates for complex systems [12].

2.3 Architecture and Development of UAS Traffic Management (UTM) System

UTM is the core of high-density UAV operations. Its architecture, communication reliability, and airspace modeling have been clearly defined, and the feasibility of high-density operation has been verified [13-16]. However, existing researches are macro-oriented, and there are still insufficient quantitative studies on terminal issues such as dynamic airspace allocation, noise control, airspace capacity assessment, and air–ground data interaction.

3 System Planning and Network Optimization: Models, Algorithms and Dynamic Evolution

System planning is the core connecting policy blueprint and commercial operation, and its essence is the complex optimization problem of integrated site selection-path-scheduling.

3.1 Take-off and Landing Site Selection: From 2D Discrete to 3D Continuous Space Optimization

Site selection is evolving towards continuous space, 3D constraints and dynamic adaptation. Researches adopt POI data and clustering algorithms for site selection and zoning [17], introduce low-altitude obstacle constraints, propose "cluster distribution" of take-off and landing sites to improve coverage [1], and optimize the number, location and demand allocation of take-off and landing sites in truck-UAV collaboration scenarios [5].

3.2 Vehicle Routing Problem and Its Integration with UAV Models

Path planning is the core of operation optimization. Classic models include the Flying Sidekick Traveling Salesman Problem [18], VRP model considering energy consumption [19], and path models for multi-compartment and pure UAV delivery [20-21]. The optimal payload is clarified: 6–8 kg for line-haul UAVs and 3–4 kg for end-distribution UAVs in the three-level network [1].

3.3 Dynamic and Real-time Adaptive Optimization: Responding to Uncertainty

Researches face dynamic environments, realizing real-time re-routing, optimal energy consumption path under time-varying wind fields, dynamic traffic adaptation, and weather-aware path optimization [22-26]. Reinforcement learning has been employed to solve complex post-disaster routing problems, highlighting the capability of AI [27].

3.4 System Integration and Cloud-based Intelligent Scheduling

UAVs access cloud management systems as network nodes [28], integrate into urban Internet of Things, and realize unified global scheduling and optimization of passenger and freight resources [29-30].

4 Core Enabling Technologies: Flight Control, Navigation and Multi-level Security Support

Safe, reliable and high-precision flight control and operation are the technical foundations for large-scale application.

4.1 Advanced Flight Control Algorithms

To cope with the nonlinearity, model uncertainty and external disturbances of UAVs, control algorithms are continuously upgraded. Nonlinear hierarchical control, agile flight control for quadrotors, robust backstepping control based on ESO, and command-filtered backstepping method significantly improve disturbance compensation and trajectory accuracy [12,31-33].

4.2 High-Precision Navigation, Height Fixing and Terminal Precise Operation

In terms of navigation and terminal operation, researches have realized sliding mode guidance for fixed-wing UAVs, anti-interference compensation of barometric altimeters, and autonomous precise landing on dynamic platforms [32,34-35]. AI is comprehensively empowering UAV environmental perception, real-time decision-making and swarm collaboration [25].

4.3 Construction of a "Technology-Management-Ethics" Integrated Security Governance System

Safety has expanded into a comprehensive governance system including four dimensions:

1. Cybersecurity and data privacy: clarifying the risks of cyberattacks and privacy leakage [10,36];
2. Physical security and detection: developing passive radar systems to detect non-cooperative UAVs [37];
3. Operational safety and human factors: attaching importance to operator cognitive load and adhering to "human-in-the-loop" [38];
4. Technical ethics and governance: technological development must simultaneously consider social, ethical and legal requirements [39].

5 Innovation of Collaborative Distribution Mode, Performance Verification and Special Scenario Application

5.1 Truck-UAV Collaborative Distribution: Deepening and Challenges of the Mainstream Mode

Truck-UAV collaboration is the most commercially promising core mode, as it can reduce logistics costs, alleviate congestion, and improve social benefits [5,40-41]. However, most existing studies rely on static, idealized scenarios, and it is urgent to solve online re-planning and large-scale heterogeneous equipment collaborative scheduling under real-time orders, traffic, weather and airspace conditions.

