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The unmanned aerial vehicle routing and trajectory optimisation problem, a taxonomic review

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ABSTRACT

Over the past few years, Unmanned Aerial Vehicles (UAVs) have become more and more popular. The complexity of routing UAVs has not been fully investigated in the literature. In this paper, we provide a formal definition of the UAV Routing and Trajectory Optimisation Problem (UAVRTOP). Next, we introduce a taxonomy and review recent contributions in UAV trajectory optimisation, UAV routing and articles addressing these problems, and their variants, simultaneously. We conclude with the identification of future research opportunities.

1. Introduction

Unmanned Aerial Vehicles (UAVs) are aircraft that do not need a human pilot on board. In general, these vehicles are either controlled by an embedded computer or by a pilot operating a remote control. Drones, remote controlled helicopters and unmanned gliders are examples of UAVs. Gliders differ from the other types due to the lack of on-board propulsion (e.g., an electric or combustion engine). Modern UAVs were first developed in the 1920s to support military operations in which the presence of human pilots was either impossible or too dangerous (Beard & McLain, 2012; Keane & Carr, 2013). However, UAVs have recently become very popular for logistics and surveillance applications (Tsourdos, White, & Shanmugavel, 2010).

A report from the National Purchase Diary has shown that sales of drones increased by 224% in twelve months from April 2015, reaching a total of 200 million dollars (NPD, 2016). Due to being able to embed several transmitters, sensors and photographic equipment, UAVs can be used in a large range of applications. Successful cases have been reported in, for example, aerial reconnaissance (Ruzgienė, Berteška, Gečyte, Jakubauskienė, & Aksamitauskas, 2015), aerial forest fire detection (Yuan, Zhang, & Liu, 2015), target observation (Rysdyk, 2006), traffic monitoring and management (Kanistras, Martins, Rutherford, & Valavanis, 2013), online commerce (Wang, Poikonen, & Golden, 2017), geographical monitoring (Uysal, Toprak, & Polat, 2015), scientific data collection (Stöcker, Eltner, & Karrasch, 2015), meteorological sampling (Elston et al., 2014) and disaster assessment and response (Nedjati, Vizvari, & Izbirak, 2016; Quaritsch et al., 2010; Xu et al., 2014). In Hayat, Yanmaz, and Muzaffar (2016), several applications of UAV networks are reviewed. The use of UAVs for 3D mapping is surveyed in Nex and Remondino (2013). A literature review about the applications of UAVs in humanitarian relief is provided by Bravo and Leiras (2015). More examples of the growing applications of UAVs are presented in Rao, Gopi, and Maione (2016).

The academic routing community has acknowledged the interest of companies and organisations in adopting UAVs in their operations. A recent example is the approach of combining UAVs and trucks for distribution activities by dispatching drones from trucks for the last mile distribution within city centres (Ha, Deville, Pham, & Há, 2015; Murray & Chu, 2015; Wang et al., 2017). It has been shown that this solution can reduce truck travel time, and the corresponding CO_2 emissions, by up to 50%. The UAV Task Assignment Problem (UAVTAP), which is closely related to the UAV routing problem, consists of optimising the assignment of a set of UAVs to a set of tasks subject to mission constraints (Khamis, Hussein, & Elmogy, 2015). A growing body of literature appeared on the UAVTAP in the last decade, e.g., Ramirez-Atencia, Bello-Orgaz, R-Moreno, and Camacho (in press), Wang, Zhang, Geng, Fuh, and Teo (2015), Hu, Cheng, and Luo (2015a), Thi, Nguyen, and Dinh (2012), Alidaee, Gao, and Wang (2010) and Edison and Shima (2011). However, the UAV routing and task assignment literatures have often neglected constraints due to the flight dynamics of the UAVs. Finding feasible trajectories for UAVs in a routing problem is a complex task, but it is necessary to ensure the feasibility of the UAVs routes. For some real-world applications involving more complex UAV systems, such as unmanned gliders and fixed-wing vehicles, the definition of routes must be coupled to the design of flyable trajectories, otherwise the assigned routes might become inefficient or

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even infeasible for these UAVs.

