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Optimization of Truck-Drone Distribution Paths: A Review

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Abstract:The rapid development of unmanned aerial vehicle (UAV) technology has led to a notable increase in the use of cargo drones across various civil logistics sectors. Small rotor UAVs are particularly advantageous for last-mile logistics distribution due to their flexibility in takeoff and landing and their cost-efficiency. Nonetheless, their limited load capacity and range hinder their ability to perform long-distance deliveries and transport heavier cargo. This limitation has prompted the evolution of truck-drone distribution systems, where trucks function as mobile warehouses and charging stations for UAVs, thereby significantly extending their operational range. This paper provides a review of the relevant literature on optimizing distribution routes for truck-mounted UAVs, summarizing current research progress and discussing potential future research directions in this area.

Keywords:UAV; trucks; distribution path optimization.

1. Introduction

The path optimization of cooperative distribution by UAV and truck is derived from vehicle routing theory. The vehicle routing was first put forward by Dantzig and Ramser in 1959[1], and then many different extensions and variants were produced, thus forming a relatively mature theoretical system. At present, related research focuses on solving the new problems caused by environmental change, such as the structure of road network, traffic restrictions, green and low carbon requirements, uncertainty, emergency material distribution and loadingconstraints, and so on.

2. Review of Research on the UAV Path Optimization

Early UAV was mainly used in the military field[2, 3]. With the breakthrough development of related technology, UAV was also widely used in the application of civil field[4-6], ranging from carrying a single equipment for geological exploration[7, 8] and disaster investigation to carrying a variety of supplies to implement architectural coatings and urban power grid maintenance[9]. The research on UAV path optimization mainly focuses on airborne geophysical survey, transmission line inspection and other special fields. These studies are only aimed at the mission of one UAV, which can be regarded as an extension of the classical traveling salesman problem (TSP). In addition, some literatures have studied the path planning of multi-UAV mission performing based on vehicle routing theory [10], which focuses on how to control UAV to cover the target area with the best path combination, and avoid known obstacles and unknown threats, without considering the constraints related to cargo transportation, such as load capacity and demand. With the development of UAV application practice in the field of logistics distribution, a number of research results on UAV distribution path optimization have emerged one after another[11]. For example, Dorling et al. have proposed a multiple-pass vehicle routing method that allows UAV to travel to and from the warehouse multiple times [12]. Coelho et al. have studied the multi-objective path optimization problem of UAV heterogeneous fleet. Their research considers the constraints of UAV when carrying out distribution tasks [13], but ignores UAV's cooperative distribution with other means of transportation, and does not carry out experimental analysis on distribution efficiency.

3. Review of Research on Optimization of Multi-resource Cooperative Distribution path

Cooperative distribution with UAV and truck can be classified as multi-resource collaborative distribution, including multi-means of transport cooperation, tractor and cargo device coordination. Gelareh have studied the routing optimization problem of an intelligent autopilot vehicle (IAV) used for port container transit [14]. The containers can join or leave nearby IAV, which is similar to UAV leaving or returning to the truck. The goal of the research is to find the best route from the beginning to the end in a given network, which is essentially the shortest path problem . Dr. Drexl studied the path optimization of the cooperative collection of milk by trucks, tractors and trailers in his doctoral dissertation. Trucks transport milk to transit stations, then the milk is transferred to trailers, and several trailers are connected by the tractor along the way to return to the warehouse [15]. In 2012, the research results of Drexl were published in the journal of Transportation Science [16]. Although what Drexl studied belongs to the vehicle routing problem, he sets the transit station in several fixed positions, so the modeling difficulty is low and the solution space is small.

Chao has raised a more common routing problem about truck and trailers (Truck and Trailer Routing Problem, TTRP): trucks connect trailers from distribution centers, decoupling trucks from trailers before visiting customers with poor road conditions, allowing trucks to complete their distribution tasks separately, and then returning to decoupling positions to reconnect trucks to trailers[17]. Compared with Drexl, Chao assumes that trucks and trailers can be separated anywhere.

Multi-resource collaborative distribution also has amounts of applications in express delivery business, and it is quite different from TTRP in terms of means of transportation, type of goods, collaborative mode and so on. Lin abstracts the path optimization problem from express delivery about heavy resources (such as trucks, vans) carrying light resources (such as bicycles,people) to pick up and deliver goods.

4. Review of Research on path Optimization of Cooperative Distributionwith UAV and truck

In view of cooperative mode and task type, the cooperative research of UAV existed is mainly focused on multi-UAV cooperative reconnaissance, UAV and truck cooperative reconnaissance, UAV and truck cooperative distribution and so on. This section focuses on the research results of collaborative distribution path optimization with UAV and truck. Because of the novelty of the problem, related research results are very few.

