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Joint routing and aborting optimization of cooperative unmanned aerial vehicles

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ABSTRACT

This paper incorporates the abort policy into the routing problem of unmanned aerial vehicles (UAV). In order to serve a number of targets, some UAVs can be deployed each visiting part of the targets. Different from other works on routing of UAVs, it is assumed that each UAV may experience shocks during the travel. In order to reduce the expected cost of UAV destruction, it is allowed that a UAV aborts the mission if it is found to have undergone too many shocks after it finishes serving a certain number of targets. The optimal routing plan together with the abort policy for each UAV are studied, with the objective to minimize the total cost consisting of the expected cost of UAV destruction and the expected cost for unvisited targets. Test case is used to illustrate the application of the framework.

1. Introduction

Unmanned aerial vehicles (UAVs) are widely employed in military forces for flying over dangerous areas to perform surveillance or combat missions [7,9,20]. UAVs may fly much longer than those of manned aircrafts, and they may visit many sites or targets during a mission. Therefore it is important to route the UAVs properly with consideration of various routing requirements. Often there are different kinds of considerations, say, a particular target can only be visited within a certain time window [4].

The routing of UAVs in military environments is a perfect example of a real-world vehicle routing problem (VRP), which is one of the most important and widely studied combinatorial optimization problems [5,24,27]. However, UAV routing problem is more complicated because of its own specifications [8,15,16]. The UAV routing problem has been addressed in some recent papers, such as Kinney et al. [10], Obelin et al. [17], and Coelho et al. [2]. Shima et al. [22] proposed a cooperative multiple task assignment problem and analyzed its computational complexity. Shetty et al. [21] studied the routing of unmanned combat aerial vehicles, which are equipped to carry dumb bombs or missiles to destroy targets. Edison and Shima [3] proposed a new approach for solving integrated task assignment and path optimization for cooperating UAVs using genetic algorithms. Guerriero et al. [6] studied the routing of UAVs considering soft constraints of time windows based on a multi-objective optimization approach. Avellar et al. [1] studied the routing of multiple cooperative UAVs for remote sensing. Liu et al. [14] studied the routing of aerial photography UAVs based on hierarchical optimization. Yakici [25] studied the optimal location and routing of small UAVs based on an ant colony algorithm. However, all these papers have not considered the option to abort the UAVs in case that the UAVs have experienced some shocks during the flight or service.

For systems executing dangerous tasks, sometimes it may be preferable to abort the mission if the benefit for continuing the mission is not enough to cover the expected loss of the system. As UAVs are usually expensive, this paper considers the risk that UAVs may experience shocks during the mission. The practical shocks may be shots by enemy, electromagnetic impulses, bad weather, etc. It is more probable that a UAV is destructed if it has experienced more shocks [26]. Thus, it may be advisable to abort the mission if it is found to have experienced too many shocks after serving a certain number of targets. Similar abort policy has been studied by some researchers recently, restricted to a single system fulfilling a single mission [12,13]. Practical applications usually involve multiple missions that need to be fulfilled sequentially [18,19]. In this case, it may be better to assign the missions to multiple UAVs for fulfilling. Therefore, the joint routing and aborting optimization problem is studied in this paper. For any given routing plan, the abort policy needs to be solved for all the UAVs. Then, given that the optimal abort policy is chosen for any routing plan, the optimal routing plan that minimizes the total cost is studied.

Section 2 describes the problem. Section 3 evaluates the performance measures. Section 4 describes the optimization problem to be solved. Illustrative examples are presented in Section 5 to demonstrate the application.

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Notation list

N	The number of targets
M	The number of UAVs
p	Shock arrival frequency
$C(i)$	The destruction probability of a UAV given that it suffers i shocks
c_u	Cost for each destructed UAV
c_t	Cost for each unvisited target
v_0	The base
v_i ($i\neq0$)	The target i
$t(i,j)$	Travelling time between v_i and v_j
$(e(i); l(i))$	Time window for visiting v_i
$s(i)$	Service time of v_i
$\boldsymbol{H_i}$	Set of targets assigned to UAV i
$\lvert\boldsymbol{H_i}\rvert$	The number of targets assigned to UAV i
$(k(i), r(i))$	The aborting policy for UAV i such that it aborts the mission and directly returns to the base if it is found to have experienced at least $r(i)$ shocks after serving the $k(i)$ th target
$T(i,j)$	The service finishing time of the jth target assigned to UAV i
$PS(i)$	the probability that each UAV i successfully visits all the targets and safely returns to the base
$PA(i)$	the probability that UAV i aborts the mission after serving the $k(i)$th target and safely returns to the base
$Pj(i)$	The probability that UAV is destructed after serving exactly j targets

2. The model

We assume that N targets are to be visited and the total number of available UAVs is M. The targets are to be assigned to UAVs so that each target is visited by at most one UAV and each target can be visited at most once. The UAVs depart from the base and return to the base after visiting the assigned targets. It is assumed that all the UAVs travel at the same constant speed. The paths between each pair of points, either base or targets, are given. It is assumed that the mission time is much shorter than the time between failures for the UAVs due to internal hardware or software problems, such that the internal failures are not considered. However, the UAVs are subject to shocks, which arrive according to a homogeneous Poisson process and the shock frequency is assumed to be a constant p for all the UAVs. It is reasonable to assume that the UAV has a bigger probability to be destructed if it has experienced more shocks. The probability that a UAV is destructed given that it experiences i shocks is denoted as $C(i)$, where i is a nonnegative integer and $C(0) = 0$. The cost for each destructed UAV is c_u, and the cost for each unvisited target is c_t.

