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UAVs and truck joint action in logistics in order to minimize energy consumption

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Abstract. This paper discusses the use of unmanned aerial vehicles (UAVs) in logistics. A number of methods and mathematical models are analyzed that describe the process of controlling the joint delivery of goods by UAVs and ground transport (trucks). The combined use of UAVs and trucks will lead to a reduction in traffic congestion on the roads, especially in cities. The problem of delivery of goods "on the last mile" is considered. The paper also pays attention to minimizing the energy consumption consumed by the UAV when solving problems in logistics.

Keywords: *unmanned aerial vehicle; logistics; energy consumption; joint delivery; mathematical model*

1. INTRODUCTION

Operational design and planning of logistics models using unmanned aerial vehicles (UAVs) is a rapidly growing area of scientific research. In recent years, UAVs have been widely used in logistics as environmentally friendly vehicles that do not pollute the environment with noise and exhaust gases [1,2]. The use of UAVs in logistics has a number of advantages: low cost, high technological effectiveness, prompt delivery of materials, very low energy/fuel consumption, no need for land delivery routes to almost any area of the country or part of the city [3,4].

The use of UAVs can reduce the number of vans and trucks plying around the city or country, thereby reducing ground traffic congestion, traffic congestion. The use of UAVs in the field of logistics can be different: regional transportation, express delivery to terminals, emergency logistics (rescue service) or system of the storage management (inventory, inspection, etc.).

This paper analyzes a number of methods and mathematical models that describe the process of controlling the joint delivery of goods by UAVs and ground transport (trucks), and also pays attention to the problem of minimizing the energy consumption by UAVs. The problem of delivery of goods "on the last mile" in urban conditions, i.e. at the last stage of delivery of goods to the recipient.

2. TRUCK AND UAV JOINT DELIVERY IN LOGISTICS AND REDUCTION OF CO_2 EMISSIONS

In [5], there had been studied how environmentally friendly the UAV delivery service is compared to the traditional ground delivery truck (GV) service. It is noted that since the operation of the UAV in logistics is multi-hop (frequent take-off and landing), which can lead to large power consumption, the authors proposed a two-stage approach in the optimal routing of delivery vehicles. First phase proposes schedules for UAV-only delivery systems and GV-only delivery systems that take into account maximum payload weights and fuel reserves.

In the second stage, CO_2 emissions are calculated as a measure of environmental sustainability based on the distance traveled by the vehicle along the optimal route obtained in first stage, taking into account the different speeds of the GV. The study shows that the UAV-only delivery system is significantly more efficient in terms of CO_2 emissions in all investigated UAV speed ranges.

In the course of research, in the proposed mathematical model, UAV and GV delivery schedules were compiled independently from each other based on the same depot (point of departure), technical characteristics and identical information about the client. The model proposed by the authors is able to independently create UAV and GV delivery schedules using various information (input data) about them: speed and carrying capacity, number of warehouses, number of delivery vehicles (UAV or GV) and the number of customer delivery tasks. The vehicle is characterized by its initial location (depot), speed, maximum travel distance and carrying capacity. The client is randomly distributed over the service area and is characterized by its location, demand volume, service process time, and service time window.

In the mathematical model, based on information about received deliveries, CO_2 emissions from delivery systems with only UAVs and only GVs are calculated. The study found that GV-only delivery generates at least 683 times more CO_2 than UAV-only delivery across all GV speed ranges.

3. JOINT OPTIMIZATION OF UAV ROUTING AND BATTERY WEAR

The paper [6] considers the problem of delivering the "last mile" in modern urban logistics, i.e. at the last stage of delivery of goods to the recipient. The use of UAVs has demonstrated the high commercial potential of this delivery method with a triple profit. However, the paper notes that the lithium-ion batteries that the UAV is equipped with, during processing and disposal, cause great harm to the environment. In order to maintain environmental and economic performance, it is necessary to minimize the negative impact on the environment. To do this, apply the principle of synergy in the joint use of the transport fleet. From this point of view, the possibility of application of the blockchain technology with the joint use of a fleet of vehicles to optimize the operation of UAVs exploration. At the same time, the problem of vehicle routing when sharing a vehicle fleet is associated with the optimization of two quantities: the shortest path and the shortest charging time.

Specifically, an optimal UAV trajectory has been developed that makes the best use of UAV sharing to minimize transportation and battery costs. Given the effect of battery wear, a non-linear mixed integer formula has been proposed to describe the associated cost component. Compared with the enumeration method and linear approximation, the proposed solution has shown the ability to solve this capacious problem in a short time. Experiments have been carried out to illustrate how the use of fleet sharing affects various operating costs compared to operations without fleet sharing. Given the strong impact of depth-of-discharge on battery life, UAV operators are advised to maintain a moderate depth-of-discharge level. Improvements in battery technology will help UAV operators optimize their operational planning to reduce the environmental impact of the battery. To effectively solve the problem of planning the sharing of the UAV and the fleet, an exact algorithm was developed using the graph method for 100 clients for practical use.