5.2 Emergency Logistics and Special Scenario Application: Value and Deficiencies

UAVs have prominent value in emergency logistics, forming a system framework integrating eVTOL, and realizing complex post-disaster scenario routing through AI [8,27]. However, there are obvious deficiencies in dynamic demand forecasting and swarm collaboration under communication disruption, complex terrain and severe weather adaptive flight.

6 Discussion

6.1 Main Contributions of Existing Researches

1. Complete theoretical system: forming a multi-disciplinary framework covering the whole chain of "policy-planning-control-management-application".

2. Innovative technical algorithms: widely applying meta-heuristics, mixed integer programming, robust control, deep learning and other methods.

3. Localized practical verification: enhancing local applicability through empirical research combined with Chinese cities.

4. Systematic safety governance: expanding from single flight safety to a comprehensive framework of network, physics, human factors and ethics.

6.2 Core Limitations of Existing Researches

Despite the extensive research progress outlined above, critical limitations persist across the core domains of urban logistics UAV systems, hindering their transition from theoretical models to large-scale, safe, and efficient real-world operations. These limitations are analyzed by domain with typical literature support as follows:

1. Airspace Governance and UTM: Most studies focus on macro UTM architecture design [13–16], but lack quantitative research on dynamic airspace allocation, noise control, and air-ground data interaction under high-density operations.

2. System Planning and Path Optimization: The majority of location-routing models, including the classic FSTSP [18] and energy-aware VRP [19], rely on static assumptions [18–21], failing to integrate real-time traffic [25], weather [24], and order changes, resulting in poor dynamic adaptability.

3. Flight Control and Navigation: Advanced control algorithms [31–33] are mostly verified in ideal simulation environments, with insufficient robustness tests under urban obstacles, communication delays, and wind disturbances.

4. Collaborative Delivery: Existing research on truck-UAV collaboration is often limited to static ideal scenarios [5, 40–41], lacking full-link coordination of “warehouse-truck-UAV-locker-person” and real-time re-planning mechanisms under dynamic conditions.

5. Safety Governance: Studies on cybersecurity [10, 36], physical detection [37], and human factors [38] are relatively fragmented, without forming a unified “technology-operation-regulation-ethics” governance framework.

6. Emergency Logistics: Current models for post-disaster routing [27] lack dynamic demand prediction, swarm collaboration under communication interruption, and adaptive flight capabilities in complex terrain and severe weather [8, 27].

6.3 Key Future Research Directions

1. Build a dynamic intelligent decision-making system driven by digital twin and real-time data.

2. Establish a multi-constraint integrated optimization model of airspace, safety, energy consumption, noise and social acceptance.

3. Create a full-link deep collaboration network of "warehouse-truck-UAV-locker-person".

4. Develop an autonomous UTM system integrating airspace planning, scheduling, conflict resolution and monitoring.

5. Innovate a full-process comprehensive governance framework with "technology-operation-regulation-society" collaboration.

7 Conclusions

This paper systematically sorts out domestic and foreign core researches on urban logistics UAVs, reviews the progress, contributions and deficiencies from six dimensions of airspace policy governance, system planning, flight control, air-ground collaboration, safety management and emergency application, and puts forward the direction of integrated comprehensive governance. The conclusions are as follows:

1. A complete academic system of "macro policy-meso planning-micro technology-comprehensive support" has been formed, showing an evolutionary trend from static to dynamic, single machine to system, and technology to governance.

2. Significant breakthroughs have been made in site selection, path planning, control and truck-UAV collaboration, but there are still shortcomings in dynamic adaptability, integration of real-world constraints, depth of collaboration, engineering verification,

and fragmented governance (i.e., technology-operation-regulation-society collaboration).

3. Large-scale safe commercial operation requires the construction of an integrated governance system with AI and digital twin as the core and the collaboration of policy-technology-operation-society.

4. Future researches should focus on dynamic intelligent decision-making, multi-constraint modeling, deep air-ground collaboration, autonomous UTM and full-process governance innovation to realize the safe, efficient, economic and sustainable development of low-altitude logistics.

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