Bulletin of Networking, Computing, Systems, and Software – www.bncss.org, ISSN 2186-5140
Volume 8, Number 1, pages 39–40, January 2019

Low-Energy Routing for Deadline-Constrained Delivery Drones under Windy Conditions

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Abstract — **Drones are expected as a promising vehicle for home delivery services in near future. Different from ground transportation such as trucks, drones are largely affected by the wind, and also are severely constrained by the battery capacity. This paper studies low-energy routing for delivery drones under windy conditions.**

Keywords — delivery drones, vehicle routing problem, energy consumption

I. INTRODUCTION

Unmanned aerial vehicles (UAVs) or drones are considered as a promising vehicle for last-mile home delivery services in near future since they do not suffer from road traffic conditions. Unlike ground transportations such as trucks, however, drones are severely affected by the wind and are constrained by the battery capacity.

This paper studies a routing optimization problem for delivery drones. Given a set of items to be delivered, the problem asks the minimum-energy route under windy conditions, while meeting deadline constraints for the items. The problem addressed in this paper is an extension of *energy minimizing vehicle routing problems (EMVRPs)* [1]. In [1], an EMVRP is formulated as an integer linear programming problem. The energy consumption is assumed to be proportional to a product of the distance traveled and the total weight of the carrying items and the vehicle itself. Although there exist several pieces of literature on EMVRPs such as [1], [2] and [3], to our knowledge, no previous work on EMVRPs takes into account the effect of the wind. This is the first paper which studies a deadline-constrained EMVRP under windy conditions.

The reminder of this paper is organized as follows. Section II formally defines our routing problem and presents an algorithm for the problem. Section III describes preliminary experiments and Section IV concludes this paper.

II. DEADLINE-CONSTRAINED EMVRP UNDER WINDY CONDITIONS

This section presents a deadline-constrained EMVRP without the wind, and then extends it for windy conditions.

A. Deadline-Constrained EMVRP

EMVRP is an extension of a traveling salesman problem (TSP). TSP asks the shortest-distance route which starts from an origin, visits all customers, and returns to the origin. On the other hand, EMVRP is tailored for delivery services using vehicles such as trucks, and asks the route with minimum energy consumption. A principle behind EMVRP is that the energy consumption of a delivery vehicle depends not only on the distance traveled but also on the weight of the payload. The heavier the payload is, the higher the energy consumption is. For example, in [1], the energy is modeled as:

$$e(d, w) \propto d \times (W_D + w) \quad (1)$$

where d denotes the distance, and W_D and w denote the weight of the vehicle and that of the payload, respectively.

For simplicity, this paper assumes that all of the items are delivered in a single trip by a single drone. All of the items are loaded on the drone at the depot, and the drone delivers them. If the total weight of the items exceeds the capacity of the drone, the items need to be partitioned into groups for multiple trips.

Table 1 summarizes important notations used in the rest of this paper.

EMVRP aims at minimization of total energy consumption throughout the delivery trip. Therefore, the objective function of EMVRP is given by:

Minimize:

$$E = \sum_{j=0}^{N} p(w(j)) \times t(x(j), x(j+1)) \quad (2)$$

Table 1. Notations

N	The number of items (customers) to deliver.
i	Index of items (customers). $0 \le i \le N$ where 0 denotes a depot.
$W(i)$	Weight of item i.
$D(i)$	Deadline of item i.
$d(i1, i2)$	Distance from customer $i1$ to $i2$.
$x(j)$	j-th visited customer. Decision variable. $1 \le x(j) \le N \quad (1 \le j \le N)$ $x(j1) \ne x(j2) \quad (1 \le j1, j2 \le N)$ $x(0) = x(N+1) = 0$
$w(j)$	Total weight of items when departing j-th visited customer. $w(0) = \sum_i W(i)$ $w(j) = w(j-1) - W(x(j))$
$t(j)$	Time when arriving at j-th visited customer. $t(0) = 0$
$p(w)$	Power consumption of the drone with payload w.
$t(i1, i2)$	Flight time from customer $i1$ to $i2$.
v_D	Flight speed of the drone.

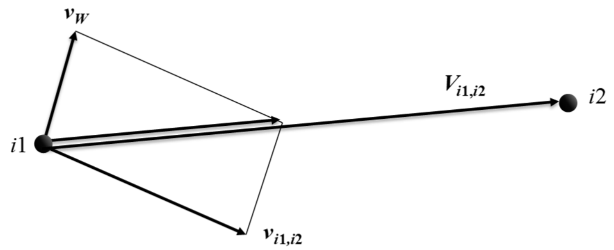

Figure 1. The effect of the wind.