Most of the UAVs used for civil applications present a low flight autonomy. Therefore, it is important for UAV routing algorithms to properly model battery life. According to Fügenschuh and Müllenstedt (2015), this can be achieved by integrating the UAVs' dynamics with routing. As mentioned by the authors, for powered UAVs, a proper modelling of the actual fuel consumption must include, for instance, the current weight, the altitude, the speed and climb/descent rate, which are usually modelled by flight dynamics.

Zhang, Chen, and Shen (2012) consider a problem where a UAV must visit a set of targets. However, after reaching a predetermined distance from a target the UAV must then adjust its *flight attitude* (i.e., its orientation) in order to perform a payload delivery. After the delivery, the UAV must complete an *escape manoeuvre* and prepare for the next delivery. According to Zhang et al. (2012), routing and trajectory optimisation must be integrated in order to ensure the safety of the vehicle and the feasibility of trajectories.

The computation of trajectories for UAVs has been widely studied in the aerospace engineering and optimal control literature (Yang et al., 2016). The Trajectory Optimisation (TO) problem consists of finding a *control history* of a given vehicle, that minimises a scalar performance index (for example, flight time or fuel consumption) while satisfying constraints on the kinematics (position, velocity and acceleration) and the dynamics (forces and moments) of the vehicle (Betts, 1998). A trajectory is generally associated with a set of Equations of Motion (EOMs) that describe the relationship between the spatial and the temporal changes to the system. The TO problem is closely related to the Optimal Control (OC) problem (Betts, 2001).

The problem named Path Planning (PP) consists of finding a flyable path for a UAV visiting a given sequence of waypoints (targets) in a two-dimensional (2D) or three-dimensional (3D) space without considering the vehicle's dynamics. According to Gasparetto, Boscariol, Lanzutti, and Vidoni (2015), PP is a *geometric* problem, because it is defined as finding a geometric path regardless any specified time law. In turn, TO consists of assigning a time law to a controlled geometric path.

More complex variants of the PP problem including, for instance, wind and motion constraints, require substantial simplifications and assumptions to be solved heuristically (Kunchev, Jain, Ivancevic, & Finn, 2006; Rathinam & Sengupta, 2007). The books by Tsourdos et al. (2010) and Beard and McLain (2012) provide good overviews of PP algorithms for UAVs. On the other hand, high fidelity TO models (i.e., using more accurate physical models) have been developed for aircraft and spacecraft (Conway, 2010; Colasurdo, Zavoli, Longo, Casalino, & Simeoni, 2014; Fisch, 2011; García-Heras, Soler, & Sáez, 2014; Raivio, Ehtamo, & Hämäläinem, 1996). These models are currently solved by OC techniques. An overview of OC methods for TO is provided in Betts (1998, 2001).

The field of TO has however not considered routing decisions: given a set of ordered waypoints, it is possible to find a feasible trajectory for a generic UAV, but it is not clear in the literature if the sequence of waypoints is appropriate. For example, for a gliding vehicle (i.e., with no onboard thrust) a given waypoint sequence might be infeasible in terms of flight dynamics. Given a fleet of UAVs, it is an open question how to combine routing and trajectory decisions in a single optimisation problem. As far as the authors are aware, there is not a survey summarising the literature about routing and trajectory optimisation for UAVs.

Research about integrated routing and TO problems seems to be still fragmented. One of the main contributions of this paper is introducing the UAV Routing and Trajectory Optimisation Problem (UAVRTOP). We believe that integrating TO and routing in a single optimisation problem is a key research challenge in adopting UAVs for real world applications.

The purpose of this survey is to present the UAVRTOP, highlighting approaches already proposed in the literature and providing a direction for further research. We introduce a taxonomy, that is able to identify the key components of routing and TO problems, as well as highlight assumptions and simplifications commonly adopted in the literature.

