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Collaborative Transportation Methods of Drones and Vehicles from the Perspective of Intermodal Transport

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Abstract:

With the rapid development of logistics driven by the e-commerce industry, drone-based cargo transportation has been partially implemented in this sector, attracting academic research on related projects. Although drone transportation has certain advantages over traditional logistics to some extent, relying solely on drones for logistics remains challenging. Therefore, this paper introduces the concept of intermodal transport and explores the progress in research on collaborative transportation of drones and vehicles from this perspective. First, the basic concept of drone-based intermodal transport is presented. In this section, the types of drones and their applicable scenarios are described, and the types of intermodal transport are analyzed. Then, the latest progress in core issues of intermodal transport is reviewed, with a categorized discussion of various research on intermodal transport under different environmental conditions. Finally, this paper discusses the accuracy issues in current models and suggests potential future research directions, specifically the possibility of constructing accurate models by integrating real-world data.

Keywords: Drone transportation; Drone collaborative transportation; Intermodal transportation theory; Last-mile delivery

1. Introduction

Since the establishment of Amazon and eBay in 1995, e-commerce has developed for 30 years, profoundly changing people's consumption patterns. According to the statistics released by the Ministry of Transport of China on the development of the postal industry, in 2024, the total express delivery volume reached 175.08 billion items, a year-on-year increase of 21.5% [1]. The report also shows that from 2020 to 2024, per capita spending on mail services, express delivery, and express usage all showed an upward trend. The explosive growth of e-commerce and the rapid increase in express delivery volume have raised higher demands for timeliness and flexibility in logistics distribution [1]. However, purely land-based transportation is often affected by various factors, such as traffic congestion caused by high population density in cities, which leads to slow transportation, or the speed limits of trucks during long-distance transport, all of which limit the speed of logistics distribution.

To accelerate cargo transportation and achieve efficient logistics, express delivery companies and governments have begun to use collaborative transportation with drones for logistics distribution. At present, drone technology can already achieve efficient delivery to some extent. SF Express's ARK80 drone, for example, can carry 20kg for 60km or 30kg for 30km (with front-loaded weight and rear flight range), while the ARK150 drone is a foldable 50kg payload drone [2]. Although drone delivery has been widely adopted in logistics, relying solely on drones can only handle a limited amount of short-distance point-to-point delivery and cannot address the problem of improving the speed of large-scale logistics transportation, as mentioned above.

To solve this problem, researchers have proposed the collaborative transportation of drones with other transportation modes, known as the Multimodal Joint Transportation of Drones (MJTD). Multimodal transportation allows drones to complement the advantages and disadvantages of ground, air, and water-based vehicles, forming a three-dimensional network for the last-mile joint trunk line transport. This aims to solve issues related to drone-only logistics or emergency supply deliveries. To gain a comprehensive understanding of the latest research progress on this issue, this paper delves into the application of multimodal transportation theory and analyzes the current state of research from multiple dimensions, aiming to understand and explore the future development directions.

2. Theoretical Foundations of Drone Multimodal Transport

2.1 Common Types of Drones and Their Technical Parameters

In logistics transportation, drones are primarily divided into two categories: multirotor drones and fixed-wing drones. Multirotor models (such as quadcopters or hexacopters), with their vertical takeoff and landing capabilities, are suitable for short-distance, small payload end deliveries, such as medical supplies or small parcels. These drones typically have a payload range of 2-5 kg and a flight time of about 30-60 minutes, making them ideal for urban or complex terrain areas. However, the payload and endurance capabilities of multirotor drones are limited, and the tasks they perform are generally short-distance, lightweight cargo transportation that meets economic efficiency. In contrast, fixed-wing drones have stronger endurance (up to several hours) and higher payloads (10-20 kg), making them suitable for cross-regional transport. For example, they are used to connect distribution centers in remote rural areas with residential areas. To meet these requirements, freight fixed-wing drones are usually larger and require takeoff and landing on drone runways. Therefore, fixed-wing drones have certain limitations, as they need a large-scale launch center to launch and recover the drones, which requires businesses to equip the necessary facilities and locations.

2.2 Application Scenarios and Advantages of Drone Transport

Drones are most notable in last-mile delivery, where they can transport goods in low-altitude areas, avoiding ground traffic congestion or environmental obstacles, and directly delivering goods to the geographic coordinates of the user. For example, Zipline uses drones to transport medical supplies to hospitals in Rwanda. Zipline uses fixed-wing drones to transport blood and vaccines, with drones launching from distribution centers in Rwanda or Ghana, achieving emergency deliveries of blood and vaccines within 15-45 minutes [3]. The quick response of drones enables patients to receive the necessary medical supplies more quickly, improving the survival rate by 72% compared to traditional local transportation methods [3]. In natural disasters or pandemics, drones can overcome road restrictions. For example, in earthquake-stricken areas where road blockages exist, drones can quickly transport emergency supplies in low-altitude airspace, achieving point-to-point logistics delivery. Similarly, during the COVID-19 pandemic, drones were used to transport medical supplies and daily necessities, reducing the impact of transportation disruptions on people's lives.

