Applied Mathematical Modelling 38 (2014) 839–852

Contents lists available at SciVerse ScienceDirect

Applied Mathematical Modelling

journal homepage: www.elsevier.com/locate/apm

# A multi-objective approach for unmanned aerial vehicle routing problem with soft time windows constraints ☆

F. Guerriero [a,*], R. Surace [a], V. Loscrí [a], E. Natalizio [b]

[a] University of Calabria, Italy
[b] Heudiasyc, UMR CNRS 7253, Université de Technologie de Compiègne, France

ARTICLE INFO

Article history:
Received 27 June 2012
Received in revised form 1 June 2013
Accepted 2 July 2013
Available online 20 July 2013

Keywords:
UAV routing problem
Multicriteria optimization
VRP with soft time windows
$\epsilon$-Constraint method

ABSTRACT

Aerial robotics can be very useful to perform complex tasks in a distributed and cooperative fashion, such as localization of targets and search of point of interests (PoIs). In this work, we propose a distributed system of autonomous Unmanned Aerial Vehicles (UAVs), able to self-coordinate and cooperate in order to ensure both spatial and temporal coverage of specific time and spatial varying PoIs. In particular, we consider an UAVs system able to solve distributed dynamic scheduling problems, since each device is required to move towards a certain position in a certain time. We give a mathematical formulation of the problem as a multi-criteria optimization model, in which the total distances traveled by the UAVs (to be minimized), the customer satisfaction (to be maximized) and the number of used UAVs (to be minimized) are considered simultaneously. A dynamic variant of the basic optimization model, defined by considering the rolling horizon concept, is shown. We introduce a case study as an application scenario, where sport actions of a football match are filmed through a distributed UAVs system. The customer satisfaction and the traveled distance are used as performance parameters to evaluate the proposed approaches on the considered scenario.



## 1. Introduction

Technological advances in the area of unmanned aerial vehicles (UAVs, for short), commonly known as drones, are opening new possibilities for creating teams of vehicles able to perform complex missions with some degree of autonomy. A possible application of a team of UAVs, equipped with camera (referred to as camera-drones), is represented by a live sporting event filming, where the use of the camera-drones gives the audience the feeling to be part of the sport competition itself.

This kind of application falls in the general class of dynamic and distributed scheduling problems, whose aim is to ensure both spatial and temporal coverage of given set of point of interests (PoIs). In the specific case of sport event, a PoI could be the movement of the ball that has to be followed and filmed. The spatial coverage implies that the PoI where the event occurs will be "covered", whereas the temporal coverage is related to a time constraint associated to the event. In practice, the PoI needs to be covered when the event starts and for the whole duration of the event itself. Based on the previous considerations, it is evident that the strategic level of the mission planning needs a dynamic scheduler, deciding what event the system should consider at each time and which drone should be used. In addition, the concept of soft time windows is used to

☆ This work has been carried out in the framework of the Labex MS2T, which is funded by the French Government, through the program "Investments for the future", managed by the National Agency for Research (Reference ANR-11-IDEX-0004-02).

* Corresponding author. Tel.: +39 0984 494620; fax: +39 0984 494713.

E-mail addresses: francesca.guerriero@unical.it (F. Guerriero), rsurace@deis.unical.it (R. Surace), vloscri@deis.unical.it (V. Loscrí), enrico.natalizio@hds.utc.fr (E. Natalizio).

0307-904X/$ - see front matter 
http://dx.doi.org/10.1016/j.apm.2013.07.002

take into account temporal coverage constraints. Soft time concept allows us to find feasible scheduling schemes by introducing a penalty in terms of lower satisfactions of the customers every time a drone is not able to reach "quickly" a PoI.

In this paper, we present a mathematical formulation of the UAVs routing problem in which conflicting objectives are optimized simultaneously. In particular, the proposed multi-criteria optimization model takes into account three objective functions: the total distances traveled by the UAVs (to be minimized), the customer satisfaction (to be maximized) and the number of used UAVs (to be minimized). The customer satisfaction is modeled by using soft time windows constraints. Since the considered criteria are conflicting objectives and thus it is not possible to find a unique optimal solution, the $\epsilon$-constraint method [1] is applied to determine the set of efficient solutions. In addition, in order to capture the dynamicity of the considered scenario, a rolling horizon approach is defined.

