European Journal of Operational Research 238 (2014) 348–362

Contents lists available at ScienceDirect

European Journal of Operational Research

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

Innovative Applications of O.R.

Online stochastic UAV mission planning with time windows and time-sensitive targets

Lanah Evers [a,b,c,*], Ana Isabel Barros [a,b], Herman Monsuur [b], Albert Wagelmans [c]

[a] TNO, P.O. Box 96864, NL-2509 JG, The Hague, The Netherlands
[b] Netherlands Defence Academy, Faculty of Military Sciences, Enys House, Het Nieuwe Diep 8, 1781 AC, Den Helder, The Netherlands
[c] Econometric Institute, Erasmus University Rotterdam, P.O. Box 1738, 3000 DR, Rotterdam, The Netherlands

ARTICLE INFO

Article history:
Received 17 June 2013
Accepted 8 March 2014
Available online 17 March 2014

Keywords:
Stochastic orienteering problem
Time windows
Online planning

ABSTRACT

In this paper we simultaneously consider three extensions to the standard Orienteering Problem (OP) to model characteristics that are of practical relevance in planning reconnaissance missions of Unmanned Aerial Vehicles (UAVs). First, travel and recording times are uncertain. Secondly, the information about each target can only be obtained within a predefined time window. Due to the travel and recording time uncertainty, it is also uncertain whether a target can be reached before the end of its time window. Finally, we consider the appearance of new targets during the flight, so-called time-sensitive targets, which need to be visited immediately if possible. We tackle this online stochastic AV mission planning problem with time windows and time-sensitive targets using a re-planning approach. To this end, we introduce the Maximum Coverage Stochastic Orienteering Problem with Time Windows (MCS-OPTW). It aims at constructing a tour with maximum expected profit of targets that were already known before the flight. Secondly, it directs the planned tour to predefined areas where time-sensitive targets are expected to appear. We have developed a fast heuristic that can be used to re-plan the tour, each time before leaving a target. In our computational experiments we illustrate the benefits of the MCS-OPTW planning approach with respect to balancing the two objectives: the expected profits of foreseen targets, and expected percentage of time-sensitive targets reached on time. We compare it to a deterministic planning approach and show how it deals with uncertainty in travel and recording times and the appearance of time-sensitive targets.

1. Introduction

Unmanned Aerial Vehicles (UAVs) are valuable assets in information gathering for both military and civilian purposes. UAVs are aircraft without a human pilot actually on board, and are therefore remotely operated from a control station on the ground. They can be used to record still and full motion and even real-time imagery of certain 'target' locations or areas of interest. In military missions, they are used for example to inspect locations where possibly Improvised Explosive Devices (IEDs) were placed by insurgents (Royset & Reber, 2009). An example of the use of UAVs for a civilian purpose is to provide up-to-date information about locations where riots may potentially arise during sports events, in order to adequately direct a police force to the conflict locations, if necessary (Evers, 2012).

Due to resource limitations with respect to available time, UAV fuel capacity and/or the number of available UAVs, the number of interesting targets is often larger than the number of targets that can be visited during one mission. One relatively simple model to obtain a design of a UAV tour in such situations is the Orienteering Problem (OP). The OP is a generalization of the well-known Traveling Salesman Problem (TSP). The OP is defined on a graph where a weight is associated to each arc and a profit value is associated to each node. Contrary to the TSP, the OP does not require all nodes to be visited. The aim is to find a tour, starting and ending at a depot location, that maximizes the total profit of all nodes selected in the tour, such that the total weight of the arcs in the tour does not exceed a predefined capacity. For a comprehensive survey on this problem see Vansteenwegen, Souffriau, and van Oudheusden (2011). When modeling the design of the UAV tour as an OP, the profit values represent the importance of the targets and the weights model the time required to fly from one target to the other. In this paper, we consider the situation where the duration of the UAV mission should not exceed a predefined time limit,

---

* Corresponding author at: Quintiq, The Netherlands.
E-mail address: lanah.evers@quintiq.com (L. Evers).

http://dx.doi.org/10.1016/j.ejor.2014.03.014
0377-2217/

zzzrepresented by the capacity in the OP. Such time constraint is relevant when the UAV has to be deployed for another mission at a predefined moment or is only available for a limited amount of time in case the UAV is a shared asset between several stakeholders. The UAV will start and end its tour at the UAV recovery point, represented by the depot location in the OP.

The standard OP has to be extended and/or adjusted to fit the dynamics and complexity of a specific UAV mission situation. We will discuss three different elements that are often encountered in reality in UAV mission planning. First, due to deviations from the expected weather circumstances, the experience of the UAV operator, and recording times that may take longer or shorter than expected, the real time required to complete the planned tour will deviate from the expected time. Obtaining the UAV tour by a standard OP where this uncertainty is ignored, is likely to result in an infeasible or suboptimal flight plan. Thus, the first extension considers the OP with uncertain travel and recording times.