In addition, drones can help reduce the cost of last-mile logistics and improve the economic efficiency of logistics transportation. With a reasonable delivery method, the cost of drone transportation is lower than that of traditional ground logistics, reducing the total operating cost of logistics transportation. Different geographic environments (urban environments) require different transport methods. For example, in low-population-density areas like the suburbs of Paris and the Gothic Quarter of Barcelona, where housing is dense, different drone multimodal transport strategies should be adopted based on the investment and cost of installing various equipment. These strategies can

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reduce the total operating cost by 25% in low-population-density areas and by 60% in high-population-density, small-range areas [4]. Of course, different operational strategies may lead to different results, and this relates to the importance of model application. The more parameters considered in the model, the more accurate the results.

2.3 Collaborative Modes in Multimodal Transport

2.3.1 Serial Collaborative Transport

Serial collaboration between drones and ground vehicles primarily refers to information exchange between the two. The core of this model lies in path planning through information chaining. Under this mode, when either the drone or the ground vehicle is unable to obtain correct route data from GPS, they can still function as mutual relay nodes, exchanging communication data to obtain real-time transport information and complete logistics tasks. For instance, in OMER's study, drones are used as information nodes leveraging their low-altitude maneuverability to assist vehicles in addressing on-board communication failures due to broken links [5]. Camila introduced the concept of Vehicle-to-Everything (V2X) communication to facilitate such data exchange, and proposed integrating drone-sensed road obstacle data with V2X to help ground vehicles update their decisions in the absence of complete information.

Within this serial information-sharing environment between drones and ground vehicles, drones can also receive data that their onboard sensors cannot capture—such as path conditions, obstacles, or weather—through return-loop information exchange with vehicles. This allows drones to make more optimized routing decisions, improving both safety and operational efficiency [6].

2.3.2 Parallel Collaborative Transport

Parallel collaborative transport is a novel logistics model in which drones and ground vehicles work simultaneously to fulfill cargo delivery tasks. Unlike the serial mode, which focuses on information relaying, the core of parallel collaboration lies in the concurrent involvement of multiple transport agents in physically moving the goods. This model addresses logistics bottlenecks encountered when a single mode of transport is obstructed in complex traffic networks. While ground vehicles operate, drones can concurrently execute deliveries. By building an IoT-enabled seamless communication network, this approach leverages the strengths of each transport vehicle to create a highly efficient and fluid logistics system, enhancing circulation efficiency and reducing societal costs [7].

3. Core Technology Research Progress in Drone Multimodal Transport

3.1 Path Planning and Dynamic Obstacles in MJTD

The collaborative transport of drones in multimodal transport has become a research hotspot in recent years. In theoretical research, scholars primarily focus on collaborative path planning, task assignment algorithms, and multi-objective optimization models. For example, in the scenario of emergency material scheduling for air-ground cooperation, a truck-drone-helicopter collaborative scheduling model was proposed, which optimizes transport time using genetic algorithms and dynamic programming algorithms [8]. In terms of technical implementation, the key breakthrough lies in the construction of a multi-agent collaborative control architecture, such as the hierarchical optimization framework proposed in the literature, which enables synchronous decision-making between drones and ground vehicles through real-time information exchange [9]. In practical applications, this model has been validated in scenarios such as medical emergency material transport and post-disaster rescue, where drones can bypass road damage and reach the target point directly, while trucks and helicopters, acting as mobile bases, provide endurance support and material transfer [10]. Current research challenges are focused on the complexity of conventional ground vehicle collaborative scheduling, dynamic environment adaptability, and safety risk control. Future directions may extend to AI-driven joint vehicle simulation optimization, integration of new energy power systems, and low-altitude traffic network integration.

3.2 MJTD Strategy under Time Constraints

In time-constrained scenarios, the collaborative transport of drones with trucks or helicopters has become a core issue in multimodal logistics optimization. Existing literature mainly focuses on dynamic path planning, time window constraint modeling, and multi-objective collaborative scheduling. For the mixed demands of dynamic delivery and on-demand pickups, researchers typically adopt hierarchical optimization frameworks to integrate real-time traffic data and drone endurance limitations. Wei proposed the time-dependent vehicle routing model (TDVRP-D), which optimizes paths using grid-based path optimization and dynamic priority adjustment strategies to balance delivery cost and timeliness under no-fly zone constraints [11]. This study, under time constraints, uses a time penalty mechanism to allocate drone transport paths within specified time limits. For example, when a truck acts as a mobile warehouse to support emergency drone deliveries, the removal-and-insertion algorithm is used to dynamically coordinate multi-drone paths and shorten the target arrival time through relative motion models [11]. Simulations show that this algorithm reduces delays by 15%-20% compared to traditional methods [11].