The remainder of this paper is organised as follows. In Section 2, we formally define the UAVRTOP. In Section 3, a background on TO problems is provided. The same is done in Section 4 for vehicle routing problems. In Section 5, a taxonomy of UAV routing and TO problems is provided. An application of the proposed taxonomy to a selected number of papers is demonstrated in Section 6. This section continues with an analysis of the results obtained from the taxonomic review. In Section 7, we discuss future research opportunities.

2. The UAV routing and trajectory optimisation problem

In this section, we formally define the UAV Routing and Tra jectory Optimisation Problem (UAVRTOP), the problem in which a fleet of UAVs has to visit a set of waypoints assuming generic kinematics and dynamics constraints. Wind conditions, collision avoidance between UAVs and obstacles can also be incorporated in the model.

2.1. A mathematical formulation for the UAVRTOP

In the following, we assume a fleet C of UAVs is available at the launching site 0. Let $G = (V,A)$ be a graph, where the set V represents all the waypoints that need to be visited by the UAVs and A represents the set of arcs between waypoints. In addition, let $0'$ represent the landing site. The cost of using a vehicle $k \in C$ is F_k. The parameters (e.g., mass, wing area, aerodynamics coefficients) of the UAV k travelling between i and j are stored in the vector $\mathbf{p}_{ijk}$. Note that these parameters may change during the mission due, for example, to a change in flight mode (if hybrid UAVs are used). The state of a UAV is a vector fully defining the position, orientation and velocity of the vehicle in some coordinate system (alternative state representations will be described in Section 3).

For simplicity, we recall $\mathbf{y}_{ijk}(t_{ijk}) \in \mathbb{R}^{n_y^k}, n_y^k \in \mathbb{Z}$, the state variable of the UAV k travelling between waypoints i and j at time $t_{ijk} \in \mathbb{R}$. Similarly, the control variables model the inputs that are given to the physical systems in order to achieve a desired trajectory. Typical control variables for UAVs are the thrust (the impulse given by the UAV engine, if any), the roll angle, a.k.a. bank angle (which banks the aircraft to change its horizontal flight direction), and the angle-of-attack (which is related to how much lift the aircraft's wing generate). We define $\mathbf{u}_{ijk}(t_{ijk}) \in \mathbb{R}^{n_u^k}, n_u^k \in \mathbb{Z}$, the control variables for a UAV k flying on arc (i,j) at time $t_{ijk} \in \mathbb{R}$.

The physical laws governing the UAV k travelling between the waypoints i and j at time t_{ijk} are referred as *system dynamics*. In general terms, the system dynamics can be expressed by a set of EOMs in the form of a system of Ordinary Differential Equations (ODEs) as follows:

$$\dot{\mathbf{y}}_{ijk} = \mathbf{f}_k(\mathbf{y}_{ijk}(t_{ijk}),\mathbf{u}_{ijk}(t_{ijk}),\mathbf{p}_{ijk},t_{ijk}) \quad \forall\ i,j \in V, \quad \forall\ k \in C \tag{1}$$

The functions $\mathbf{f}_k, \forall\ k \in C$, in the right hand side of the EOMs (1), represent the relationship between the variables and parameters with the derivatives over time of the state variables (here denoted by "·").

State and control variables have to be specified for a time instant to initialise the ODEs. In what follows, we assume that the initial conditions need to be specified at time $t = 0$. It is also reasonable to assume that only the control variables need to be optimised since the values of the states can be determined, provided an initial condition and the evolution of the controls over time.

Let $w_k(.)$ be a function computing the cost of using UAV k along an arbitrary trajectory. The routing cost for a UAV k to travel between waypoints i and j can be computed as:

$$\int_{t_{ijk}^o}^{t_{ijk}^f} w_k(\mathbf{y}_{ijk}(t_{ijk}),\mathbf{u}_{ijk}(t_{ijk}),\mathbf{p}_{ijk},t_{ijk})\mathrm{d}t_{ijk}. \tag{2}$$