Routing of Unmanned Aerial Vehicles: State of Art

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Abstract

Recently, several projects started to include unmanned aerial vehicles (UAVs) into different applications, which might create very dense airspace when UAVs start to be actually used in these applications. This paper reviews the research work performed on UAVs routing in order to identify research gaps. A total of 46 articles related to optimization of UAV routing were reviewed to highlight the most considered modeling aspects in the literature and the aspects that need to gain more focus. As a result, the most considered modeling aspects include single depot, time windows, payload, and recharging. However, aspects such as the number of trips performed by UAV (single or multiple) and other factors that may affect UAV operations such as wind and variable speed shall be considered for future work. In addition to integrating the operational concept of UAVs within the routing.

Keywords
UAV, Routing, Optimization, Mathematical Modelling, Trip number.

1. Introduction

As the technology of unmanned aerial vehicle (UAV) advances, possibilities for UAV to perform complex missions with some degree of autonomy are being considered, which requires new methods to plan the routes of a fleet of UAVs (Alighanbari, Kuwata, & How, 2003). Routing of small UAVs is one of the topics that has started to receive significant attention in the last decade (Sundar & Rathinam, 2014). Combining vehicle routing with pre-defined locations started in the early 1960s, and it advanced with the development of computer technology (Yakıcı, 2016).
Routing or path planning can be defined as "finding a route to visit a given set of points or areas under some constraints" (Ergezer & Leblebicioğlu, 2014). It is necessary to find and ensure the feasibility of UAV routes despite its complexity (Coutinho, Battarra, & Fliege, 2018). Although UAVs have several advantages, they also have constraints due to their size and limited payload. Small UAVs typically have energy constraints, which can impact the operations of the UAVs as they may not be able to complete their mission (Sundar & Rathinam, 2014). Taking a surveillance mission as an example, an UAV starts from one location (depot) and visits a set of targets. Due to the energy constraint, an UAV will have to perform multiple trips where an UAV visits a subset of targets and then recharges in one of the depots and then continues the mission. In addition, most of the UAVs used for civil applications have low flight autonomy, and therefore, the routing algorithm should include battery life (Coutinho et al., 2018). To do this, the UAVs' dynamics should be integrated with routing. A realistic model of energy consumption must include the weight of the UAV, the altitude and the speed. Therefore, this paper aims to provide a review of the research work performed on UAV routing. The paper aims to highlight which modeling aspects are the most considered in the literature and which modeling aspects need to gain more focus.

2. Methodology

A structured literature review has been conducted in this paper. Articles were gathered from the following databases and search engines: Scopus, Google Scholar, and Science Direct. A combination of synonyms of drone (drone, unmanned aerial vehicle, UAV) and synonyms of routing (routing, routes plan, path planning) were used as search keywords. More than 60 articles were downloaded, and a total of 46 articles were found relevant based on the title and keywords. The downloaded articles were filtered by skimming their abstracts, and only papers that addressed mathematical models (i.e., optimization) were kept. Figures 1 and 2 show the distribution of the reviewed articles based on the year of publication and the source of publication, respectively. The literature review provided in this paper aims to shed light on the various mathematical models' aspects, including the objective functions, model characteristics, number of depots, number of trips performed by the UAV and the method of transportation, whether a combination of road transport and UAV or only UAV. However, this paper does not focus on the solution approach of the mathematical model. As the target of the paper is to highlight the critical aspects used in drone modeling in order to excel in the model development to consider more realistic conditions. The solution approach aspect might be considered in future work.