Gu proposed the dynamic truck-drone routing problem for scheduled deliveries and on-demand pickups (D-TDRP-SDOP) logistics delivery strategy model. This model features a dynamic truck-drone routing with time-dependent constraints to enhance the functionality of ground vehicles and achieve higher system profits in more demanding environments [12]. Under this newly proposed logistics model, the profits of the delivery system increased by at least 15%, while the acceptance rate for on-demand pickups also rose by over 50% [12]. Notably, multi-objective optimization has become a mainstream method in this field, such as the use of a Pareto optimal dual-objective model to establish a trade-off curve between cost and time metrics, and validating the robustness of the solution through data-driven simulations. Current challenges include insufficient dynamic environment adaptability and heterogeneous vehicle time synchronization accuracy issues. Future research may extend to real-time decision systems driven by digital twins, while also addressing the impact of extreme weather on drone time window compliance rates.

3.3 MJTD under Environmental Constraints

In drone and truck/helicopter collaborative transport systems, air traffic congestion and weather restrictions are also key factors that limit low-altitude logistics efficiency. Regarding air congestion, studies typically combine dynamic path planning with multi-agent scheduling strategies. For example, Sorin proposed a two-layer optimization model that monitors drone density and airspace capacity in real-time, using graph neural networks to predict congestion hotspots and trigger dynamic adjustments to drone release batches by mobile truck-based stations. Experiments have shown that this method can improve route passage efficiency by 28% during peak hours [13]. Furthermore, reasonable air management policies are used, employing UAV Service Systems (USS) or data exchange platforms for drone cloud control. USS primarily ensures the efficiency and effectiveness of drone operations by establishing bidirectional communication channels with operators to ensure airspace safety. Data exchange platforms handle real-time transmission and standardized interactions between heterogeneous systems, mainly providing underlying communication support, such as transmission protocols and real-time network coverage. National and regional efforts are underway to explore the use of displayed, detailed elevation maps to establish fixed drone flight paths above urban areas, addressing low-altitude airspace congestion or safety concerns related to low-altitude buildings [14].

In terms of weather-related influences, three-dimensional path planning algorithms (such as the improved A* algorithm) integrate dynamic weather layers like wind speed, temperature, and precipitation to optimize urban logistics, drone obstacle avoidance, and energy consumption efficiency [15]. Trucks provide local weather warnings to drones via onboard radar and dynamically take over no-fly zone tasks triggered by strong winds. Meanwhile, helicopters can bypass low-altitude congestion layers by flying at higher altitudes or cooperate with high-altitude communication towers to provide relay communication support for drone fleets. At the algorithmic level, the improved Rapidly-exploring Random Tree Star (RRT*) algorithm is used, which approaches the global optimal path through progressive optimization while retaining the efficient exploration characteristics of the original RRT algorithm. This algorithm incorporates a spatiotemporal conflict detection module, effectively avoiding dynamic obstacles and meteorological no-fly zones, and its computational efficiency is 3.2 times greater than that of the traditional A* algorithm [13]. Current technical bottlenecks are mainly focused on the coordination response delay of large-scale heterogeneous carriers, and future research may extend to digital twin-driven airspace simulation systems.

4. Conclusion

Drone multimodal transport, by integrating aerial and ground transportation resources, has established a three-dimensional, intelligent logistics network that plays a crucial role in logistics transportation. It has become a key pathway for improving economic efficiency and optimizing community logistics networks. This paper primarily introduces the theoretical foundations and advantages of multimodal transport, categorizes the core issues of current drone multimodal logistics transportation, discusses the solutions to these issues in various environmental scenarios, and summarizes the current research progress.

However, many theoretical models in current literature lack practical data support. The idealized assumptions in these models (such as constant speed and zero-interference environments) differ significantly from real-world scenarios. Applying idealized model conclusions to real-world situations often leads to results that contradict ac-

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tual conditions. Most models rely on simulation data and lack validation with real operational data from businesses, which has led to discrepancies in energy consumption, such as in pharmaceutical delivery cases, between theory and practice. Meanwhile, the low-altitude airspace is still lacking government regulations, and the enforcement of airspace rules remains problematic. Based on these issues, future developments may involve collaboration between enterprises, governments, and researchers, sharing relevant data to design models that reference real-world data for calculations.

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