In 2015, Murray et al. firstly began to study the problem of cooperative distribution path optimization with UAV and truck, having considered the following two scenarios: one is that UAV and truck start independently from warehouse, serve customers separately and then return; secondly, truck carries UAV to complete distribution task together, which can be used as a platform for UAV launch and reception [18]. In this paper, the mathematical model of UAV and traveling salesman problem (TSP) about truck cooperative distribution is constructed and the algorithm is designed, which opens up ideas for the study in this direction, but there still exists some shortcomings: only the traveling salesman problem (TSP) of single vehicle is studied, but the multiple vehicles is not solved; taking the earliest completion time as the objective function, without taking the total time and cost into account; The practical requirements such as multi-vehicle, multi-machine, time window are ignored; only a simple heuristic rule solution optimization model is designed, the solving speed of which is slow and the solution quality is not high; the calculation experiment is not sufficient, no deep experiments are carried out for a large number of examples, and there is no experiment and analysis for the actual road network environment.

Subsequently, Wang et al. studied the efficiency improvement when changing from truck distribution to UAV and truck collaborative distribution. The results show that even in the worst case, collaborative distribution mode can still save time, and in the best cases, the delivery completion time can be reduced by 75%. On the basis of the classical vehicle routing problem, the optimization objective function is deformed and deduced, but the complete mathematical model of UAV and truck cooperative distribution path optimization is not constructed.

Recently, Carlsson et al. further studied the efficiency improvement of cooperative distribution of UAV in long-term decision-making. Through the theoretical analysis in Euclidean plane and the numerical analysis of actual road network, it is proved that the efficiency of cooperative distribution is proportional to the square root of the velocity of truck and UAV. Related research results are published in the first issue of Management Science in 2018 [19]. This paper has done some work in the theoretical derivation and calculation analysis of the efficiency of cooperative distribution with UAV and truck, but not comprehensive enough: the inadequacy of the model is basically the same as that of Murray et al. The modeling idea is to find the best path scheme of UAV after a given truck path, resulting in the objective function not having global optimality. The Monte Carlo simulation is used to generate the circular route, which leads to a very large amount of computation. Only the factors affecting the improvement of distribution efficiency are analyzed, and the distribution cost is not modeled and analyzed.

5. General Comment

It can be found from the review above that the existing problems including vehicle routing, UAV distribution routing optimization, UAV and truck coordinated distribution routing optimization are still worthy of improvement and further exploration:

(1) the existing research results have a narrow scope of application. Current research mainly involves the traveling salesman problem (TSP) of cooperative distribution with a truck and a UAV. The traveling salesman problem (TSP) is only a special case of the vehicle routing problem, which can not fully reflect the advantages of flexible distribution, wide coverage, low price and high efficiency, and is not suitable for most logistics distribution environment.

(2) The existing research is not well-considered to the characteristics of complex distribution. Some typical distribution characteristics, such as time window constraints to serve customers, the use of different types of trucks for distribution, multiple drones-carrying truck, taking off and landing at any point, etc. These characters are widespread in express delivery, blood (virus) sample collection and other logistics distribution practices. But in the existing UAV and truck coordinated distribution research, these characteristics need to be further explored.

(3) New algorithm needs to be developed. The path optimization problem of cooperative distribution with UAV and truck belongs to NP-Hard problem, and the development of efficient algorithm for solving large-scale problems has always been a highly concerned research topic. The existing optimization algorithms have achieved good results in vehicle routing problem and its variety. But when they are applied to the solution of UAV and truck cooperative distribution path optimization problem, it is necessary to fully consider the influence of UAV routing, synchronization and other constraints on coding mode, evaluation function construction and optimization iterative process. Involved many factors, the solution space is greatly increased due to the complexity of the environment. Therefore, it is also necessary to consider how to improve the computational efficiency and effect of the algorithm. In addition, some new intelligent algorithms and logical Benders decomposition methods have been successfully applied in combinatorial optimization problems. But these algorithms need to be further explored and studied in the fields of UAV path optimization, multi-resource collaborative path optimization and so on.

(4) There is a lack of sufficient computational experiments in the existing research. On the one hand, in the existing research of cooperative distribution path optimization with UAV and truck, there is no computational performance analysis based on Benchmark standard case base, which leads to the inability to provide strong support for the effectiveness, applicability and generalization of the algorithm. On the other hand, there is a lack of experiments and analysis for different logistics distribution environments, such as the number of customers (more or less), the sparse degree of

node distribution (sparse or dense), the density of road network (sparse or dense) and the structure of road network (free, sector, square format, ring, grid-ring- radiation) and so on. All these logistics distribution environmental factors will affect theefficiency and cost of cooperative distribution with UAV and truck. By demonstrating the efficiency improvement and cost reduction of cooperative distribution with UAV and truck in different environments, we can acquire important reference for the formulation of cooperativedistribution strategy with UAV and truck.

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