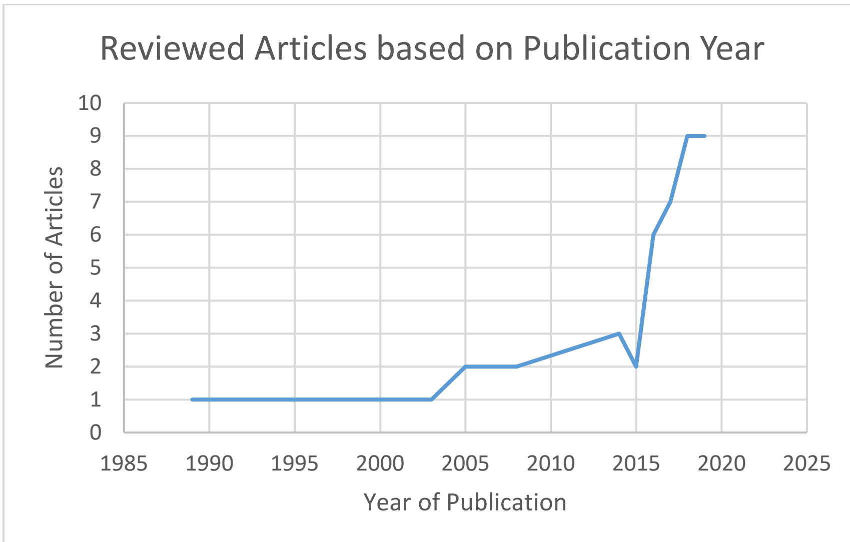

Figure 1: Reviewed articles based on year of publications

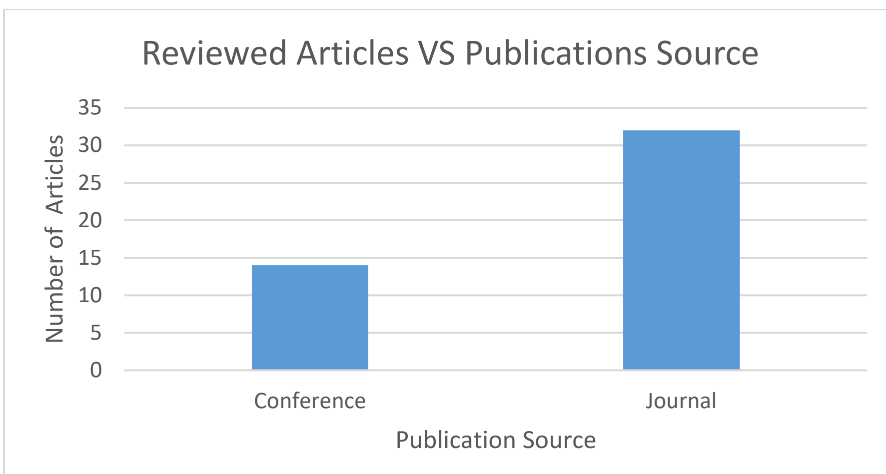

Figure 2: Reviewed articles based on publication source

3. UAV Routing and Management

The research work on UAV mission planning has increased recently. For the UAV routing, the research on combining routing with the location has developed since the early 1960s, and it increased with the development of computer technology (Yakıcı, 2016). For instance, Salhi & Rand (1989) compared optimizing routing and locations separately and optimizing them combined and found that the optimization of routing and locations separately provides inferior results.

Computing UAV routing has been studied widely in aerospace engineering (Yang et al., 2016). Several research works have been done regarding optimizing the flight trajectories. The following sections provide a detailed review of the routing optimization models developed in the literature.