The flight time without the wind is simply calculated by the following formula.

$$t\big(x(j), x(j+1)\big) = d\big(x(j), x(j+1)\big)/v_D \qquad (3)$$

It should be noted in Formula (2) that the energy consumption is approximated by a product of the power consumption and the flight time.

Item i must be delivered within its deadline time $D(i)$. The deadline constraint is formulated as follows.

Subject to:

$$\forall k (1 \le k \le N), \qquad \sum_{j=1}^{k} t\big(x(j-1), x(j)\big) \le D(x(j)) \qquad (4)$$

B. The Effect of the Wind

Under windy conditions, the flight time cannot be calculated by Formula (3), and it must be redefined.

Let us consider the flight time from customer $i1$ to $i2$. Figure 1 illustrates a flight from $i1$ to $i2$ under the wind. In the figure, $\boldsymbol{v_W}$ denotes the velocity vector of the wind. As a first step, this paper assumes that the wind $\boldsymbol{v_W}$ blows constantly all through the delivery flight. $\boldsymbol{V_{i1,i2}}$ denotes the position vector from customer $i1$ to $i2$. In order to reach customer $i2$ from $i1$, the drone should head towards velocity vector $\boldsymbol{v_{i1,i2}}$ as shown in Figure 1 in such a way that a sum of two vectors $\boldsymbol{v_{i1,i2}}$ and $\boldsymbol{v_W}$ goes to the same direction as $\boldsymbol{V_{i1,i2}}$. This paper assumes that the magnitude of vector $\boldsymbol{v_{i1,i2}}$ is fixed and is equal to v_D which is defined in Section II-A.

Given $\boldsymbol{v_W}$ and $\boldsymbol{V_{i1,i2}}$, we need to find the direction of $\boldsymbol{v_{i1,i2}}$ and flight time $t(i1, i2)$ for any two customers $i1$ and $i2$. The direction of $\boldsymbol{v_{i1,i2}}$ and $t(i1, i2)$ can be calculated by the following equations.

$$\forall i1, i2, \quad t(i1, i2) \times (\boldsymbol{v_{i1,i2}} + \boldsymbol{v_W}) = \boldsymbol{V_{i1,i2}} \qquad (5)$$

$$\forall i1, i2, \quad |\boldsymbol{v_{i1,i2}}| = v_D \qquad (6)$$

Then, the deadline-constrained EMVRP under windy conditions is formally defined. The problem asks the route $x(j)$ which minimizes the objective function (2) subject to (4), (5) and (6).

C. Algorithm

To solve the EMVRP defined in Section II-B, we develop a simple exhaustive algorithm. Note that the number of possible solutions for the problem is $N!$ including the ones which violate the deadline constraint, and the solution space can be expressed as a search tree with $N!$ leaves. Basically, our algorithm exhaustively explores the search tree in a depth-first manner. In order to reduce the search space, our algorithm checks if the deadline is violated or not, every time the algorithm visits a new node of the tree. If violated, the algorithm no longer explores the sub-tree under the node.

Table 2. Energy consumption under windy conditions

#customers	EMVRP	DC-EMVRP	this work
4	27,204	27,204	27,204
5	31,496	31,496	31,496
6	33,026	33,026	33,026
7	miss	40,755	40,755
8	miss	37,127	37,127
9	miss	38,428	38,428
10	49,777	49,777	49,777
11	39,994	39,994	39,994

III. Preliminary Experiments

We have conducted preliminary experiments with eight randomly-generated problem instances whose number of customers ranges from 4 to 11. This work is compared with two routing methods, i.e., EMVRP and DC-EMVRP. EMVRP finds the minimum-energy route without considering the deadline constraint and the wind. DC-EMVRP finds the minimum-energy route under the deadline constraint without considering the wind. Table 2 shows the energy consumption of the delivery routes obtained by the three methods. Note that the energy values in the table take into account the effect of the wind, although EMVRP and DC-EMVRP do not consider the wind effect when they search the routes. In the experiments, our work successfully finds the minimum-energy routes while satisfying deadline constraints under windy conditions for all of the eight cases. EMVRP violates the deadline for three cases out of eight. DC-EMVRP finds the same routes as our work, although it is not guaranteed theoretically that DC-EMVRP obtains minimum-the energy routes which meet the deadline.

IV. Conclusions

In this paper, we have presented deadline-constrained energy-minimizing routing for delivery drones under windy conditions. We have formally defined the routing problem and proposed an algorithm. We are currently conducting more extensive experiments to evaluate the effectiveness of this work. Also, in future, we will extend the work for more realistic conditions where the wind changes over time.

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