4. GROUND VEHICLE AND UAV ROUTING PROBLEMS FROM TWO-ECHELON SCHEME PERSPECTIVE

In recent years, much research has been devoted to optimizing a unified system of ground vehicles (GVs) and UAVs, in which GVs function as vehicles plying between points, and UAVs are means of delivering goods from GVs on the "last mile" [7]. In the proposed model of a two-echelon scheme, the GV routes originating from the depot (supplier) are in one echelon, and the UAV routes are in another echelon (consumer) [7]. Changing the GV route may affect the routes of the UAV, which indicates their mutual synchronization. In this work [7], a routing model for two-level networks is proposed based on a mechanism that connects these two echelons. Various formulations are briefly presented to describe the communication mechanisms of the two-stage scheme, in particular restrictions on GVs with a large payload, satellite synchronization, coupling/decoupling of vehicles on GVs, etc. There are several delivery route optimization modeling problems for a fleet of GV-UAV combinations that include new communication mechanisms between the two echelons. The options connected with mobile GV synchronization and GV-UAV flexible connection/decoupling are especially important.

Combined and paired modes, as well as parcel transit, require the GV and the UAV to be dependent on each other. Thanks to satellite motion synchronization, changing one GV route can affect the routes of the UAV. Most of the methods that take into account satellite synchronization and are used to design routes for two-stage networks are based on studies of two-echelon vehicle routing problem (2E-VRP), two-echelon location routing problem (2E-LRP), and truck and trailer routing problem (TTRP). The "heavy truck" constraint is the most important requirement for 2E-VRP and 2E-LRP modeling. Equipment and satellite synchronization limitations require that second tier route start points and departure times be synchronized with nodes and arrival times on first tier routes. From the point of view of the two-stage scheme, the problems of modeling the optimization of delivery routes for a fleet of combinations of GV-UAVs create new mechanisms for echelon association, for example, synchronization of cruise trucks and communication or decoupling of cruise GV-UAVs.

5. LOGISTICS SYSTEM BASED ON THE UAV, AND OPERATIVE PLANNING OF ROUTING

In [7], a structured and scalable classification of delivery systems based on UAVs is studied, and routing problems are considered with them. This classification systematically fixes the boundaries between the characteristics of the various UAV-based logistics systems and adheres with some problems of operational planning. While Pure-play multi-UAV delivery models are popular, most synchronized multi-modal delivery models focus on developing and solving a single task using a truck and a UAV. Moreover, Resupply Multi-modal models have not received adequate research attention compared to other UAV-based delivery models. Research shows that most of the models reviewed are for e-service and health/emergency applications.

In [7], UAV models are generalized for each category, taking into account their characteristics, goals and methodologies. A detailed classification and overview of logistics models based on UAV performance is proposed. Most articles deal with optimization algorithms for synchronized multimodal models and, in particular, the Flying Sidekick Traveling Salesman Problem (FSTSP). At the same time, work on other categories of models, such as the Resupply Multi-modal (RM) models, is limited. In addition, the models assume basic configurations that are far from real model configurations, such as logistics models with multiple warehouses and multiple shared main and multiple auxiliary vehicles, a realistic travel network for trucks and UAVs, dynamic and stochastic methods, and delivery models with time modes.

In all of the Synchronized Multi-modal (SM) models, it is assumed that all UAVs must move with the support vehicle (truck) and no UAVs can remain in the depot to serve customers located near the depot. Therefore, a future research direction is to combine different drone-based delivery models such as Pure-play Drone-based (PD) and SM models and evaluate the performance gains from this combination. When developing “last mile” delivery models, combining the problem of UAV and truck routing with other design and operational planning problems, such as the location and distribution of resupply points, can increase the practical relevance of these models. In addition to finding fulfillment centers, finding UAV charging stations can also be integrated with the routing problem.

In the modern literature, there is no cost analysis for logistics models using UAVs. More than 40% of papers aim to minimize travel time, while all cost minimization studies do not take into account some of the cost components of UAV logistics models, such as UAV operator hourly pay, UAV capital costs, insurance, legal issues, infrastructure, maintenance and other costs. It would be worthwhile to conduct a comprehensive analysis of UAV-based logistics models and compare their cost-effectiveness compared to other delivery methods in order to understand whether each of the models will be more profitable than conventional delivery methods.