3.1 Mathematical models' objectives

Some research works presented routing optimization models for UAVs with a single objective function, such as minimizing the completion time (Alighanbari et al., 2003; Avellar, Pereira, Pimenta, & Iscold, 2015; Jeong, Lee, & Song, 2019; Poikonen & Golden, 2019; Poikonen, Wang, & Golden, 2017; Schermer, Moeini, & Wendt, 2018; Wang, Poikonen, & Golden, 2017; Yurek & Ozmutlu, 2018; Zhen, Li, Laporte, & Wang, 2019), minimizing the total UAVs endurance time (Choi, Chen, Choi, Briceno, & Mavris, 2019), minimizing total fuel required (Sundar & Rathinam, 2014), minimize the battery consumption (Kim & Matson, 2017), minimizing the total distance travelled (Rabta, Wankmüller, & Reiner, 2018), minimize the waste time (Hu et al., 2019). Moreover, the objective functions include minimizing the waiting time such as the work of J. J. Enright, Frazzoli, Savla, & Bullo (2005) and John J. Enright & Frazzoli (2005) where they aimed to minimize the waiting time between target appearance and the time at which a UAV visits it, considering two cases which are the light load and heavy load cases. Similarly, (J. J. Enright & Frazzoli, 2006) aimed to minimize the average time between target appearance and visiting by UAV. Further, minimizing the delivery time, such as the work of Chang & Lee (2018) and Manyam, Rasmussen, Casbeer, Kalyanam, & Manickam (2017), which aimed to minimize the maximum of delivery time. In addition, minimizing the total cost such as the work of (Agatz, Bouman, & Schmidt, 2018; Marinelli, Caggiani, Ottomanelli, & Dell'Orco, 2018; Murray & Chu, 2015; Rathinam & Sengupta, 2006) and the work of Ha, Deville, Pham, & Hà (2018) which aimed to minimize the operational cost that is the transportation cost and the cost generated by the waste time when vehicles wait for others. Furthermore, Causa, Fasano, & Grassi (2018) developed a model that aims to maximize the efficiency of UAVs in task assignments in the absence of global navigation satellite systems (GNSS) coverage. Cheng et al. (2019) proposed a power-efficient routing algorithm for UAVs. Scott & Scott (2017) aimed to minimize total weighted time.

On the other hand, some research works presented routing optimization models with multiple objective functions. For instance, the model developed by Guerriero, Surace, Loscrí, & Natalizio (2014) aimed to minimize the total traveled distances and the number of used UAVs, as well as to maximize customer satisfaction. Further, Dorling et al. (2016) aimed to minimize the overall delivery time and the total cost. Coelho et al. (2017) aimed to minimize the following: total traveled distance, UAVs maximum speed, number of used UAVs, makespans of the last collected and delivered parcel, as well as the average time spent with each parcel. Also, Lamont, Slear, & Melendez (2007) developed a multi-objective evolutionary algorithm that aimed to minimize the cost, traveled distance, and the amount of UAV climbing to avoid terrain, as well as the risk from flying in areas of threats. Lim, Kim, Cho, Gong, & Khodaei (2016) developed a model that aimed to minimize the operating cost as well as the completion time of UAVs missions. Furthermore, Pohl & Lamont (2008) aimed to minimize the total distance traveled which will reduce the total path cost by defining three objectives, which are to minimize the path length, the number of vehicles used, and the total waiting time. Weinstein & Schumacher (2007) considered multiple objectives, which are to minimize the makespan, minimize total time, and the total distance.

3.2 Characteristics of UAV routing models

As some characteristics can affect the intended mission of UAV, several research works considered them when developing the routing optimization models. Such characteristics include mission completion time (Alighanbari et al., 2003), Loitering time (Alighanbari et al., 2003), time windows (Guerriero et al., 2014; Pohl & Lamont, 2008; Weinstein & Schumacher, 2007; Yılmaz, Yakıcı, & Karatas, 2019), recharging only at depot (Dorling et al., 2016; Sundar & Rathinam, 2014), reusability of UAVs (Dorling et al., 2016), payload (Dorling et al., 2016; Rabta et al., 2018; Shetty, Sudit, & Nagi, 2008), speed (Causa et al., 2018; Coelho et al., 2017; Dorling et al., 2016), UAV capacity (Coelho et al., 2017; Pohl & Lamont, 2008), recharging in fixed locations (Coelho et al., 2017; Rabta et al., 2018) and fuel capacity (Shetty et al., 2008).

3.3 Number of trips

Several research works developed models for UAVs performing single trip only, where the UAV goes to its intended location and returns with performing other trips. These research works include the work of (Alighanbari et al., 2003; Causa et al., 2018; Coelho et al., 2017; Guerriero et al., 2014; Murray & Chu, 2015; Rabta et al., 2018; Sundar & Rathinam, 2014; Weinstein & Schumacher, 2007; Zhen et al., 2019). However, other research works included multiple trips in their models such as (Carlsson & Song, 2017; Dorling et al., 2016; Ha et al., 2018; Hu et al., 2019; Manyam et al., 2017; Poikonen & Golden, 2019; Wang et al., 2017).