Another extension of the OP is required when some or all of the recordings times can only start within a specific time interval to obtain the associated information. For example, the geographical characteristics of the locations to be visited (like a location close to mountains), and expected meteorological circumstances (like fog or shadows around these mountains) might require that the process of collection information must start at certain moments of the day. The same holds for Improvised Explosive Device (IED) detection which can be done by comparing imagery of a specific area, taken on different days, and by examining whether significant changes in the surface are visible. In order to enable a meaningful imagery comparison, imagery collection should start in similar circumstances and time periods, in order to reduce the influence of, for instance, shadows. The extension that addresses the OP with time intervals is known as the OP with Time Windows (OPTW), which was first introduced by Kantor and Rosenwein (1992).

As a third extension, in a more dynamic situation, a UAV tour should be designed by taking into account the possibility that during the flight emergency recordings, new targets, become known and should take place. In this paper these new targets are the so-called 'time-sensitive' targets, which have priority over the so-called foreseen targets. They are only worthwhile visiting within a predefined time limit, the emergency reaction time defined by the mission type. Therefore, the UAV will be sent to such a target as soon as it appears if remotely possible, considering the uncertainty in the time required to travel to the target. In this dynamic situation, at each moment of the flight, the UAV is either on its way to a foreseen target, on its way to a new target that has just appeared, recording or waiting to start recording at a target, or on its way back to the depot. As long as no new targets have appeared, the UAV flies from one foreseen target to the next. Profits are obtained by recording foreseen targets that are reached in time and for which the recording time could be completed, without interruption. We focus on the situation where the possible locations of time-sensitive targets are known beforehand. In the remainder of this paper, we will often use the term 'new targets' to denote time-sensitive targets that appear during the flight of the UAV. Planning problems that take new information in the problem instance into account during the execution stage of the plan are often referred to as 'online' planning problems.

In reality, the available mission time will be partly devoted to new targets, and partly to foreseen targets. In case a planned tour to foreseen targets is purposely located in the proximity of the locations where new targets are expected to appear, the UAV will likely be in time to record a new target if it appears. On the other hand, when the planned tour does not take the possible locations of new targets into account beforehand, the expected profit to be obtained from foreseen targets might be higher. It is therefore worthwhile to consider in advance how much emphasis should be put on the possible appearance of these new, time-sensitive targets, when designing the planned tour: the 'online stochastic UAV mission planning problem with time windows and time-sensitive targets'.

To this end, we propose a re-planning type of approach that constructs a tour that balances the ability of the UAV to maximize the total expected profit obtained by recording foreseen targets and the ability of the UAV to timely reach new targets, taking into account time window constraints as well as uncertainty in travel and recording times. This approach starts by constructing a tour using the available information, and hence determining the first target to be visited. After completing recording at this target and if no time-sensitive target has appeared, the next foreseen target to visit is determined by re-planning the tour based on past travel and recording time realizations. This re-planning is based on the 'Maximum Coverage Stochastic Orienteering Problem with Time Windows' (MCS-OPTW), which we will introduce in this paper. The MCS-OPTW planning approach provides a path from the current location to the depot, containing only foreseen targets. The next target planned to be visited, is the first target in this path.

In executing this re-planning procedure, the MCS-OPTW balances two objectives: maximizing the expected profit obtained by recording foreseen targets and maximizing the so-called expected Weighted Location Coverage (WLC) of the path. The WLC relates to the distance of the arcs to locations where new targets are expected to appear. Hence, by this second objective, the MCS-OPTW selects foreseen targets such that the UAV will be sent in the direction of areas where new targets are expected to appear. In both objectives the expected values are determined based on predefined probability distributions of the travel and recording times. We will show that the OP requires a special approach to deal with uncertainty, which is quite different from the existing approaches developed for related problems, such as the TSP and the Vehicle Routing Problem (VRP) with weight uncertainty and time windows.

We have developed a heuristic that can be applied in real-time to obtain good solutions to the online stochastic orienteering problem with time windows and time-sensitive targets. In the event a time-sensitive target appears, the UAV will be re-tasked to that target if the probability of reaching that target in time is above a predefined lower bound, which depends on the current location of the UAV and the location of this new target. It may result in interrupting the recording of a foreseen target. Before leaving a (time-sensitive or foreseen) target, the MCS-OPTW planning approach is used to determine the foreseen targets to be visited next. This re-planning process continues, until the remaining time capacity limitations enforce the UAV to return to the recovery point. In our experiments we will compare the performance of this re-planning approach based on the MCS-OPTW to that of a deterministic re-planning approach, regarding both the average profit obtained by recording foreseen targets and the average percentage of new targets that are reached on time. The maximum computation time required to re-plan the tour lies between one and three seconds, depending on the test setting. We will also show the effect of balancing the objectives of the MCS-OPTW on the topology of the planned tours, and we will test if this approach is robust against deviations between the actual and the assumed probability distributions.

The approach based on the MCS-OPTW is not only applicable to UAV mission planning, but also to other (economic, or safety and security) applications. For example, ensuring the quick presence of police to respond to emergency calls is of the utmost importance. In particular, the Dutch Ministry of Security and Justice has recently prescribed that at least 80 percent of all emergency calls have to be reached within 15 minutes, (Nationale politie op koers, 2013). Our model could be applied to designing police tours that on one hand provide an efficient selection and ordering of