Security and privacy are two of the main concerns associated with using UAVs to deliver packages. They have been one of the main barriers to the adoption of UAV-based delivery models. Security concerns include not only human security, but also the security of UAVs and parcels. Problems of risk, chaos and safety increase an anxiety as the more companies deliver their packages using UAVs. The design of UAV-based delivery systems requires solutions to mitigate these negative externalities and prevent chaos, for example, through the creation of dedicated airways, the development of standardized routing protocols, and stochastic risk modeling for UAV flights.

The inclusion of UAVs in the existing distribution system requires major changes in these systems. Some of these changes include changes to the location of facilities and the addition of recharging sites, infrastructure for launching and receiving UAVs, assigning space for UAVs in facilities and trucks, changes in the use of automated storage and retrieval systems, and accounting for air traffic and navigation. Exploring these systemic effects of UAV logistics operations is a highly relevant area for future research.

6. ANALYSIS OF UAV REALIZATION IN LOGISTICS

In [8], the difficulties of UAV realization in logistics using the fuzzy Delphi method (FDM) and the analytic hierarchy process (AHP) were analyzed. The study concludes that regulations and the threat to privacy and security are the most important barriers to UAV adoption in logistics. These findings can help practitioners in the effective implementation of UAVs in the logistics industry.

UAV delivery could change the traditional “last mile” delivery process using trucks. The AHP method works well when limited information is available, as is the case with UAV logistics. This study shows that regulations, privacy and security threats are the most important barriers to UAV adoption in the logistics sector. Other important obstacles are public opinion, environmental issues, technical aspects and economic aspects, in decreasing order of their criticality. For future research, this analysis can be performed with the additional complexities associated with the growth of UAV technologies and their commercialization. Despite the potential benefits of UAV logistics in improving response times and reducing costs, widespread adoption of this disruptive logistics technology is yet to be seen. The paper [8] explores various barriers to the adoption of UAV delivery in the logistics sector and ranks them based on their criticality using a two-step methodology.

7. UAV AIR ROUTE NETWORK PLANNING MODEL IN LOGISTICS

The traditional distribution of terminal logistics in urban areas is largely land-based, resulting in increasingly serious air pollution and traffic congestion. With the development of UAV technology and the legislative reform of low-altitude airspace, it is expected that the distribution of terminal logistics will be carried out by UAVs. Therefore, it is of great importance to build a reasonable air route network for logistics UAVs in order to ensure the safety and efficiency of delivery processes. In [9], unified route planning models and an air route network planning model for UAVs were constructed, taking into account the complex urban low-altitude environment and the peculiarities of logistical tasks for regulating UAV flights. Taking the Jiangjun Road Campus of Nanjing University of Aeronautics and Astronautics as an example, an advanced cellular automata (CA) method was adopted to find the optimal route between different waypoints, and an optimal spanning tree algorithm was used to build the route network.

The experimental results have shown that the improved CA method can significantly reduce search time and obtain the best route while improving safety. To meet the needs of logistics and distribution constraints, a network was generated with smaller intersection points and redundancy. The models and main ideas proposed in this article can not only regulate the operation of UAVs, but also provide a solid foundation for the proliferation of logistics UAVs in the future.

The grid method is used to perform three-dimensional modeling of the planned area at low altitude. Then, for complex urban conditions at low altitudes and UAV characteristics, an optimal route between the target points is constructed. After that, in accordance with the regional logistics needs and the characteristics of the operation of service providers, the optimal spanning tree is used to select routes. Further, a network of air routes is being built for the main and secondary routes.

A cost function was introduced into the CA algorithm, which could effectively reduce the search time, reduce unnecessary turns, and greatly reduce the length of the route. Based on this air route network planning method, a network with less congestion and fewer minor crossing airways can be organized. With dense UAV traffic, the likelihood of conflicts between different flights increases. Therefore, it is necessary to consider the possibility of resolving conflicts between UAVs. Another promising area is the study of a dynamic route network to ensure the safe and stable operation of the UAV.

8. CONCLUSION

It is calculated that CO_2 emissions from delivery systems with only UAVs and only GVs are calculated. The study found that GV-only delivery generates at least 683 times more CO_2 than UAV-only delivery across all GV speed ranges. The paper deals with the use of UAVs in logistics. A number of methods and mathematical models are analyzed that describe the process of controlling the joint delivery of goods by UAVs and ground transport. The combined use of UAVs and trucks leads to a decrease in traffic congestion on the roads, especially in cities. The problem of delivery of goods "on the last mile" is considered. It is shown that the combined use of UAVs and trucks leads to minimization of the energy consumption consumed by UAVs in logistics and, accordingly, to a decrease in the harmful impact on the environment. It is calculated that CO_2 emissions from delivery systems with only UAVs and only trucks are calculated. The study found that trucks-only delivery generates at least 683 times more CO_2 than UAV-only delivery across all trucks speed ranges.

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