3.4 Number of depots

Some research works considered a single depot, where the UAVs launch from one location and return to it. These research works include the work of (Agatz et al., 2018; Alighanbari et al., 2003; Carlsson & Song, 2017; Chang & Lee, 2018; Choi et al., 2019; Coelho et al., 2017; Dorling et al., 2016; Ha et al., 2018; Jeong et al., 2019; Kim & Matson, 2017; Manyam et al., 2017; Marinelli et al., 2018; Murray & Chu, 2015; Pohl & Lamont, 2008; Poikonen & Golden, 2019; Poikonen et al., 2017; Rabta et al., 2018; Schermer et al., 2018; Scott & Scott, 2017; Wang et al., 2017; Weinstein & Schumacher, 2007; Yurek & Ozmutlu, 2018; Zhen et al., 2019).
On the other hand, other research works considered multiple depots where the UAVs can launch from different locations such as the work of (Causa et al., 2018; Guerriero et al., 2014; Hu et al., 2019; Rathinam & Sengupta, 2006; Sundar & Rathinam, 2014; Yakıcı, 2016).

3.5 UAVs with other transportation modes

Many research works aimed at developing routing models considering two types of transportation, which are road transportation and UAV. This research includes the work of (Kashyap, Ghose, Menon, Sujit, & Das, 2019; Poikonen & Golden, 2019) and (Agatz et al., 2018) where they compared between using road transportation and a combination of UAV and road transportation. Also, the work of Carlsson & Song (2017) where the UAV picks the parcel from a truck, deliver it to and then return to the truck to start new delivery. Chang & Lee (2018) considered both UAV and a truck for delivery where most areas need to be covered by the UAV. Jeong et al. (2019) considered the effect of payload on UAV energy consumption as well as the no-fly zones as per the FAA regulations in their Truck-Drone optimization model. Marinelli et al. (2018) considered a combination of UAV and truck for parcel delivery where the truck can deliver and pick up the UAV along the route, and not only at specific points. Ferrandez, Harbison, Weber, Sturges, & Rich (2016) studied the effectiveness of using trucks and UAVs in terms of time and energy compared with using trucks only. They also developed an algorithm to determine the optimal launch locations based on delivery requirements. Further, Ha et al. (2018) developed a model that minimizes the operational cost which includes that transportation cost and the cost generated by the waiting time of the truck and the UAVs when waiting for other vehicles. Yurek & Ozmutlu (2018) proposed an algorithm to minimize the delivery time for UAV launching from a truck. Hu et al. (2019) proposed an algorithm to support the collaboration of one vehicle and multiple drones to be used for inspection applications, which aim to minimize time wastage for both the vehicle and UAVs. Kim & Matson (2017) considered a combination of UAVs and vehicles and proposed a model that minimize the battery consumption of the UAVs used for delivery and optimize the total weighted mileage of UAVs. Murray & Chu (2015) proposed two models aiming to minimize the cost of using a truck and UAVs. Also, Chiang, Li, Shang, & Urban (2019) aimed to minimize the total cost of using a vehicle and UAV. Poikonen et al. (2017) proposed a model that aimed to minimize the delivery completion time when using trucks and UAVs, where UAV returns to the truck to recharge or swap batteries after delivering the parcels. Schermer et al. (2018) aimed at minimizing the maximum completion time to serve all customers using a combination of trucks and UAVs. Moreover, Scott & Scott (2017) proposed two models for UAVs used for healthcare delivery. The first model minimizes the total weighted time for delivery using a combination of truck and UAV, subject to cost and UAV travel distance constraint. The second model aims to Minimize the Maximum weighted time for delivery subject to cost and UAV travel distance constraint. Wang et al. (2017) aimed to minimize the maximum completion time for package delivery using trucks and UAVs, where the UAV launches from the truck and return to it.