The positions of the targets and the base can be described by the undirected graph $G(V, A)$, where $V = \{v_0; v_1;\ldots; v_N\}$, v_0 is the base, v_i ($i\neq0$) is a target; $A = \{(v_i, v_j): i \neq j, v_i,v_j \in V\}$, each arc (v_i, v_j) having a travel time $t(i,j)$. We assume that each node i ($i = 0, \ldots, n$) can only be visited within its time windows $(e(i); l(i))$. If a UAV arrives at target i ahead of its time window, it must loiter until $e(i)$ to serve the target. The service time of each target is denoted as $s(i)$. We use set $\boldsymbol{H_i}$ to denote targets assigned to UAV i. For example, $\boldsymbol{H_1} = \{3,10,32,8\}$ denotes that UAV 1 must depart from the base, and visit target 3, 10,32 and 8 in sequence before returning to the base. If there is no element in $\boldsymbol{H_i}$, UAV i is not used in the mission. The total number of targets assigned to UAV i is denoted as $|\boldsymbol{H_i}|$. For each UAV i, it aborts the mission and directly returns to the base if it is found to have experienced at least $r(i)$ shocks after serving the $k(i)$th target. Here, $k(i) \geq |\boldsymbol{H_i}|$ implies that UAV i will not abort the mission no matter how many shocks it experiences. Note that though the abort policy can be made based merely on $k(i)$ or $r(i)$, considering both of them has its advantage. Whether to abort a mission or not depends not only on how many shocks the UAV has suffered but also on how many targets it has already served. In case it is almost finishing visiting all the targets, it may be advisable to continue even it has already suffered many shocks, as visiting the rest of targets may not increase much risk. In case it still has many targets to visit when it has already suffered a lot of shocks, continuing the mission would incur a larger destruction risk comparing with aborting the mission.

3. Performance measures evaluation

3.1. The service finishing time of each target

For each fixed routing plan, the service finishing time can be obtained for each target. In particular, for each UAV i used, the service finishing time of the first target it visits equals to $T(i, 1) = \max(e(\boldsymbol{H_i}(1)),t(0, \boldsymbol{H_i}(1))) + s(\boldsymbol{H_i}(1))$ given that the upper limit of the time window for the i-th target is not violated. In order to make it easier to discuss, the upper limit of the time window is not considered in this section, but it is treated as a constraint in Section 4. The service finishing time of the j-th target assigned to UAV i can be obtained as $T(i, j) = \max(e(\boldsymbol{H_i}(j)),T(i,j-1) + t(\boldsymbol{H_i}(j-1), \boldsymbol{H_i}(j))) + s(\boldsymbol{H_i}(j))$. The total traveling time of UAV i in case it is not aborted or destructed is $T(i, |\boldsymbol{H_i}|) + t(\boldsymbol{H_i}(|\boldsymbol{H_i}|), 0)$.

3.2. The success probability of each UAV

In case $k(i) < |\boldsymbol{H_i}|$, the probability that each UAV i successfully visits all the targets and safely returns to the base is

$$PS(i) = \sum_{l=0}^{r(i)-1} \frac{\exp\{-p\cdot T(i,k(i))\}(p\cdot T(i,k(i)))^l}{l!} \sum_{v=0}^{\infty} \frac{\exp\{-p(T(i,|\mathbf{H_i}|) - T(i,k(i)) + t(\mathbf{H_i}(|\mathbf{H_i}|),0))\}(p(T(i,|\mathbf{H_i}|) - T(i,k(i)) + t(\mathbf{H_i}(|\mathbf{H_i}|),0)))^v}{v!} (1 - C(l+v)) \tag{1}$$

where $\frac{\exp\{-p\cdot T(i,k(i))\}(p\cdot T(i,k(i)))^l}{l!}$ is the probability that UAV i suffers l shocks when the $k(i)$th target is served, $\frac{\exp\{-p(T(i,|\mathbf{H_i}|) - T(i,k(i)) + t(\mathbf{H_i}(|\mathbf{H_{i}}|),0))\}(p(T(i,|\mathbf{H_i}|) - T(i,k(i)) + t(\mathbf{H_i}(|\mathbf{H_i}|),0)))^v}{v!}$ is the probability that UAV i suffers v shocks from finishing serving the $k(i)$th target until returning to the base, and $1-C(l + v)$ is the probability that the UAV is not destructed given that it has suffered $l + v$ shocks.

In case $k(i) \geq |\boldsymbol{H_i}|$, the probability that each UAV i successfully visits all the targets and safely returns to the base is

$$PS(i) = \sum_{l=0}^{\infty} \frac{\exp\{-p(T(i,|\mathbf{H_i}|) + t(\mathbf{H_i}(|\mathbf{H_{i}}|),0))\}(p(T(i,|\mathbf{H_i}|) + t(\mathbf{H_i}(|\mathbf{H_i}|),0)))^l}{l!} (1 - C(l)). \tag{2}$$

where $\frac{\exp\{-p(T(i,|\mathbf{H_i}|) + t(\mathbf{H_i}(|\mathbf{H_{i}}|),0))\}(p(T(i,|\mathbf{H_i}|) + t(\mathbf{H_i}(|\mathbf{H_i}|),0)))^l}{l!}$ is the probability that UAV i suffers l shocks from departing the base until returning to the base after visiting all the targets assigned to it.

3.3. The successful abort probability for each UAV

In case $k(i) < |\boldsymbol{H_i}|$, the probability that UAV i aborts the mission after serving the $k(i)$th target and safely returns to the base is

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