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The flying sidekick traveling salesman problem: Optimization of drone-assisted parcel delivery

Chase C. Murray *, Amanda G. Chu

Department of Industrial & Systems Engineering, Auburn University, 3301 Shelby Center, Auburn, AL 36849-5346, USA

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A B S T R A C T

Once limited to the military domain, unmanned aerial vehicles are now poised to gain widespread adoption in the commercial sector. One such application is to deploy these aircraft, also known as drones, for last-mile delivery in logistics operations. While significant research efforts are underway to improve the technology required to enable delivery by drone, less attention has been focused on the operational challenges associated with leveraging this technology. This paper provides two mathematical programming models aimed at optimal routing and scheduling of unmanned aircraft, and delivery trucks, in this new paradigm of parcel delivery. In particular, a unique variant of the classical vehicle routing problem is introduced, motivated by a scenario in which an unmanned aerial vehicle works in collaboration with a traditional delivery truck to distribute parcels. We present mixed integer linear programming formulations for two delivery-by-drone problems, along with two simple, yet effective, heuristic solution approaches to solve problems of practical size. Solutions to these problems will facilitate the adoption of unmanned aircraft for last-mile delivery. Such a delivery system is expected to provide faster receipt of customer orders at less cost to the distributor and with reduced environmental impacts. A numerical analysis demonstrates the effectiveness of the heuristics and investigates the tradeoffs between using drones with faster flight speeds versus longer endurance.

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1. Introduction

Amazon CEO Jeff Bezos recently captured headlines when he announced on the CBS broadcast of *60 Minutes* that his company has developed a fleet of unmanned aerial vehicles (UAVs) for small parcel delivery (Rose, 2013). The plan set forth by Bezos would use UAVs to deliver parcels from distribution centers (warehouses) directly to customers via Amazon's *Prime Air* UAV, pictured in Fig. 1a. In the warehouse-to-customer operation, parcels are loaded into a container that is held by the UAV, also known as a *drone*, *unmanned aircraft system* (UAS), and *remotely piloted aircraft* (RPA). The UAV departs from the warehouse and travels to the customer location, where it navigates via the onboard global positioning system (GPS). The container (with parcel inside) is dropped off near the customer's front door and the UAV returns to the warehouse. All of this takes place without human intervention or guidance.

While some dismissed this announcement as a publicity stunt (Carlson, 2013 notes that the story aired the night before "Cyber Monday," one of the busiest online shopping days annually), Amazon is not alone in the race towards delivery-by-drone. German postal and logistics group Deutsche Post DHL recently announced that their *Parcelcopter*, pictured in

* Corresponding author. Tel.: +1 334 844 7931; fax: +1 334 844 1381.
E-mail addresses: cmurray@auburn.edu (C.C. Murray), agc0009@auburn.edu (A.G. Chu).

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Fig. 1b, has been authorized to deliver medical supplies to a car-free island off the coast of Germany (Bryan, 2014). Australian textbook distributor Zookal has begun testing delivery-by-drone in Australia, Singapore, and Malaysia, with hopes of entering the U.S. market in 2015 (Welch, 2013). UPS is also said to be considering the use of drones for moving packages within, or between, warehouses (Stern, 2013). More recently, Google entered the arena with the announcement of their *Project Wing*, featuring a vertical-takeoff-and-landing aircraft with a wing-shaped body (Madrigal, 2014).

The use of UAVs for "last-mile" parcel delivery promises to change the landscape of the logistics industry. However, there remain several significant regulatory and technological barriers to overcome before drones realize widespread adoption in the commercial sector. In the United States, Federal Aviation Administration (FAA) rules currently prohibit the use of UAVs for commercial purposes (although other countries have less restrictive regulations). The FAA also requires UAVs to be operated under a ceiling of 400-feet and within the "pilot's" line-of-sight, severely limiting their effective range and forcing a human operator to be occupied throughout the flight. However, while Amazon's fleet of drones remains grounded for now, the FAA has cleared oil and gas company BP (formerly British Petroleum) to fly UAVs at sea and over Alaska (Jansen, 2014). This move may signal that companies like Amazon could be given the green-light soon, as the FAA is expected to provide updated guidance on the use of commercial UAVs in 2015.

From the technical perspective, researchers are working to improve the endurance and safety of UAVs. Because UAVs of the size appropriate for small parcel delivery are battery operated, one such research area involves the improvement of battery energy storage. Limited battery capacity impacts the flight endurance of these aircraft, which can also be affected by flight speed and payload. Additionally, for safety and reliability purposes, these UAVs may require redundant systems (e.g., additional motors and sensors) that further reduce flight endurance. Furthermore, UAVs rely on GPS, which has a limited accuracy of about 10 m without corrective technologies (Arnold and Zandbergen, 2011). UAVs operating in heavily forested areas or so-called *urban canyons* may lose contact with a GPS signal. As such, there is increased interest in localization and navigation approaches that enable UAVs to function in GPS-denied environments (c.f., Clark and Bevly, 2008; Marais et al., 2014). Similar research is also being conducted to combat GPS "spoofing," whereby false signals are broadcast to enable the hijacking of a UAV (c.f., Humphreys, 2012; Faughnan et al., 2013). Even with perfect localization information, (semi-)autonomous UAVs require the ability to perform obstacle detection and avoidance. This is a fertile research area in robotics, where vision-, sonar-, and laser-based methodologies are being improved (c.f., Jimenez and Naranjo, 2011; Merz and Kendoul, 2013; Apatean et al., 2013; Pestana et al., 2014; Park and Kim, 2014). Given the potential for UAV applications, it is not surprising that a recent market study by the Teal Group forecasted that UAV spending will more than double over the next decade, with cumulative worldwide expenditures exceeding $89 billion. Although much of this research will be for military purposes, small UAVs (those weighing less than 55 lb) of the type suitable for commercial applications represent the highest growth potential (Teal Group, 2014).

While research related to overcoming the aforementioned *technical* issues is abundant, we are aware of no studies addressing the *operational* challenges. For example, consider the direct warehouse-to-customer operation proposed by Amazon. The *Prime Air* UAV has a range of 10 miles (Gross, 2013). Thus, UAV deliveries must originate from distribution centers located in close proximity to customers. This may require a relocation of existing distribution centers, or the construction of new ones. To enjoy economies of scale, these distribution centers (DCs) would presumably be located near densely populated urban areas where, paradoxically, customers tend to live in high-rise housing with no "front door" on which to receive deliveries via UAV. Furthermore, although Amazon indicates that 86% of its deliveries weigh less than the five-pound payload capacity of its *Prime Air* UAVs (Gross, 2013), the remaining percentage of deliveries would still require delivery by traditional means. Such a system is depicted in Fig. 2b, where circular nodes indicate customers whose parcels cannot be delivered via UAV.

Depending upon the number of available UAVs, as well as the performance characteristics of the fleet, it may not be optimal to deliver-by-drone to all eligible customers. For example, in Fig. 2c the total time required to deliver to all customers is decreased if the truck delivers parcels to some of the customers that could feasibly be served by the UAV.

In cases where the distribution center is located far from the customers, an alternative is to pair the UAV with a traditional delivery truck, as depicted in Fig. 3b. The delivery truck departs from the DC carrying a UAV and all customer parcels. As the driver makes deliveries, the UAV is launched from the truck, carrying parcels for individual customers.

(a) Amazon's *Prime Air* UAV (source: amazon.com)

(b) DHL's *Parcelcopter* (source: dhl.com)

Fig. 1. UAVs under evaluation for small parcel delivery.

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