4. Summary of routing optimization research

Routing research can be described in terms of *optimization objectives*, route *characteristics*, and *cross-modality*. *Optimization objectives* include completion time; UAV endurance; fuel consumption; battery consumption; travel distance; waste time; waiting time; and delivery time. Further, optimization research has addressed composite functions, including optimizing and balancing several objectives. The *main routing characteristics* are the number of trips and depots. *Secondary routing characteristics* are items such as mission completion time, loitering time, time windows, recharging locations, UAV reusability, payload, speed, and capacity. *Cross-modality* has been studied in particular regarding UAV and road transport, introducing issues such as no-fly zones, cross-modal energy consumption, launch locations, total operational cost, UAV delivery times in cross-modal scenarios, time wastage, battery consumption, completion time (including battery recharging/swap times). Table 1 below provides a summary of the literature review.

Table 1: Summary of the Literature Review

Author	Objectives		Route Characteristics				Cross-modality
			Depot		Trips		
	Single	Multiple	Single	Multiple	Single	Multiple	
Alighanbari et al. (2003)	✓		✓		✓		
Rathinam & Sengupta (2006)	✓			✓			
Weinstein & Schumacher (2007)		✓	✓		✓		
Pohl & Lamont (2008)		✓	✓				
Guerriero et al. (2014)		✓		✓	✓		
Sundar & Rathinam (2014)	✓			✓	✓		
Avellar et al. (2015)	✓		✓				
Murray & Chu (2015)	✓		✓		✓		✓
Dorling et al. (2016)		✓	✓			✓	
Yakıcı (2016)	✓			✓			
Wang et al. (2017)	✓		✓			✓	✓
Coelho et al. (2017)		✓	✓		✓		
Kim and Matson (2017)	✓		✓				✓
Poikonen et al. (2017)	✓		✓				✓
Manyam et al. (2017)	✓		✓			✓	
Carlsson & Song (2017)			✓			✓	✓
Scott & Scott (2017)	✓		✓				✓
Schermer et al. (2018)	✓		✓				✓
Yurek & Ozmutlu (2018)	✓		✓				✓
Ha et al. (2018)	✓		✓			✓	✓
Rabta et al. (2018)	✓		✓		✓		
Causa et al. (2018)	✓			✓	✓		
Agatz et al. (2018)	✓		✓				✓
Chang & Lee (2018)	✓		✓				✓
Marinelli et al. (2018)	✓		✓				✓
Poikonen & Golden (2019)	✓		✓			✓	✓
Zhen et al. (2019)	✓		✓		✓		
Choi et al. (2019)	✓		✓				

Hu et al. (2019)	✓			✓		✓	✓
Jeong et al. (2019)	✓		✓				✓

5. Conclusion

In conclusion, UAV routing is one of the topics that has started to receive significant attention in the last decade. In this paper, we presented a review of the research works developed for UAV routing and path planning. We have found considerable variation in the characteristics studied. Although our summary has shown that the research at large has covered a rich variety of optimization characteristics, each study has had a much more narrow focus on very few characteristics. The most considered modeling aspects in the literature were a single depot, time windows, payload, and recharging. Some research works included additional characteristics in their models such as fuel capacity of UAVs, customer time windows, UAV recharging either at the depot or at fixed recharging stations, payload size, UAV speed, and capacity. Although some models considered only one depot, others considered multiple depots. In addition, some research works considered a combination of road transport and UAV for delivery applications. Future research could, on the one hand, focus on widening the range of characteristics considered, such as the number of trips performed by UAV (single or multiple) and other factors that may affect UAV operations such as wind and variable speed. On the other hand, future research could focus on integrating and balancing the numerous factors identified here into more complex comprehensive models. Finally, integrating the operational concept of UAVs within routing shall be considered in future research. For instance, route flexibility in the light of changing airspace constraints (e.g. unplanned geofences, route interference due to congestion or unregistered drone activity), and contingencies should be considered.

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