Transportation Research Part C 90 (2018) 198–212

Contents lists available at ScienceDirect

Transportation Research Part C

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

A range-restricted recharging station coverage model for drone delivery service planning

Insu Hong[a,*], Michael Kuby[b], Alan T. Murray[c]

[a] Department of Geology and Geography, West Virginia University, United States
[b] School of Geographical Sciences and Urban Planning, Arizona State University, United States
[c] Department of Geography, University of California at Santa Barbara, United States

ARTICLE INFO

Keywords:
Unmanned aerial vehicles
Spatial optimization
Euclidean Shortest Path
GIS
Location modeling

ABSTRACT

Unmanned Aerial Vehicles (UAVs) are attracting significant interest for delivery service of small packages in urban areas. The limited flight range of electric drones powered by batteries or fuel cells requires refueling or recharging stations for extending coverage to a wider area. To develop such service, optimization methods are needed for designing a network of station locations and delivery routes. Unlike ground-transportation modes, however, UAVs do not follow a fixed network but rather can fly directly through continuous space. But, paths must avoid barriers and other obstacles. In this paper, we propose a new location model to support spatially configuring a system of recharging stations for commercial drone delivery service, drawing on literature from planar-space routing, range-restricted flow-refueling location, and maximal coverage location. We present a mixed-integer programming formulation and an efficient heuristic algorithm, along with results for a large case study of Phoenix, AZ to demonstrate the effectiveness and efficiency of the model.

1. Introduction

Unmanned aerial vehicles (UAVs), or drones, have developed rapidly for commercial and personal uses, from military to surveillance/monitoring, journalism, scientific research, photography, emergency response, and recreational activities (Finn and Wright, 2012; Clarke, 2014; Sandbrook, 2015). Deploying drones for delivery service of small packages has attracted much attention, and several companies and public agencies have proposed or tested drone delivery service at a small scale (Hern, 2014; Murray and Chu, 2015; Ha et al., 2015a,b; Weise, 2017). Amazon (2017) is considering a premium delivery service called Amazon Prime Air, which would provide rapid delivery of packages within 30 min of ordering online. While not ready to completely replace the familiar delivery trucks, anytime soon, drones appear well-suited to augment existing road deliveries for high-margin, last-minute service to single-family homes and stand-alone businesses, and to bypass road congestion (Agatz et al., 2015). Another promising application is for reaching areas lacking road access, such as small islands and rainforest (Zhang and Kovacs, 2012; Hern, 2014; Toor, 2016).

To develop a stand-alone drone delivery service, a route planning strategy is necessary, based on efficient delivery routes in continuous two-dimensional space. Although a drone may not need to follow a pre-defined transportation network, barriers such as high-rise buildings, mountains and flight-restricted zones may impede a more direct flight path. In the literature, the problem of finding the best obstacle-avoiding route is known as the Euclidean Shortest Path (ESP) problem (Lozano-Pérez and Wesley, 1979; Asano et al., 1986; Hong and Murray, 2013).

* Corresponding author.
E-mail address: insu.hong@mail.wvu.edu (I. Hong).

https://doi.org/10.1016/j.trc.2018.02.017
Received 15 November 2016; Received in revised form 9 October 2017; Accepted 20 February 2018
Available online 22 March 2018

Another factor to consider in path planning for delivery drones is the limited flight range of battery-powered or fuel-cell drones. Several logistical strategies have been proposed to deal with the range limitation in a drone delivery system. A multi-modal approach would combine drones with trucks, using the advantages of one to offset the disadvantages of the other, such as by launching drones from trucks for the "last-mile" only (Murray and Chu, 2015; Agatz et al., 2015; Ha et al., 2015a). Alternatively, a single-mode (drone-only) door-to-door drone delivery system from warehouse to customers would have to rely on single or multiple stops at battery-recharging, battery-replacing, or hydrogen-refueling stations (Sundar and Rathinam, 2014; Dorling et al., 2017; Yu et al., 2017). Our paper contributes to the development of the drone-only strategy by optimizing new locations of recharging stations for efficient drone delivery service without other modal needs.