Since the problem we deal with in this work belongs to the NP-hard class, we have also considered some efficient heuristics and compare their behavior with the benchmark obtained by using the optimization model, in terms of minimization of distance traveled and maximization of customer's satisfaction. The rest of the paper is organized as follows. Section 2 is devoted to a presentation of the related works. The UAVs routing problem and the proposed multi-criteria optimization model for its representation are described in Section 3. The solution strategies developed to define the set of efficient solutions are presented in Section 4, whereas their behavior is evaluated experimentally in Section 5. The paper ends with some concluding remarks given in Section 6.

## 2. Related works

The main motivation for this work comes from the development of UAVs that have many characteristics that make them attractive for cooperative monitoring applications [2]. UAVs can be tailored for a specific mission and are typically low-cost. These characteristics make them very useful in disaster related situations [3,4] and able for performing complex missions with some degree of autonomy. Typically, this kind of networks is mainly used in Information, Surveillance and Reconnaissance missions (ISR) [5]. In some cases ISR can be represented effectively through dynamic scheduling problems.

In this work we address a task scheduling problem combined with the motion planning one, aimed at reaching a certain coverage degree both spatial and temporal. This specific application belongs to the general class of Dynamic Vehicle Routing (DVR) problem. For this reason, in what follows the terms "vehicle", "drone" and "UAV" are used in an interchangeable way.

Similarly to [5], we focus on mission planning at the strategic level, deciding what event the system should consider at each time and which vehicle must be used. In [5] authors consider available a probabilistic description of the environments dynamics, whereas we consider a rolling horizon approach to face with the dynamicity of the environment. Moreover, authors in [5] add switching costs penalizing the travel of vehicles between the sites to inspect, while we consider the costs associated to the "transition" of a vehicle from a point to another point, by considering explicitly the distances associated to.

Another example of dynamic scheduling application has been considered in [6]. They consider $m$ aircrafts tracking the positions of $n$ submarines with $m < n$, so that aircraft has to change task from time to time if each submarine needs to be monitored. Authors consider a restless version of the Multi-Armed Bandit Problem (MABP), in order to accomplish simultaneous events observation with a smaller number of aircrafts. In the specific application scenario we considered in this work, we only consider an active event at each time, but the proposed optimization model is defined to handle simultaneous events and heuristics can easily be tailored to consider events occurring at the same time. Moreover, in [6] authors do not introduce explicitly the soft time windows concept. In fact, while a submarine is under observation information associated to are gained. While it is not, information is being lost. In our approach, we explicitly introduce the satisfaction parameter in order to quantify the degree of observation of the events and we measure the effectiveness of the approaches in terms of degree of satisfaction and in terms of costs, namely, the distance traveled by UAVs.

In [4] the main goal is to provide overview images of certain regions with a specified resolution. Typically they need multiple images in order a certain area to be covered. Optimization criteria are minimizing the number of pictures and energy consumption and maximizing the coverage. They formulate their problem as an integer linear programming model. In practice, they consider only a spatial coverage type while the optimization formulation and the heuristics we derived focus on both spatial and temporal coverage. In fact, we formulate our problem as a particular instance of the VRP.

An example of dynamic UAV routing problem is considered in [7]. Specifically, they focus on scheduling UAVs in military operations subject to dynamic movement and control constraints. In their approach, the authors do not consider explicitly time windows concept while we need to introduce explicitly the concept of time in order to make the dynamic scheduling more effective with time constraints applications. Moreover, they consider a central far controller and take into account of this in the mathematical model. While, we assume UAVs able to communicate and self-organize in a distributed fashion. In [8] authors consider a VRP with soft time windows in a fuzzy random environment. They focus on the minimization of the distance traveled and the maximization of the satisfaction of the customers. The concept of soft time windows is realized through the concept of fuzzy random environment.

## 3. Problem statement and mathematical formulation

The considered scenario is characterized by a set of UAVs that fly over a finite dimension area in order to reach all the events, which occur in a finite time horizon. The satisfaction degree achieved by the customer is determined by considering the instant of the time that a drone reaches a particular event location. Indeed, it is a measure of the temporal event coverage.