A substantial literature has emerged for optimizing the locations of recharging facilities on a network for alternative-fuel vehicles. Kuby and Lim (2005) developed the Flow Refueling Location Model that explicitly takes into account the travel range of alternative-fuel vehicles when locating refueling or recharging stations on road or rail networks.[1] The flow refueling model locates a given number of stations to maximize the origin-destination flow volume that can travel without running out of fuel. The drone-recharging problem, however, is more complex. Unlike road or rail vehicles operating on a defined network, the designation of candidate station sites changes the potential routes over which drones may fly, from which optimal flight paths are derived. In addition, the potential service area of stations will be determined by the flight range of drones. Therefore, a coverage location model integrating the ESP is needed to optimize the location of stations for drone delivery service.

In this paper, we propose a new location model for optimally siting recharging stations to support commercial stand-alone drone delivery service in an area with obstacles. The new model combines elements of the ESP, the flow refueling, and the maximal cover location model to locate stations and construct a feasible and efficient delivery network in order to serve a region efficiently. A heuristic technique is developed that exploits spatial knowledge. Application results are presented to demonstrate the effectiveness of the proposed approach.

2. Background

The utility of UAVs has been rapidly expanding, especially in the civilian sectors (Finn and Wright, 2012; Clarke, 2014; Mohammed et al., 2014). The low operating cost of drones creates numerous opportunities for small-scale applications (Zhang and Kovacs, 2012; Sundar and Rathinam, 2014). UAVs have been deployed for data collection of disease propagation (Fornace et al., 2014), agricultural applications (Zhang and Kovacs, 2012; Pérez-Ortiz et al., 2015), vegetation analysis (Paneque-Gálvez et al., 2014), wildlife monitoring and conservation (Linchant et al., 2015; Sandbrook, 2015), nighttime lighting assessment (Murray and Feng, 2016), and many more. Other applications include disaster response (Adams and Friedland, 2011), disease control (Amenyo et al., 2014), traffic monitoring (Kanistras et al., 2014), urban planning (Mohammed et al., 2014), mapping (Tahar et al., 2012), and law enforcement (Finn and Wright, 2012; Clarke, 2014). The U.S. Federal Aviation Administration (FAA) prohibits commercial operations of drones but issues exemptions on a case-by-case basis for applications such as aerial surveying and photography, utility inspection, and filming (Dillow, 2015). Amazon, DHL Germany, and UPS have recently tested or attempted delivery service using drones (Hern, 2014; Amazon, 2017; Weise, 2017).

With growing commercial interest in drone delivery systems, researchers have begun developing operations research models for optimizing delivery systems. Several papers have proposed multi-modal drone-truck systems, where delivery trucks function as moving depots and drones launch from the trucks (Ha et al., 2015a,b). Murray and Chu (2015) coined the term "flying sidekick traveling salesman problem," which first constructs traveling salesman truck routes and then substitutes drones that deliver to certain customers and return to the truck down-route. A variant allows customers close to the warehouse to be served directly by drones, which either return to the warehouse or meet a truck route (Murray and Chu, 2015). Agatz et al. (2015) studied the Traveling Salesman Problem with Drone, where the drone must follow the road network. Ha et al. (2015a) proposed two heuristics for the minimax delivery time traveling salesman with drone problem, while Ha et al. (2015b) proposed a cost-minimizing objective. Mathew et al. (2015) modeled the Heterogenous Delivery Problem, in which drones launched from trucks from a road endpoint deliver to isolated customers located off the road network.

A second but smaller group of drone delivery models focuses on drone-only strategies. Dorling et al. (2017) propose a vehicle routing and traveling salesman problem with a flight range restriction that allows UAVs to make multiple returns to the depot to pick up additional packages and swap for a fresh battery. Sundar and Rathinam (2014) optimize routes using the existing locations of recharging facilities away from the base. The model proposed in this paper extends this second group of drone-only approaches to the problem of locating a limited number of stationary recharging stations assuming that drones deliver to one customer per trip, consistent with the preliminary descriptions of Amazon Prime Air (2017) but with flying range extended via multiple recharging stops.

We know of no previous papers that optimize where to build a limited number of new stations for drone refueling during deliveries. The closest work is by Yu et al. (2017) who propose two generalized traveling salesman problems for drones capable of carrying multiple packages: one for multiple stationary charging stations and another for a single mobile charging station. Their stationary charging model, however, locates stations everywhere charging takes place, with no limit on the number that can be

[1] For the remainder of this paper, we will use the general term "recharging" for any method of restoring a drone's energy storage system to 100%. The term "fuel" or "refueling" will only be used where it has become standard in the literature, such as alt-fuel vehicles or the flow-refueling location model. Nevertheless, these terms are interchangeable.